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Assessment methods for comfort of consumer products at early stages of the development process

Stavrakos, Stavros Konstantinos; Ahmed-Kristensen, Saeema; Goldman, Tomasz

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Assessment methods for comfort of consumer products at early stages of the development process

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Stavros - Konstantinos Stavrakos

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This thesis is prepared by

Stavros - Konstantinos Stavrakos

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ISBN ……………………………

Supervisor
Saeema Ahmed – Kristensen
Industrial Supervisor
Tomasz Goldman

DTU Management
Division of Technology and Innovation Management
Produktionstorvet 426
DK – 2800 Kgs. Lyngby
Denmark
www.man.dtu.dk
Tel: (+45) 4525 4800

Printer: ……..............

Abstract

Design engineers who are involved in the early conceptual phase of the development of products such as seats, headphones and domestic appliances stress the increasing importance of comfort. Comfort is taken into account in the purchasing decisions of buying a chair, a bed, and when driving a car, or flying. The terms comfort and discomfort are widely used in studies where prototypes are tested for comfort. Despite the frequent use of these terms there is an absence of a general notion of comfort or discomfort. There are three main issues when designing a product to achieve comfort: 1) the exact cause of comfort is unknown, 2) comfort relies to a certain extent on subjectivity and, 3) there is a lack of a methodology for considering comfort in the design process [Vink, 2005].

This thesis describes an investigation to gain an understanding of the nature of comfort in product design at the early stages of the design process and, to investigate the factors that influence the different dimensions of comfort (physical, physiological and psychological). The investigation has been conducted in strong collaboration with an industrial partner working with ear-worn devices, providing access to data, products and possibilities to test methods.

Three empirical studies were carried out within the industry of external-ear body worn products for commercial use. Key findings included the identification of associations between human dimensions and product dimensions by providing an extended matrix of human dimensions advancing the understanding of human geometry and product complexity. The findings of this research also revealed that there are strong dependencies between comfort and the attractiveness towards the visual profile of a product. Positive attractiveness towards a product enhances the expectation and experience of comfort and vice versa. Additionally, archetype individuals were identified for the issuing of representative user panels to be used in the comfort studies conducted at the early conceptual phase of the design process.

From the findings, a methodological framework was developed summarizing all the applications of 2-dimensional and 3-dimensional data. In addition, a matrix of archetype persons was also generated with the aim to support designers in streamlining users for the creation of more reliable user panels for the execution of comfort studies to evaluate prototypes in terms of comfort.

The methods have been evaluated and implemented within the collaborating company of external-ear body worn products. The research has contributed towards understanding the multidimensionality of comfort and towards providing with methods to assess comfort at the early stages of conceptual development.

Abstract (In Danish)

Designingeniører, der er involveret i den tidlige konceptuelle fase i udviklingen af produkter som sæder, hovedtelefoner og husholdningsapparater, understreger den stigende betydning af komfort. Komfort er et element der tages i betragtning i mange købsbeslutninger, som f.eks. når vi køber en stol, en seng eller når vi kører bil eller er på flyrejse. Begreberne komfort og ubehag er meget brugt i undersøgelser, hvor prototyper testes for brugbarhed. På trods af den hyppige brug af disse begreber mangler vi en generel opfattelse af komfort eller ubehag. Der er tre udfordringer vi møder, når vi designer et produkt for at opnå komfort: 1) den nøjagtige årsag til komfort er ukendt, 2) opfattelsen af komfort er til en vis grand subjektiv og 3) vi mangler en metode til at inddrage komfort i designprocessen [Vink 2005].

Denne afhandling beskriver en undersøgelse, der skal hjælpe os til at få en forståelse af karakteren af komfort i de tidlige faser af designprocessen. Den undersøger endvidere de faktorer, der påvirker de forskellige former for komfort (fysiske, fysiologiske og psykologiske). Undersøgelsen er gennemført i tæt samarbejde med en industriel partner, der arbejder med produkter, som bæres på øret, som f.eks. høretelefoner. Denne partner har endvidere givet adgang til data, produkter og mulighed for at teste metoder.

I løbet af projektet blev tre empiriske undersøgelser gennemført inden for branchen af kommercielle produkter som bæres på øret. Undersøgelsens konklusioner omfattede identifikation af sammenhænge mellem menneskelige proportioner og produktproportioner. En udvidet matrix af menneskets proportioner fremmer forståelsen af sammenhængen mellem den menneskelige geometri og produktets kompleksitet. Resultaterne af denne forskning viste også, at der er en stærk indbyrdes afhængighed mellem produktets komfort og dets visuelle tiltrækningskraft. Et andet resultat af undersøgelsen var identifikationen af arketype-individer til brug for dannelsen af repræsentative brugerpaneler, der skal anvendes i komfortundersøgelser i den tidlige konceptuelle fase af designprocessen.

På baggrund af disse resultater blev der udarbejdet en metode som sammenfatter alle anvendelsesmulighederne af 2-dimensionelle og 3-dimensionelle data. Desuden blev der genereret en matrix af arketyper med det formål at støtte designere i at strømline brugere til oprettelse af mere pålidelige brugerpaneler for gennemførelsen af komfortundersøgelser.

Metoderne er blevet vurderet og implementeret i samarbejde med den industrielle partner. Forskningen har bidraget til forståelsen af flerdimensionalt komfort og til at skabe metoder til vurdering af komfort på de tidlige stadier af konceptuel udvikling.

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To stelios (and nefeli)

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Chapter 1 Introduction

This thesis describes an investigation to gain an understanding of the nature of comfort in product design at the early stages of the design process and the factors that influence the different dimensions of comfort (physical, physiological and psychological). A method to help designers in creating a representative user panel for the various comfort studies has been developed and ergonomic guidelines for the achievement of physical comfort are also provided based upon the findings of the research.

The research was carried out in collaboration with a company, which designs (external) ear worn products for commercial use, such as Bluetooth devices and headphones. The industry of external-ear, body worn products is a mature design industry with a typical project lasting a few months. Unlike the hearing aid industry, which uses expensive individual fitting process and custom-fit products, the headset industry relies for cost reasons on using standard products fitted using adjustable mechanics. Comfort is an issue addressed from the beginning of the conceptualization of a product (early prototype phase) until the later stages of conceptual design. During these phases, comfort is an important consideration, with products that interact with humans. However, the lack of an operating definition of comfort, affects the quality of the comfort studies executed at the early prototype phase, and most companies use a trial-and-error approach to evaluate the more matured prototypes, compromising the time-to-market and the goal for comfortable products overall.

The industry of external-ear worn products, along with other industries, has recognized the need for a more generalized methodology to streamline the process of designing comfortable products. The collaborating company, working on external ear body worn devices, has invested in initiatives to address this issue, having included small scaled projects in the past, focusing more on the achievement of wearing comfort.

1.1 Motivation for research

Industry aims for products that are comfortable in order to stay ahead of competition. It is important to achieve comfort when designing products that are to be worn. On the other hand, discomfort should be prevented in order to allow for satisfactory rates of human performance as well as to reduce any negative effects on the user during the user-product interaction. For example a bus cabin should be designed around the driver so that it facilitates the driver’s performance. The environment around an assembly worker or the software environment for an office worker, in the same sense, should be designed in a way which boosts their productivity.

A longitudinal study has linked negative comfort (discomfort) to musculoskeletal problems and a series of complaints in the back, neck and other body parts [Merllié *et al.* 2002]. The Second European Survey on Working Conditions [Merllié *et al.* 2002] which took place in 1996, where a sample of 1000 workers from each member state were interviewed, revealed that back pain (30% of the workers) and muscular pains in arms or legs (17% of workers) are among the most common work-related health problems. Absenteeism due to work-related health problems affects 23% of workers each year (averaging out at 4 working days lost per worker). These health problems strongly relate to postural musculoskeletal discomfort. Reducing discomfort is, therefore, of high importance.

A debate lies in the literature regarding the definition of comfort and there is to our knowledge no prior art describing comfort for headsets (or other product devices that are worn around the ear) as much of this knowledge is kept confidential. However, comfort has been investigated for other products like office chairs [Zhang *et al.* 1996], and hand tools [Kuijt-Evers *et al.* 2004]. Therefore such prior studies could provide insight into how comfort is evaluated in other industries and also provide methodologies that can be utilised.

Limited literature exists regarding the external ear anatomy. The internal ear anatomy is much better understood as hearing aid companies are collecting ear-canal imprints for statistical ear-canal size and diameter analysis. The few studies that do focus on the external ear, (e.g. [Ruiz, 1986], [Knight *et al.* 2002], [Redström *et al.* 2006]) are focusing on the geometrical parameters that are not relevant for headsets. An advancement of the knowledge of the external ear anatomy is needed. Therefore, a collection of anthropometric data could have greater applicability (beyond headsets) and could also benefit the hearing aid industry.

Regarding the testing of users during the conceptual phase of the design process, the current state of the art is to select test panels at random with little considerations for whether the selected individuals are representative for a population at large and relying on anecdotal knowledge of specific users exhibiting unusual ear geometry, e.g. as used in the assessment of comfort of wearable computers [Knight *et al.* 2002]. This requires a large number of users to represent the intended population. The domain of design research has undertaken investigations of the relation between design and use [Redström *et al.* 2006], participation [Greenbaum *et al.* 1991], and co-creation [Sanders, 2006], where studies observing the product in use and context are often utilized. Both of these approaches are time consuming and expensive as the number of users required, ensuring that conclusions from the data is extractable to a wider population, is over 100. In addition, user driven research tends to be context dependent. The user test approach needs to be defined taking the specific problem of comfort and great variability of ears (sizes, angles) into account. General user test approaches are known, and can be used as input for analysis.

These studies suggest that there is a need to define comfort in product design and advance the knowledge in external ear anthropometry. A reliable method needs to be investigated to create representative user panels to include in the comfort studies executed during the early conceptual design. In addition, the industry of external-ear worn products along with other industries of consumer products which are in physical contact with the human body has recognized the need to *strive* for comfort. In order to achieve this, the nature and influencing factors of comfort need to be more clearly understood.

1.2 Aims of research

The project aims to develop an interdisciplinary methodology to assess comfort of consumer products (in this case, headsets) for comfort. The specific aims of the research project are:

- To bring the assessment of comfort (and knowledge) earlier in the concept phase of the design process rather than relying on the testing of prototypes.
- To develop an approach to streamline user testing for comfort.
- To create computational support to allow evaluations of product designs to identify problem areas early in the development lifecycle leading to faster development cycles and higher quality products.

This project hopes to advance the state of the art and contribute to the field of user driven design (or more specifically user testing) through developing a general methodology to streamline this process, by identifying archetype ears, and creating computational support to evaluate product designs (in this case headsets) to identify comfort areas. The project contributes to the general area of user involvement and does not expect to replace the role of users, but to focus the user involvement. It is expected that the methodology employed can be transferred to other user involvement research.

The scientific approach to headset comfort evaluation is an important new knowledge area which will contribute to understanding how a seemingly difficult design, evaluation and test process involving many users and many variables can be transformed into a structured approach using a combination of understanding of statistics of ear geometry variations and actual user tests. In particular, the problem of excluding outliers and including archetypes for the test panel is a new approach for product testing. This area of research is also of interest to the hearing aid industry where today only expensive custom-fit products are being used.

1.3 Thesis structure

The thesis is an article based thesis. The research methodology employed is described in Chapter 3, section 1.1.

The structure of the thesis is summarized below.

Chapter one, Introduction. This chapter provides the background to the research together with the research aims and discusses the main terms used. The structure of the thesis is also outlined.

Chapter two, Literature Review. This chapter provides the background to the research area and identifies areas for further research. Literature is reviewed in the areas of: (1) comfort terminology, (2) influencing factors of comfort, (3) comfort methodologies and (4) methods of collection of anthropometric data.

Chapter three, Research Approach. This chapter describes the overall research methodology and the research methods employed for each of the studies carried out. The research issues related to carrying out empirical research within industry are also discussed.

Chapter four, Findings. This chapter describes the findings from each of the studies carried out and relates these to the findings from the literature reviewed.

Chapter five, Method of support and preliminary evaluation. This chapter describes a proposed methodological framework to collect, generate and analyze anthropometric dimensions from a 3-D dataset and a proposed methodology to generate archetypes to represent populations at large.

Chapter Six, Conclusions. This chapter presents a summary of the research findings together with the main conclusions. Possible areas for future research are also discussed.

The thesis contains the following Appendices:

Appendix 1. The 7 papers written in the course of this project are included.

Chapter 2 Literature Review

This chapter presents a review of the literature in 4 areas, namely; (1) comfort terminology; (2) influencing factors of comfort; (3) comfort methodologies and; (4) methods to collect anthropometric data.

The literature review provides a background to the area of comfort theory. The review on comfort terminology examines mainly scientific definitions with the aim to select an operational definition for comfort. Through investigating influencing factors of comfort, areas where concepts regarding comfort are underdeveloped can be identified. The review on different methods of comfort aims to collect together different approaches to research on comfort. Reviewing the various methods of collection of anthropometric data turns the focus on ergonomics and physical comfort. Elements of the review can be found in Paper 1, see Appendix 1.

2.1 Comfort Terminology (CT) – Definitions in dictionaries and the scientific literature

This section will introduce comfort definitions. In dictionaries, comfort is linked to "feelings of relaxation" [Webster, 2008] and "things which bring physical ease or contribute to a state of well-being" [Webster, 2008]. Comfort is also seen as a state of "freedom from pain" as well as comfort is explained as a "convenience of the interior" [Oxford, 2005]. In medical dictionaries comfort is described as "a subjective state of well-being in relation to an induced environment including mechanical vibration or shock" [Mijnwoordenboek, 2012]. Comfort is commonly associated with terms such as, "assistance, relief, support" [Webster, 2008] and is also seen as "a feeling of freedom from worry or disappointment" [Mijnwoordenboek, 2012]. Hence, comfort is associated with the environment and with products which bring bodily ease. Moreover, physical (freedom from pain) and emotional aspects (relief, freedom from worry or disappointment) of comfort are identified.

In the scientific literature, comfort has been linked to the term "discomfort" since the first attempt to operationally define comfort as "the absence of discomfort" [Hertzberg, 1958]. Slater [1980] defines comfort as a pleasant state of physiological, psychological and physical harmony between a human being and the environment. Richards [1980] states that comfort is the state of a person that involves a sense of subjective well-being in reaction to an environment or a situation. In regards to the subjective nature of comfort, Vink [2005] states that "Comfort is a subjective experience. For example, for passenger 1 on a long distance flight, back discomfort may be of great importance, whereas passenger 2 wants a reduction in noise and passenger 3 needs more space."

2.1.3 Comfort as an attribute; comfort as an achievement

Two contrary positions on a definition for comfort support the need to involve the individuals actively in the assessment of comfort experience: Comfort is seen as an attribute or as an achievement. Before the term comfort was materialized in the 1920's, early definitions saw comfort as a state of mind; later, comfort came to be considered to be an attribute – of food, furniture, clothing, or the indoor climate – and this way, it became commoditised [Jaffari *et al.* 2009]. If comfort can be technically specified, then controlling comfort consists only of controlling technical parameters. Following a period of energy-intensive mechanical systems, responsibility for achieving comfort was placed on the technology rather than the occupants [Cole *et al.* 2008]. These technical approaches to comfort provisioning involved comparatively unstructured ideas about building users [Hitchings, 2009], seeing individuals as passively moving through tightly specified, technically – controlled spaces rather than actively engaging with those spaces in order to practice comfort in a mixture of technical and non-technical ways [Jaffari *et al.* 2009].

A contrary position views comfort as an achievement. This view recognizes that individuals have the ability to choose from a range of technologies and practices in order to achieve comfort, seeing this as positive, in contrast to "comfort-as-attribute" approaches that tend to view individual agency as a risk to be minimized and managed [Cole *et al.* 2008]. Individuals may devise their own strategies to manage comfort, which may not overlap with those that mechanical engineers and designers have provided for [Jaffari *et al.* 2009]. The "comfort-as-achievement" view sees comfort as being "personally idiosyncratic, culturally relative, socially influenced and highly dependent on temporality, sequence and activity" [Cole *et al.* 2008], where individuals may choose to manage their comfort in different ways and may feel differently about different ambient conditions [Hitchings, 2009]. This contrasts with the "comfort-as-attribute" view which assumes that comfort is a more-or-less uniform physiological property.

2.1.4 The dis-continuum of comfort

Comfort is not a well-defined concept yielding an on-going debate in the literature. Several researchers [Hertzberg, 1958], [Floyd *et al.* 1958], [Richards, 1980], [Leuder, 1983], [Bishu *et al.*

1981], are making a distinction between two different states of comfort, that is, the absence of comfort and the presence of comfort, in which the term comfort is defined as the absence of discomfort. This does not necessarily entail a positive effect [Branton, 1969]. In fact according to Bishu *et al.* [1981], in the context of seating design, “the goal of the designers is to reach the state of absence of discomfort, where the working individual is oblivious of the fact that he or she is seated.” In his study, Richards [1980] has suggested that the fact that people rate their subjective responses across the entire continuum indicates that positive discomfort is part of a bipolar dimension that can be attributed to characteristics of design.

This statement is supported by a number of papers in hand tool evaluation studies in which comfort is measured in terms of discomfort [Chao, 2000], [Fellows, 1991]. In hand tools, comfort is mainly determined by functionality and the physical interaction between the user and the product. As discomfort factors are present in hand tool use, comfort may be dominated by discomfort [Kuijt-Evers *et al.* 2004]. In their study, Kuijt-Evers *et al.* [2004] identified factors having the closest relationship to comfort among 40 descriptors, such as good fit in hand, functional, easy to use, reliable, etc. These factors were clustered, and the statistical analysis identified 6 comfort factors: functionality, posture and muscles, irritation and pain of hand and fingers, irritation of hand surface, handle characteristics and aesthetics. These factors explain 53.8 % of the variance. In the use of hand tools it was concluded that the same descriptors related to both comfort and discomfort.

Two studies in the design of seats support the above statement. A comfort study [Jianghong *et al.* 1994] carried out to evaluate the comfort of a passenger seat for a new type of bus and a comfort study [Wilder *et al.* 1994] comparing two different track seats (with and without suspension) when changing driving postures. Both studies used a multistage comfort scale (MSC), Electromyograms (EMG) and general posture analysis. They concluded that comfort and discomfort can be seen as two opposites on a continuous scale. This stems from the fact, that people frequently and naturally distinguish ordered levels of their subjective responses across the entire continuum from strongly positive to strongly negative [Richards, 1980]. The same principle underlies the graded scales [Habsburg *et al.* 1977], which have been used to evaluate seats.

Opposing the theory of seeing comfort and discomfort as two extreme states on a continuous scale ranging from extreme discomfort through a neutral state to extreme comfort, several studies have questioned the intuitive assumption of comfort/discomfort as a single dimension on a continuous scale. These studies [Kleeman, 1981], [Zhang *et al.* 1996], [Kamijo *et al.* 1982], argue that comfort and discomfort are affected by distinctly different variables, and assessment of comfort and discomfort should therefore be based on different types of criteria [Kamijo *et al.* 1982]. Zhang *et al.* [1996] focused upon the identification of these variables. Descriptors of feelings of comfort and discomfort were solicited from office workers and validated in a questionnaire study. 104 respondents provided descriptors of the feelings they experienced when they felt comfortable (e.g. agreeable, at ease, calm) or uncomfortable (e.g. fatigue, cramped, restless) in a seated workplace. Secondly, to validate these descriptors, another group of 34 participants was asked to rate these descriptors on a 5-points scale, from 'very closely related to comfort/discomfort' to 'not related at all'. From this study, 43 descriptors emerged. 21 descriptors related to discomfort and 22 related to comfort. The participants rated the similarity of all 903 pairs of descriptors, and the resulting similarity matrix was subjected to multidimensional scaling, factor analysis, and cluster analysis. Two main factors emerged, which were interpreted as comfort and discomfort. Feelings of discomfort are mainly associated with pain, tiredness, soreness and numbness. These feelings are assumed to be imposed by physical constraints and mediated by physical factors like joint angles, tissue pressure and circulation blockage. Comfort, on the other hand, is associated with feelings of relaxation and well-being [Paul, 1997]. It was concluded that comfort and discomfort were identified as independent entities associated with different factors: discomfort is related to biomechanics and fatigue factors, whereas comfort is related to a sense of well-being and aesthetics. Comfort and discomfort need to be treated as different and complementary entities in ergonomic investigations.

In a later study Zhang *et al.* [1997] analysed discomfort by carrying out a field study. Two groups of subjects (ten secretaries and ten managers) evaluated two groups of ten chairs. Subjects assessed each chair three times during a workday using three different types of scales. Analysis of variance demonstrated that discomfort was related to fatigue accumulated during the workday, but was not related to chair design. Since discomfort and comfort are based on independent factors a reduction of comfort does not necessarily bring about feelings of comfort. In fact, from their independence it would follow that there is no connection between the two entities [Helander, 1997].

In addition, low values of discomfort factor scores were associated with a full range of values of overall comfort ratings from 1 to 9, while comfort ratings decreased sharply with increasing discomfort scores. This indicates that, when discomfort factors are present, comfort factors become secondary in the comfort/discomfort perception, hence, discomfort has a dominant effect [Ellegast *et al.* 2012]. Paul *et al.* [1997] propose the nurturing/pampering paradigm, indicating the need for different strategies for reducing discomfort (nurturing) and increasing comfort (pampering) in the work place. This could provide a unifying focus for ergonomists and designers alike.

From the reviewed literature, there was little consensus on whether comfort and discomfort should be regarded as being a bipolar continuum or as composing of two experiential dimensions, however, the theory of Zhang *et al.* [1997] has led to the understanding that comfort and discomfort should be addressed as two concepts affected by different sets of factors, and this is the perspective adopted in this thesis.

Summary

From the review of the literature so far, a number of conclusions are presented here regarding the definitions of comfort. Comfort is affected by factors of various nature, i.e., physical (physical contact to the product), psychological (emotional impact of the human-product interaction on comfort assessment) and physiological (comfort or discomfort are experienced over time) and there seems to exist a division or discontinuity between comfort and discomfort scales. However, both comfort and discomfort should be addressed since discomfort is more tangible, hence, easier for the individual to express.

Early indications show that comfort is related to a sense of well-being and aesthetics. Knowledge of the dependencies between comfort and aesthetics should be advanced. There is a need to investigate aesthetic and emotional design and their relationship to the concept of comfort.

Comfort is seen as “a pleasant state or relaxed feeling of a human being in reaction to its environment” and “discomfort is seen as an unpleasant state of the human body in reaction to its physical environment” [Vink, 2011].

2.2 Infuencing Factors (IF) of comfort

This section will investigate new knowledge in the field of comfort and highlight the influencing factors of comfort.

2.2.1 Context and type of activity

Ellegast *et al.* [2012] aimed to evaluate the effects of four specific dynamic chairs on erector spine and trapezius Electromyograms (EMG), postures/joint angles and Physical Activity Intensity (PAI) compared to those of a conventional standard office chair. All chairs were fitted with sensors for measurement of the chair parameters (backrest inclination, forward and sideward seat pan inclination), and tested in the laboratory by 10 subjects performing 7 standardized office tasks and by another 12 subjects in the field during their normal office work. All chairs were compared to a reference chair. The comparison of all specific dynamic chairs with the reference chair revealed no significant effect for any of the muscles. By contrast, the tasks performed strongly affected the measured muscle activation, postures and kinematics. The standardized tasks performed in the laboratory had a significant impact on the posture of the different joints, whereas no significant differences were found for the chairs and for the comparison of the specific dynamic chairs to the reference chair. The characteristic dynamic elements of each specific chair yielded significant differences in measured chair parameters, but these characteristics hardly affected the body dynamics of the subjects sitting on the chairs. The results of the study emphasize that many aspects of workplace design, such as variability of tasks should be considered in order to prevent physical aspects of discomfort, such as musculoskeletal disorders [Ellegast *et al.* 2012].

In a similar context, Groenesteijn *et al.* [2012] investigated the effect of office tasks on posture and movements in field settings, and the comfort rating for chair characteristics and correlation with type of task. The task of computer work showed the lowest physical activity, together with upright trunk and head position and low backrest inclination whereas conversation shows the highest activity of head legs and low back together with the highest cervical spine extension. In contrast, desk work provoked the most cervical spine flexion and showed the second lowest activity. In conclusion, positive comfort correlations were found among different types of activities and different types of chairs. These confirm the findings of Ellegast *et al.* [2012], showing that comfort assessment is affected by the assigned tasks. Hence, it is necessary to define the context and the type of activity when assessing comfort and not assess the product without this context.

2.2.2 Product Form, Memory and State

Vink [2005] indicates that “discomfort is mainly related to physical characteristics, whereas comfort is related to experience, emotion, unexpected features, and luxury”. In her study, Kamp [2012] describes the contour of three different car-seat designs, including a light weight seat, and the recorded corresponding emotion and tactile experience of 21 persons sitting in the seats. The seats were all deliberately covered with white sheets so that the participants are not influenced by the appearance of the seats and instead could focus on the seats' sitting comfort. For the rating of emotions the Emocard method was applied. This is a nonverbal self-reporting method developed by Desmet *et al.* [2001] based on the circumplex of emotions created by Russell [1980]. This circumplex is based on two dimensions; 'pleasantness' and 'arousal'. The 16 Emocards are placed on eight distinct places on this circumplex. Participants can express their emotional responses to the seats by marking the face that best indicates their response. Results show that the new light weight car-seat concept rated well on experienced relaxedness, even with the lack of a side support. Of all participants, 19% had neither a pleasant nor a negative feeling, although the arousal level was high. This would mean that people were surprised by the actual feeling of the seat. Before they sat down, they expected to experience a different feeling. Another finding also informed that hard seats with rather high side supports are rated sporty and seats that are softer are rated more luxurious [Kamp, 2011].

Individuals estimate comfort based on product form and assess the products depending on their current state. Moreover, they have a preconceived notion of comfort based on past experiences with similar products. Hence, the product memory of the individual creates a comfort expectation.

2.2.3 Sensory impact

Among the various papers that have investigated the Human Computer Interaction, Aarts *et al.* [2009] and Cook *et al.* [2009] introduced the Ambient Intelligence system (AmI), which refers to electronic systems embedded in everyday environments and are sensitive and responsive to people in a seamless, unobtrusive, and often invisible way. In the context of AmI, Aarts *et al.* [2009] identified the "nudging" issue, that is, when the Ambient Intelligence system suggests to the user to perform a certain task at opportune moments. In their study De Korte *et al*. [2009] investigated the use of different types of non-obtrusive feedback signals in order to change unhealthy behavior of office workers. Thus, four different feedback systems were selected to remind computer users to rest their hand from the mouse when they do not use it to avoid developing repetitive strain injury [Jensen *et al.* 2009]. Two of the feedback systems were two types of vibrations in a computer mouse and the other two were visual signals appearing on the computer screen. Notable differences between types of feedback were seen, relating to comfort and task satisfaction. The 24 participants rated the feedback system which does not interfere with their primary task as the most effective.

The feedback system, which activates another sense than the one used for in the execution of the primary task, creates a better sense of comfort.

Hence, the impact on the senses should be taken into account when designing comfortable products. Stimulating a different sense can alter the comfort experience.

2.2.4 Neighboring body surface

Franz et al. [2012] describe the design of a neck-rest / headrest to increase car comfort. Two studies were undertaken to create a new comfortable headrest with neck support. In experiment one, neck and headrest data were gathered using 35 test subjects. The pressure distribution, stiffness of the foam material and position of the head and neck support were determined. In experiment two a full adjustable final headrest with adjustable neck support was constructed and tested with 12 subjects using a new adjustable headrest under virtual reality driving conditions. Experiment two showed that the headrest with the new/adjustable neck support was favored by the majority of the subjects. 83% were satisfied with the stiffness of the material. 92% were satisfied with the size of the neck- and headrest. All subjects mentioned that the neck support was a great comfort benefit in calm traffic conditions or during driving on the motorway. The back side of the head, the neck and the shoulder area all need different foam characteristics.

These findings show that the feeling of comfort during a human – product interaction is affected by the neighboring surface to the product and that it is important to use the right material for each area. The neighboring/ contacting surface needs to be investigated when deciding the material characteristics.

2.2.5 Discomfort and physical loading

Among the many comfort studies that link discomfort to physical loading, Kee *et al.* [2012] investigated the relationships between subjective measures of discomfort and objective measures related to the assessment of postural stresses based on literature survey. Objective measures included posture holding time, Maximum Holding Time (MHT), torque at joints, Lifting Index (LI) and compressive force (CF) at L5/S1. The major relationships identified in this literature survey were the following: 1) postural discomfort linearly increased with increasing holding time, and holding force, 2) whole body discomfort was inversely linearly proportional to the MHT, 3) body-part discomfort was related to objective measures such as torque at the relevant joint, 4) discomfort was strongly linearly related to LIs and CFs, and 5) the discomfort measured with the magnitude estimation was linearly related to that measured with Borg CR10. Thus, it is thought that discomfort might be used as a measure for quantifying postural stresses.

In a similar context, Zenk *et al.* [2011] conducted an objective assessment approach evaluating the concept of "optimal load distribution", based on the identification of a close relationship between the pressure on the seat and the discomfort felt by the person sitting. The results indicate that in the seat position with the pressure distribution corresponding to the most comfortable posture the pressure in the intervertebral disc is lowest.

There is a strong connection between discomfort and physical dimensions. If the physical loads forced on the user during a human – product interaction is maintained to low levels and the exposure of users to the load lasts for a considerable amount of time then their response can relate to objective measures.

2.2.6 The effect of emotional responses towards a product

Aesthetics within the context of design research stands for the features of a product that create its appearance and have the capacity to generate immediate responses during the experience of an object through the sensory system. The response to aesthetics is rapid, involuntary and can be biased positively or negatively [Ulrich, 2006]

Aesthetic responses are characterized for taking place during a short time and to be mainly stimulated by visual information. However, there is no agreement if aesthetic responses are a cognitive or a non-cognitive process. Some authors [Ulrich, 2006] state that aesthetics is a cognitive process (meaning that there is an evaluation), however, Norman [2004] argues that it is a non-cognitive process and states that aesthetic perception takes place at the Visceral level of information processing, which is defined as the stage where the initial impact of the product is perceived through appearance, touch and feel.

According to Myers [2004], emotions are the mental experience of an individual when the individual interacts with internal (physical) and external (environment) stimuli. Physiological arousal, expressive behaviors and conscious experience characterize human emotions [Myers, 2004], [Muñoz Roussy, 2011]. Emotions are what we feel, the physical reaction to a stimuli. However, there is no agreement on what the basic universal emotions are and each author defines their own set of emotions. Emotions can be classified in a number of different ways and theories; from the field of psychology the basic set of emotions can be described as between 2 and 10 different emotions [Ortony *et al.* 1990]. Hence, an emotion involves an interaction with external stimuli and an evaluation of the stimuli, which then triggers body responses.

The following approaches discuss the relation between emotions and products. The Pleasantness approach is explained by Jordan [2000] as psychological pleasantness. He defines pleasure as the opposite to pain and he states one can perceive three different benefits from products: practical, emotional and hedonic benefits, and proposes four kinds of pleasures, which are summarized in the Table 2-1 below [Jordan, 2000]

Physio pleasure	Socio pleasure	Psycho pleasure	Ideo pleasure
Pleasure from the sensory organs	Pleasure from social interaction. Driven from the relationship with others	Mental or emotional reactions	People´s tastes, values and aspirations

Table 2-1 The four pleasures from products [Jordan, 2000]

The Appraisal approach is explained by Desmet *et al.* [2010] as a cognitive appraisal. This approach suggests that it is during the evaluation of the product where the individual classifies something as potentially beneficial or harmful [Desmet *et al.* 2010]. Events on their own do not determine emotional responses. Emotional responses are determined by evaluation and interpretation of events. The appraisal is considered a non-conscious evaluation since it mediates between events and emotions, which explains why different people perceive different emotions for the same event [Desmet *et al.* 2010], [Hekkert, 2006].

The Process-level approach is explained by Norman [2004] as a neurobiological emotion-framework. Three different levels of information are described [Norman, 2004]. The characteristics of each of them are explained in Table 1 below [Norman, 2004]. According to Norman [2004] an emotional response to a product can be either described as: visceral, behavioral and reflective and these interweave both cognitive and emotional responses [Richards, 1980]. Visceral responses refer to the most immediate level of processing, and appealing to the senses before interaction with the product occurs; behavioral responses are related to the experience of using the product and is usually concerned with the product’s interaction and reflective responses are about one’s thoughts after using and owning a product, hence is often connected to self-image and status.

Visceral responses allow users to make quick judgments upon the product and how it is perceived [Achiche & Ahmed-Kristensen, 2008]. The visual input influences our experiences and visual information plays a major role; it is the first impression of comfort [Vink, 2005]. Ulrich [2006] also argues that “aesthetics response is also the first response to an artefact and it gives a sense of quality to the product because attractive things do not occur at random, it takes time to make them look appealing. Attractiveness is not an emotion but it is linked to the visceral response of a human towards a product.

Visceral level	Behavioural level	Reflexive level
• Where the initial impact of a product takes place through appearance, touch and feel • Is an automatic layer (reactive) • Almost the same all around the world	• Where we perceive pleasure and effectiveness of use • Not conscious • Sensitive to experiences, training, education and culture	• Where rationalization and intellectualization of a product takes place • Sensitive to experiences, training, education and culture • Consciousness • Highest level of feeling, emotion and cognition • Self-image, personal satisfaction, memories • In the mind of the beholder

Table 2-2 Norman’s [2004] three levels of information processing

Hence, comfort is linked to the aesthetic properties of the product and the visceral response of a human towards a product is the first stage of the emotional process and is realized through the sensory inputs of the participant (appearance, touch and feel).

Summary

From the review of literature on the influencing factors of comfort a number of conclusions are derived. The type of task plays an important role when investigating comfort and the individual’s memory of past interactions with similar products creates a comfort expectation. There is also a strong connection between discomfort and physical dimensions. If the physical loads forced on the user during a human – product interaction is maintained to low levels and the exposure of users to the load lasts for a considerable amount of time then their response can relate to objective measures.

In addition, stimulating a different sense can alter the comfort experience; hence, the impact on the senses should be taken into account when designing comfortable products. The feeling of comfort during a human – product interaction is also affected by the neighboring surface to the product; therefore, it is important to use the right material for each area. The neighboring/ contacting surface needs to be investigated when deciding the material characteristics.

Finally, the attractiveness towards a product is strongly linked to visceral responses realized by the individuals' senses and it can be considered as a strong evaluative term for comfort.

2.3 Theoretical models of Comfort (CM)

This section presents a review of different comfort models. A comfort model often cited with respect to product comfort is the model by De Looze *et al.* [2003], which shows a relationship between physical product feature experiences with respect to discomfort and comfort
(see Figure 2-1).

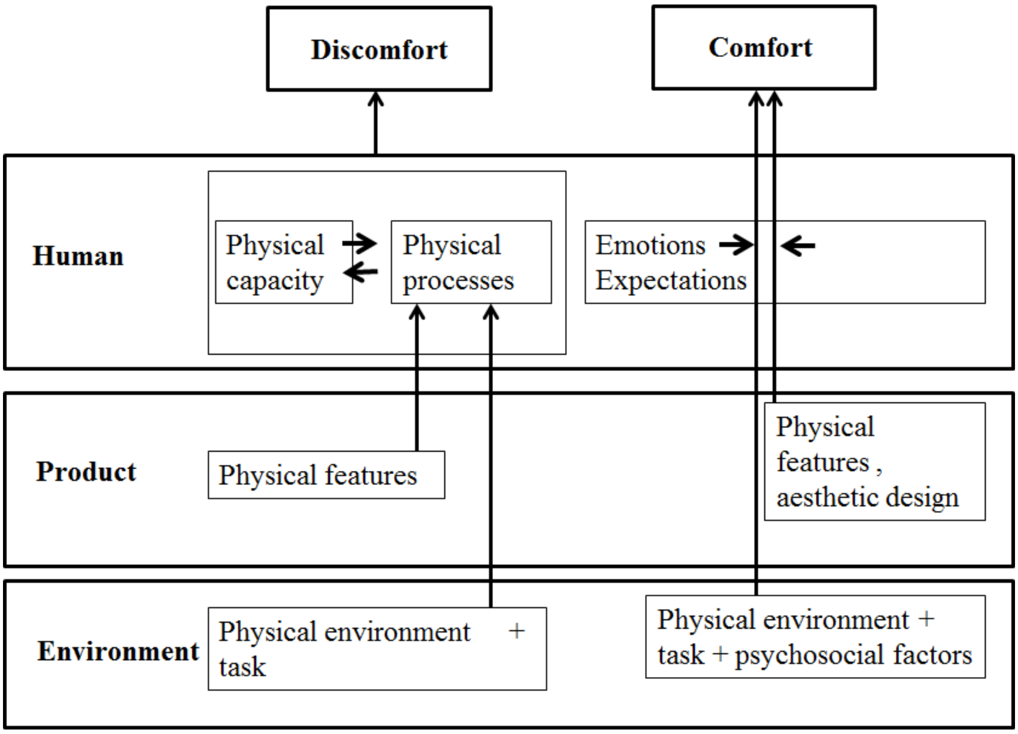


Figure 2-1 The comfort model for sitting described by De Looze *et al.* [2003]

In the comfort model shown in Figure 2-1, different factors underlying sitting discomfort and comfort are described, as well as the relationships among these factors. Confirming the discontinuity of discomfort and comfort, the left side of this theoretical model concerns discomfort. The physical processes, which underlie discomfort, incorporate model parameters on the aetiology of work-related physical complaints [Armstrong *et al.* 1993], which consider exposure, dose, response and capacity. According to Armstrong [1993], exposure refers to the external factors producing a disturbance of the internal state (dose) of an individual. The extent to which external exposure leads to an internal dose and response depends on the physical capacity of the individual. With regard to seating, the physical characteristics of the office seat (product level, e.g., form, softness), the environment (context level, e.g., table height), and the task (context level, e.g., the performance of VDU activities) expose a seated person to loading factors that may involve forces, joint angles and pressure from the seat on the body. These external loads may yield an internal dose in terms of muscle activation, internal force, intradiscal pressure, nerve and circulation inclusion, and skin and body temperature, all provoking further chemical, physiological, and biomechanical responses. The perception of discomfort may be established by exterocepsis (stimuli fromskin sensors), propriocepsis (stimuli from sensors in the muscle spindle, tendons, and joints), interocepsis (stimuli from internal organ systems), and nocicepsis (stimuli from pain sensors).

The right side of the model concerns comfort only, that is, feelings of relaxation and well-being. Again, using the seating example from above, the influential factors are presented on human, product, and context levels. At the context level, not only the physical features are assumed to play a role, but also psychosocial factors such as job satisfaction and social support. At the product level, the aesthetic design of a product as well as the product's physical features may have an impact on the assessment of comfort. At the human level, the influential factors are assumed to be individual expectations and other individual feelings or emotions.

Another model that could be utilized to explain the process of discomfort experience is the model of Moes [2005]. Moes [2005] has established five phases in the process before discomfort is experienced (see Figure 2-2).

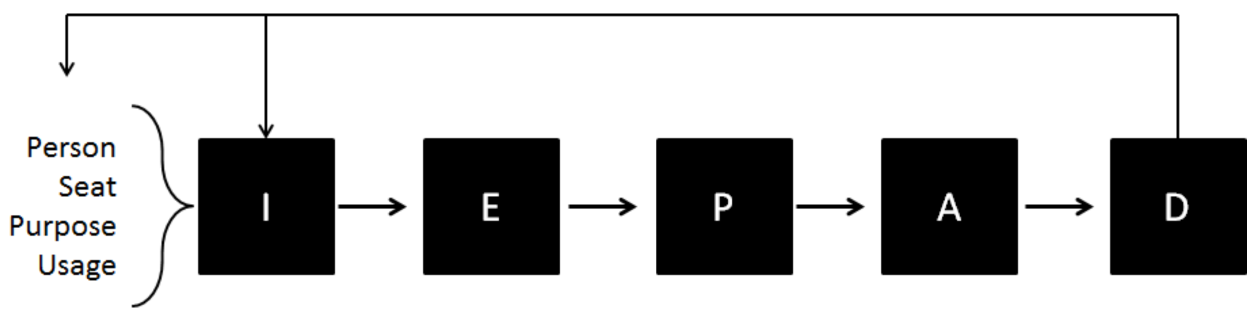


Figure 2-2 A part of the comfort model of Moes [2005]

I - interaction, E - effect in the internal body, P - perceived effects, A - appreciation of the effects and D - discomfort. Moes [2005] also describes that this process is dependent on the person, the seat, the purpose and why the seat is used. Moes [2005] describes that if a person uses a seat with a specific purpose, the interaction (I) arises. For example, this interaction can consist of the pressure distribution of the contact area between the subject and seat. An interaction results in internal body effects (E), such as tissue deformation or the 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).

2.3.1 Both models reflected

The model of Moes [2005] is simple and linear and explains the process more clearly than as the step between interaction and internal effects and weighting the internal to check whether it is appreciated are explicitly shown. The model correlates with the findings by Franz et al. [2012], where subjects compare the various comfort experiences to each other, which is the weighing process and the paper by Kamp *et al.* [2012], where the tactile experience of the seats is also compared. The advantage of the model of De Looze *et al.* [2003], over Moes' [2005], is that the environment is explicitly shown. The model of De Looze *et al.* [2003], has also the advantage that the connection to expectations is presented, which is important in the mental process of deciding whether or not a product is comfortable. Another advantage of the model by De Looze *et al.* [2003], is that it can end with "comfort" as an outcome.

The model by De Looze *et al.* [2003], has two separate processes, one on comfort (right) and one on discomfort (left), reflecting the prevailing concept of two distinct scales, one for discomfort and one for comfort (not just lack of discomfort). In reality, physical contact can also lead to comfort, having the same process. Often "more comfort than expected" is reflected in a comfort experience, which is a valuable outcome of the De Looze *et al.* [2003] model. Interestingly, in the model by Moes [2005] discomfort in the usage or interaction parameters could be changed by, for instance, shifting in the seat.

Vink (2010) presented a combination of the above models by De Looze *et al.* [2003] and Moes [2005] (See Figure 2-3). The interaction (I) with the environment is caused by the contact (could also be a non-physical contact, like a signal in the study of De Korte *et al.* [2010]) between the human and the product and its usage. This can result in internal human body effects (H), such as tactile sensations, body posture change and muscle activation. The perceived effects (P) are influenced by the human body effects, but also by expectations (E). These are interpreted as comfortable (C) or you feel nothing (N) or it can lead to feelings of discomfort (D).

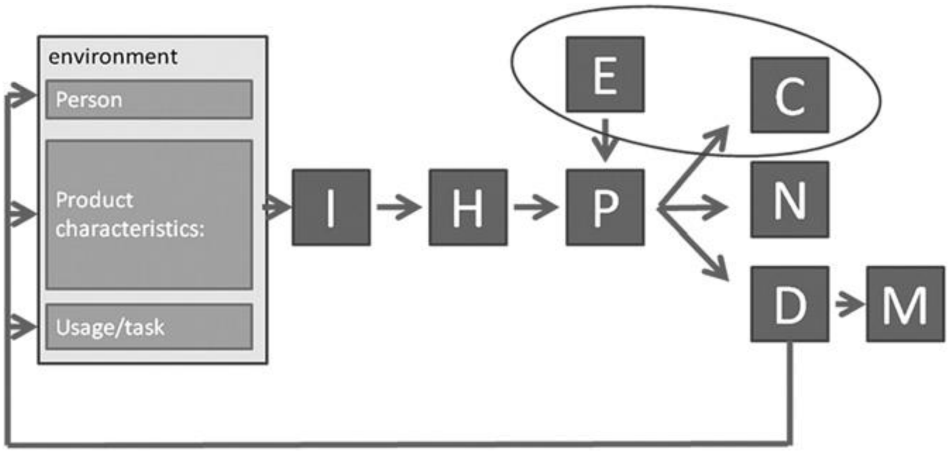


Figure 2-3 The new proposed comfort model by Vink [2012]

There is not one form of comfort or discomfort experience, but it can vary from almost uncomfortable to extremely comfortable and from no discomfort to extremely high discomfort. The possibility lies that that both comfort and discomfort are experienced simultaneously. For instance, an individual may experience discomfort from a seat during a flight but have a feeling of comfort created by a flight attendant. In this case discomfort could result in musculoskeletal complaints (M). There is a circle around E-C as expectations (E) are often linked to comfort (C). If discomfort is too high or if comfort levels are not high enough, then there is a feedback loop to the person who could act accordingly, with the aim to adapt the product or to change the task/usage.

Summary

The review of comfort models concluded that comfort is linked more to feelings of well - being and relaxedness whereas discomfort is strongly linked to a more physical dimension with respect to feelings of tiredness and pain. It was also assessed that the physical dimension of comfort is explained in a satisfactory way. Finally, an emphasis should be given in the emotional dimension of comfort as well as in the subjective nature of comfort as these aspects appear to be underdeveloped in the existing models.

2.4 Methods of collection of anthropometric data.

As part of the thesis required the collection of anthropometric data, in this section studies related to the physical dimension of comfort and the different methods of collection of anthropometric data are presented.

Anthropometry is considered the very ergonomic core of any attempt to resolve the dilemma of fitting the tasks to the human [Sanders *et al.*, 1993]. In regards to external ear products such as Bluetooth headsets and headphones, *good fit* is a crucial physical factor of comfort to ensure the success of these products. Designers require anthropometric data to identify human factors and inform design decisions with respect to external ear devices. Current studies of comfort are restricted in the presentation of anthropometric data only. The collection of ear data includes the use of various measurement instruments. Jung *et al.* [2001] provided anthropometric dimensions of ears of Korean subjects using digital calipers. Other methods suggest the use of simple geometric calculations to acquire dimensions from a 2D photograph by setting reference points before taking the photographs. In regards to data collection of other body parts, such as head and legs data, other, relatively noninvasive, 3D imaging techniques are applied. These include various forms of stereophotogrammetry [Weinberg *et al.* 2006], topography techniques [Ghoddousi *et al.* 2006] and surface scanning technologies [Hennessy *et al.* 2007]. In their paper (see Appendix 1), Stavrakos & Ahmed-Kristensen [2012] compared three methods of collection of ear data (with a digital caliper, photogrammetrtic method and 3D scanning method), in terms of cost, time, accuracy and comfort and concluded that the 3D scanning method is the most costly, yet the most accurate of all, see Table 2-3.

In other disciplines such as seating design, design engineers have attempted to design desks and chairs based on anthropometric data [Hibaru *et al.* 1994], [Parcells *et al.* 1999]. Parcells *et al.* [1999] studied the mismatch between furniture and students' dimensions by measuring anthropometric characteristics of American children aged 11–13 years and the dimensions of their classrooms' desks and chairs, reporting that only 18.9% of students could find an appropriate match [Gouvali *et al.* 2005]. Other studies provide detailed anthropometric data and some of them also offer recommendations for design [Klamklaya, 2002].

	Accuracy	Cost		Time		Comfort		Personnel	Parameters
Instru-ment method	Instrument: 0.01 mm Method: not significantly different than the photographic method	Cost of Equipment	90€	Time of one cycle	3 min.	Biological	Yes	Not required	All
		Cost of test	-	Result processing	2 min.	Physiological	Yes		
		Cost of maintenance	-	Specialised Personnel	-	Psychological	Yes		
Result	Satisfactory (for fast data collection)	Satisfactory		Satisfactory		Satisfactory		Satisfactory	Satisfactory
Photo-graphic method	Instrument: 0.055 mm	Cost of Equipment	420 €	Time of one cycle	8 min.	Biological	Yes	Image Software skills required	All
		Cost of test	-	Result processing	15min.	Physiological	Yes		
		Cost of maintenance	-	Specialised Personnel	-	Psychological	No		
Result	Satisfactory (for fast data collection)	Satisfactory		Satisfactory		Satisfactory (?)		Satisfactory	Satisfactory
3-D Camera method	Instrument: 0.03 mm	Cost of Equipment	130.000 €	Time of one cycle	40-45 min.	Biological	No	3-D modeling software skills	All
		Cost of test	-	Result processing	30min.	Physiological	No		
		Cost of maintenance	-	Specialised Personnel	1.5 hr	Psychological	No		
Result	Satisfactory	Satisfactory		Not satisfactory		Not satisfactory		Satisfactory	Not satisfactory

Table 2-3 Table of criteria

In their study, Stavrakos & Ahmed-Kristensen *et al.* [2014] presented a validated methodological framework of how to generate archetypes from an anthropometric dataset of ears measured manually with a Vernier caliper, in order to build test panels for the execution of more reliable comfort studies.

Summary

Reviewing the different methods of collecting anthropometric data indicates that the majority of the studies on comfort focuses on the acquirement of anthropometric data, and this is limited to physical match, i.e., how the product fits the human. Hence, the fit of a product to the human body is a strong evaluative term for physical comfort. In addition, in particular in the ear industry, there appears to be a gap in the definition of a validated methodological framework to link ear anthropometry to design and a lack of methodologies to define a reliable user group and focus groups for user studies.

2.5 Conclusions

This chapter has reviewed literature relevant to the thesis. The main conclusions in each of the areas reviewed have been documented here. Similar findings that have been identified from different areas have been grouped and presented below.

The review on comfort terminologies provides a background in comfort theory. It is concluded that Comfort is seen as "a pleasant state or relaxed feeling of a human being in reaction to its environment" and "discomfort is seen as an unpleasant state of the human body in reaction to its physical environment" [Vink, 2012]. Comfort is affected by factors of various nature, i.e., physical, psychological and physiological, and a division or discontinuity exists between comfort and discomfort scales. Additionally, early indications show a relation between comfort and aesthetics.

The review of literature on the influencing factors of comfort revealed that there is strong connection between discomfort and human physical dimensions, such as the pressure load, [Ellegast *et al.* 2012], [Groenestein *et al.* 2012], discomfort and the type of task during the interaction between the human and the product, and finally (dis) comfort and product attributes such as neighboring interfaces to the product under investigation, the product material and the product form [Kamp, 2012]. In addition, reviewing the different methods of collecting anthropometric data confirmed that *good fit* is one of the dominating factors of physical comfort.

Additionally, comfort is more influenced by cognitive and psychological factors, such as the memory of past interactions to similar products, as well as the impact on the senses should be taken into account to achieve comfort. The review on the impact of the emotional parameters of a product on the assessment of comfort acknowledged that the attractiveness towards a product is strongly linked to visceral responses realized by the individual's senses and it can be considered as a strong evaluative term for comfort.

The review of comfort models confirmed some of the early findings of the review of comfort definitions. It concluded that comfort is linked more to feelings of well - being and relaxedness whereas discomfort is strongly linked to a more physical dimension. An emphasis should be given to the emotional dimension of comfort as this aspect appears to be underdeveloped in the existing models.

Reviewing the different studies on comfort indicates that these focus in their majority on the acquirement of anthropometric data, and that there is a lack of a validated methodological framework to link ear dimensions to design and a lack of methodologies to define a reliable user group and focus groups for user studies.

The main conclusion is that there is a clear need to understand more deeply how comfort is perceived by individuals during a human – product interaction and, in particular, how emotional factors and the streamlining of user testing affect the assessment of comfort. This understanding could then provide the basis of a tool or the providing of guidelines to reduce the time of the development cycles and design more comfortable products.

Chapter 3 Research Approach

3.1 Introduction

This chapter describes the overall research approach and that of the studies conducted during this research project. This includes description of the participants, the research methods employed, the analysis methods, and the limitations of the studies.

The goal of this research is to establish an approach to assess the comfort of headset designs during the development phase, resulting in a faster development process and better quality product. The previous chapter discussed the literature, focusing on comfort theory, comfort methodologies and methods to collect anthropometric data with respect to physical comfort. Comfort was defined as a dual, discontinued concept with each part (comfort – discomfort) being affected by a set of different factors (physical, physiological, psychological). The review of comfort methodologies identified a gap with respect to the emotional dimension, which, in the reviewed models appears to be underdeveloped. The reviewing of different studies of collection of human data revealed a lack of methods to issue reliable panels for user testing and to link the anthropometric datasets to design decisions based on the improved understanding of comfort and anthropometry. Hence, a mixed setup of empirical research in the laboratory and the industry was selected as the most appropriate method to gain this understanding. This understanding can then provide the basis of a method or guidelines to support designers, in their efforts to design comfortable products in a faster way.

The overall design methodology employed for this research is that proposed by Blessing *et al* [2009]. The methodology consists of four main stages: Criteria, Description 1, Prescription and Description 2, see Figure 3-1. The four stages are described briefly in relation to this research and are discussed in more detail elsewhere. The criteria stage is the motivation for the research and, therefore, is discussed in Chapter 1. The research methods employed during studies carried out at the Description 1 stage are discussed in the following sections. The findings from these studies are discussed in Chapter 4. The Prescription and Description 2 stages are discussed in Chapter 5.

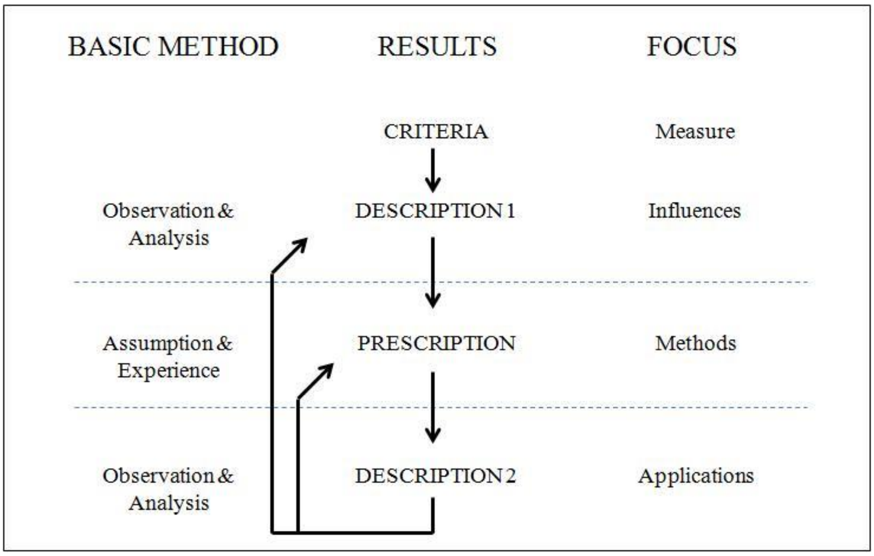


Figure 3-1 Design Research Methodology [Blessing, 2009]

For this research project the four main stages in relation to the Design Research Methodology were:

1) Criteria: The overall aim of design research is to understand how designers produce successful products and hence develop methods and tools to support them. Comfort has been identified as one of the key criteria for the success of a new body-worn product, i.e., in the case of this project, an external-ear headset. There are many factors that contribute to comfortable products; as discussed, for example, in Chapter 2, section 2.4, good fit was identified as one of the dominating factors that influence physical comfort; the emotional and aesthetic parameters of a product, expressed as the attractiveness or visual response to a product, are expected to have an impact on the assessment of psychological comfort, see Chapter 2, section 2.2.4; and the need for reliable user-testing will have an impact on the overall assessment of comfort as discussed in Chapter 2, section 2.4.

2) Description 1: Blessing *et al* state that descriptive studies should be carried out to understand more deeply the criteria for a successful product, in this case, good fit, the attractiveness of a product and reliable user-testing. Empirical research was carried out to understand the impact of fit and the emotional parameters of a product, such as the visual response or attractiveness towards a product, as well as the impact of issuing and utilizing representative samples of user panels on the assessment of comfort. This understanding can then be used to help designers design more comfortable products. The following research methods were employed at this stage: an ergonomic study, a comfort study on visual response and the archetypes study.

3) Prescription: During the prescription stage a methodological framework is developed and guidelines are provided upon the findings of the Description 1 Stage. The development of the method is described in Chapter 5, section 5.2.

4) Description 2: Blessing *et al* propose a further study to investigate the effect of the introduction of the proposed method or tool. A further descriptive study was carried out to evaluate the proposed method. The evaluation included: (1) the validation of the proposed method; (2) the design implications of the method; and (3) the managerial implications of the method.

Figure 3-2 outlines the structure of the thesis and describes each of the chapters in relation to the overall DRM research methodology.

The elements of the project that have been presented so far are also included. These are, namely: the motivation for the project as discussed in Chapter 1, section 1.2; the main aims of the project as discussed in Chapter 1, section 1.3; and the main findings of the literature review, found mainly in Chapter 2, section 2.5.

The three studies presented briefly in Chapter 3, section 3.1 are also included in Figure 3-2 under research approach and findings, with the aim to justify the reasoning for their execution from a design research and methodological point of view.

Finally, the 7 papers written during the time of the project are also reported here. Each paper contributes either as a whole or as excerpts, to different elements and phases of the project. These contributions are briefly mentioned in Figure 3-2 and all papers are referenced throughout the whole report of this project. The papers written during this project can be found in Appendix 1.

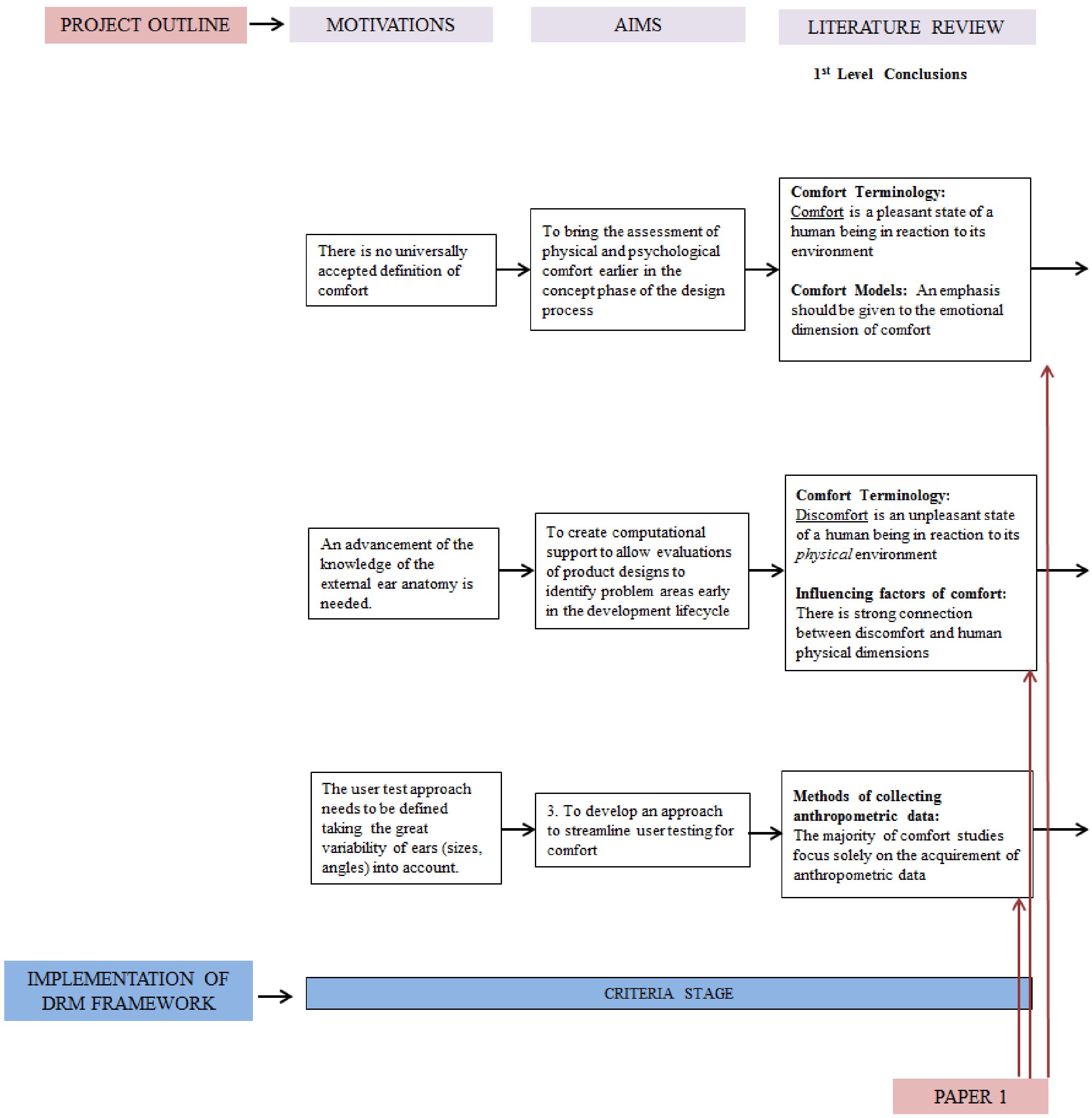


Figure 3-2 Outline of thesis in relation to project analysis and papers written

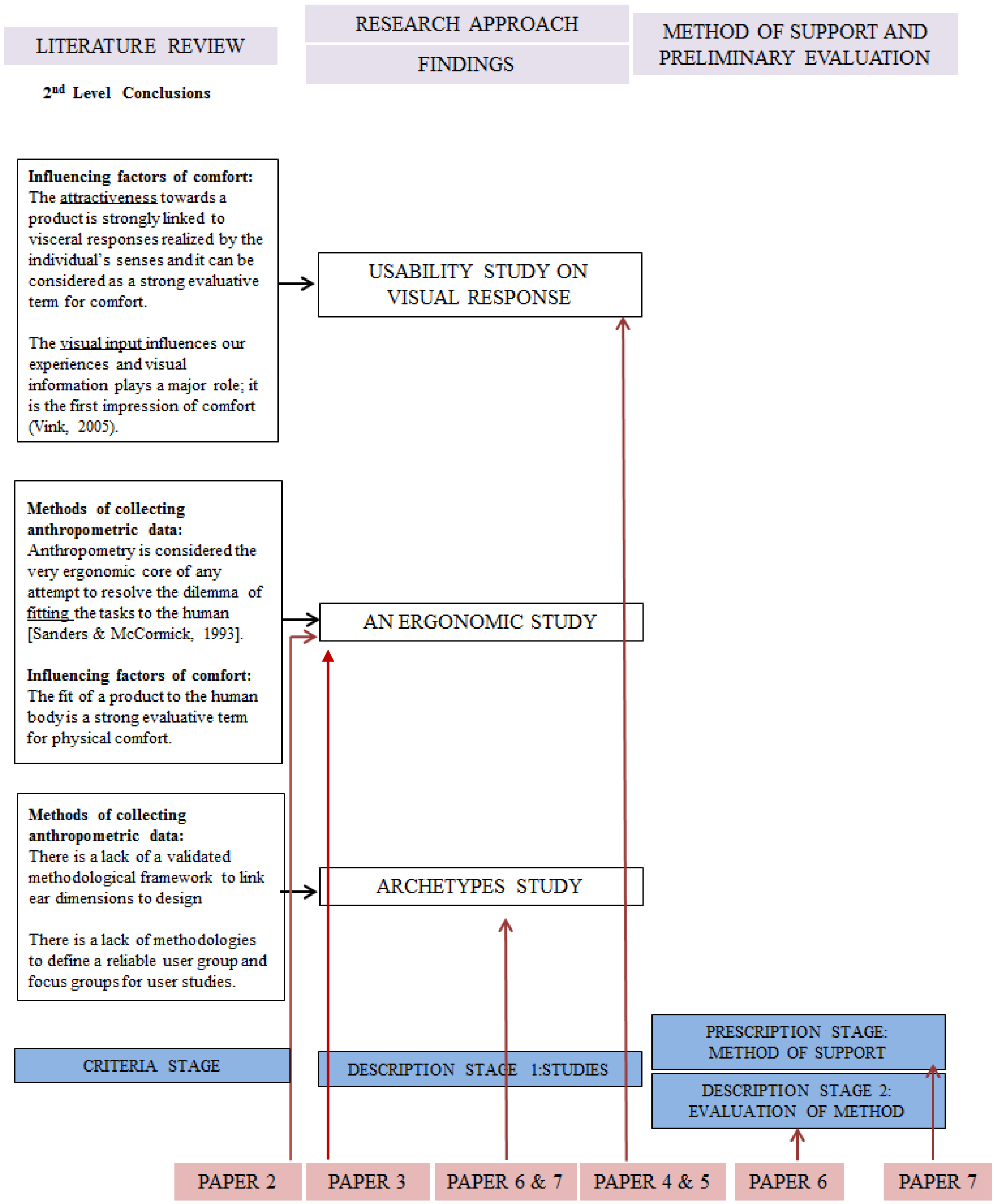


Figure 3-2 Outline of thesis in relation to project analysis and papers written

3.2 Description 1: Empirical research

When planning the empirical research, several methods adapted from the social sciences, anthropometry and ergonomics were investigated. The methods were selected based on how well they fulfilled the criteria established by the research objectives and also their practicality. The fulfillment of the following research objectives was considered:

- To bring the assessment of physical and psychological comfort (and knowledge) earlier in the concept phase of the design process rather than relying on prototyping.
- To develop an approach to streamline user testing for comfort.
- To create computational support to allow evaluations of product designs to identify problem areas early in the development lifecycle leading to faster development cycles and higher quality products.

The following issues relating to empirical studies in the laboratory were considered:

- To reduce any bias of the participants towards the products (by, for example, ensure the products were not familiar to them)
- To ensure that the duration of all human-product interactions is similar; for this project the duration of interaction between a human and a product was defined as *a short interaction, lasting for about 2-3 minutes.*
- To respect the commercial sensitivity of the industry of the external-ear worn products. The brand of the company is not revealed and the prototypes have been replaced with pictures of similar products, for the sake of the documentation of this project and the issue of confidentiality.

A combination of research methods used as multiple sources of evidence increase the reliability of data [Yin, 2014]. Three studies were conducted: (1) an ergonomic study; (2) a comfort study on visual response; and (3) an archetypes study. The research was based on the multidimensionality of comfort and the findings from each study influenced the direction of subsequent studies. The structure for data collection was redefined as necessary, to avoid excluding data. The studies are discussed further in the following sections, together with their research methods, analysis methods and limitations.

The studies gained access to different parts of the company's product development process. All of the studies concern the company's product development process, i.e. preliminary concept definition (concept design). The ergonomic study provided an insight into the physical aspects of comfort; the comfort study on visual response investigated the causal relationship between the visual response to a product and the assessment of comfort during a human-product interaction; and the archetype study provided an insight into user-testing when performing comfort studies for the improvement of the concept products during the early phases of conceptual development. The research methods employed for each of the studies are described in: section 3.5 (An ergonomic study); section 3.6 (A comfort study on visual response); and section 3.7 (The archetypes study).

The empirical research methods employed for the evaluation of the support method eventually developed as part of this research are discussed in Chapter 5.

3.3 Participants

This section presents the participants in the three studies conducted during this research project. In total, 440 individuals participated in the three studies. Regarding the Ergonomic study and the Archetypes methodology study, two anthropometric datasets (2-dimensional and 3-dimensional data) of ear dimensions of approximately 400 individuals were collected to represent the population of Denmark (= 5,500,000 persons). The calculation of the sample size was based on a statistical analysis which is presented further in Chapter 3, sections 3.5.2 and 3.7.1of the respective studies. Table 3-1 shows the breakdown of participants for the studies. For the sample of the comfort study on visual response, the target population consisted of 44 participants, who were men and women of similar age, social and, professional background. All participants of the comfort study reported in advance a low or zero familiarity towards the products to-be-tested in order to avoid bias and eliminate the reflective respond of the products (Norman, 2004). The selection of the 400 individuals regarding the ergonomic study and the archetypes study was realized in a randomized way to avoid issues of homogeneity and bias. However, the majority of the participants were company employees and this occurred for practical reasons, i.e. so that the participants could be re-included during the methods of support and preliminary evaluation of the three studies, and could later be used as archetypes for user testing, i.e. to provide access to a large user group. More information regarding the data is provided in the following section.

Study	Ergonomic study	Comfort study on visual response	Archetypes study
Sample size for 2-dimensional data	200		200
Sample size for 3-dimensional data	196		
Sample size		44	

Table 3-1 Distribution of participants

3.4 Characteristics of descriptive studies

Characteristics have been identified by Blessing *et al* [2009] to describe the nature of a research study. These characteristics need to be considered when assessing the findings of a particular study. The three studies undertaken in this research project, namely the ergonomic study, the comfort study on visual response and the archetypes methodology study are mapped using these characteristics in Table 3-2. In summary:

- The studies were exploratory in nature since no prescriptive methods or tools are introduced.
- The environment for the comfort study was the laboratory. The 2- dimensional anthropometric dataset collected during the ergonomic study and the archetypes study was executed by measuring the participants at their working stations in the company environment. The 3 dimensional data for the ergonomic study was collected in the laboratory through using a 3D scanner.
- The interaction between the participants and the external ear products during the research survey study on visual response lasted for 2-3 minutes and focused upon the physical comfort.
- The remaining characteristics varied with each study and will be discussed where appropriate.

Characteristics	Options	Characteristics of studies conducted		
		Ergonomic Study	Comfort study on visual response	Archetypes study
Environment	Industry Laboratory	Industry	Laboratory	Industry

Nature of study	Exploratory research: research to identify the influencing factors where no prescriptive methods or tools are introduced Comparative exploratory research: Exploratory research which compares cases with different characteristics Action research: A method or tool is introduced and its effects are studied Comparative-action research: Action research compared to a group where no method or tool is introduced	Exploratory research	Exploratory research	Exploratory research
Data Collection Methods	Real-time methods such as: observation, participant-observation, questionnaires	Measurement Techniques using instrumentation (manual measurements using a digital caliper, and 3D scanning)	Experiment, Structured interviews	Measurement Techniques using instrumentation (manual measurements using a digital caliper)
Subjects	Nationality Gender	196 men (Danish) 196 women (Danish)	22 men 22 women (various nationalities)	100 men (Danish) 100 women (Danish)
Number of Cases	Number of datasets collected	2 Datasets: 2-Dimensional Data, 3-Dimensional Data	44	396
Number of manual measurements executed		2-D: (6 Ear dimensions) x (2 ears per person) x (200 persons) = **2,400** 3-D: (34 Ear dimensions) x (198 persons) = **6,664**	N/A	2-dimensional Dataset(same as in ergonomic study):
Number of Ear dimensions collected	Basic Measurements Advanced measurements (after mathematical calculations)	2-Dimensional Data: 12 Basic Dimensions 3-Dimensional Data: 25 Basic Dimensions 9 Advanced Dimensions		
Duration	Length it took to collect the data	2-Dimensional Data: 15 minutes (duration of each measurement cycle per participant)	2-3 minutes	2-Dimensional Data: 15 minutes (duration of each measurement

		3-Dimensional Data: 20 minutes (duration of each measurement cycle per participant)		cycle per participant)
Time Constraint	Limits imposed for subjects	None	None	None
Role of Researcher	Contribution of researcher	Facilitator	Facilitator	Facilitator
Required results	Required design	None	None	None
Topic	Task/Object to be designed	N/A	Interaction with 2 sets of 3 ear products	N/A

Table 3-2 Characteristics of studies conducted

The methods of analysis used for each of the studies are summarized in Figure 3-2 and are described in more detail in the following sections.

The research issues for the Description 1 Stage are discussed in the following sections. For each of the three studies: the ergonomic study; the comfort study on visual response; and the archetypes study, the following aspects are covered:

- The research method in general (e.g. section 3.5 Study one: Ergonomic study)
- The specific use of the research method for this study (e.g. section 3.5.1 Ergonomic Study: Description and experimental Set-up)
- The limitations of the approach (e.g. section 3.5.4 Limitations of the ergonomic study)
- The method of analysis for the study (e.g. section 3.5.5 An ergonomic study: Analysis method)

3.5 Study one: Ergonomic study

Parts of the study can also be found in Papers 3 and 7 (refer to Appendix 1). Ergonomics and anthropometry are two disciplines strongly connected to each other. Ergonomics has provided anthropometric data regarding most areas of the human body. Hibaru *et al.* [1994], Jung *et al.* [2001], Parcells *et al.* [1999] and a few ergonomists have attempted to make use of existing human datasets to inform design decisions. Research on anthropometry stresses that comfort is achieved when there is sufficient knowledge of human factors and that comfort for consumer products is influenced by good fit and alliance between product dimensions and human dimensions. Current databases for anthropometric ear data, e.g. Peoplesize Software [Peoplesize, 2008] contain data which is measured either manually or require the use of 3D systems for body areas which measurement instrumentation such as calipers are difficult to measure (e.g. back ear area). An ergonomic study is typically attempting to benchmark the human body against the product. Figure 3-3 shows typical examples of ergonomic studies where an attempt has been made to link anthropometric dimensions to design elements.

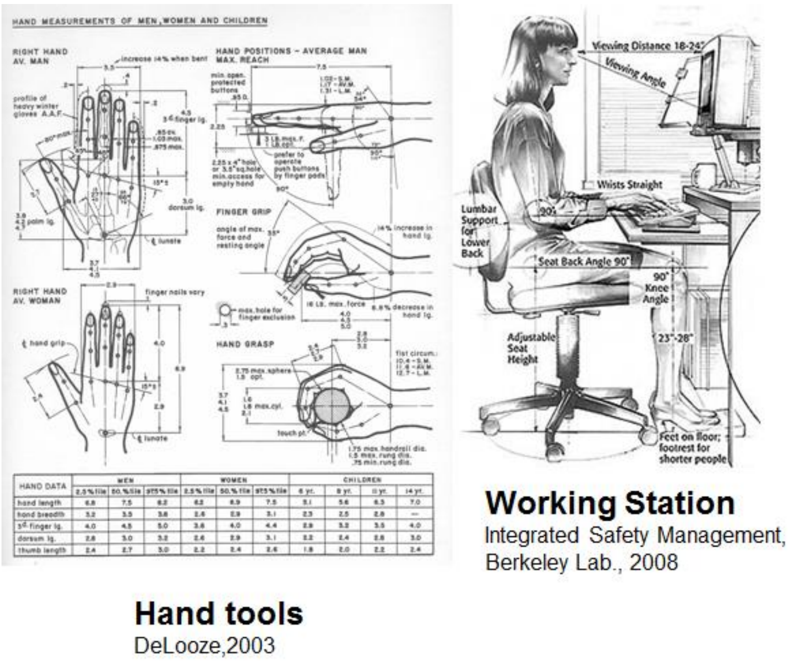


Figure 3-3 Typical examples of ergonomic studies

3.5.1 Ergonomic Study: Description and Experimental set-up

The overall contribution of this study was to provide different methods to support design by various applications (ways of analysis) of 2-dimensional and 3-dimensional head and ear data with a focus on external ear products based on the analysis of a 2-dimensional and a 3-dimensional external ear and head data set. The main aims of the ergonomic study were: (1) to investigate how human dimensions can be benchmarked against product dimensions with the aim to support product design; and (2) how product dimensions can be predicted through qualitative methods of visualisation of human data.

At an early stage of this research an analysis of different methods of collecting 2-dimensional and 3-dimensional data was conducted. The methods were compared and the 3-dimensional method of collection was found to be the most accurate. More information on the comparison of different methods of anthropometric data can be found in Paper 3 (see Appendix 1). In total, 200 individuals (100 men and 100 women) participated in the issuing of the 2-dimensional data set. The measurement of the dimensions was executed with the help of a Vernier calliper for the linear dimensions. For the non-linear dimension, a pliable silicon tube (diameter = 2mm) was used. The tube was inserted in the ear cavity (concha), (see Figure 3-5), and the dimension was extracted after the tube was straightened and its length measured against a ruler. The individuals were asked to pose in a sitting position and be relaxed to ensure that they remain as still as possible.

In total, 196 individuals (98 men and 98 women) participated in the scanning session for the retrieval of the 3-D head scans that were later used for the extraction of the 3-dimensional data. The steps of the scanning process are briefly depicted in Figure 3-4. The 196 persons were scanned using a system consisting of one projector and two cameras that were both calibrated. A structured design was employed where patterns are projected onto the object's surface, pixel values are assigned by calculating the exact distance between points on the object's surface and the focal plane of the camera. In this system all visible points were calculated simultaneously in a single capture in a few seconds.

The 196 3D models were later processed using a 3D imaging software (G.O.M. Inspect 2.0). The purpose of this iteration was to refine critical areas which were hard to scan on site, such as areas behind the ears and human surface covered with hair. The G.O.M. Inspect 2.0 imaging software allowed these areas to be restored by making use of a predictive algorithm that generated the missing areas by using the data of neighbouring human surface.

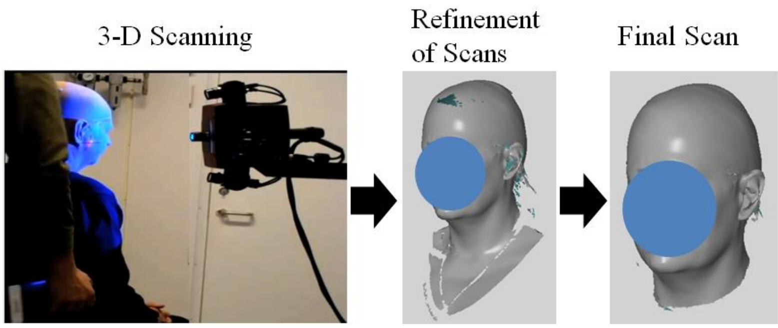


Figure 3-4 Scanning and Refinement of Scans

Regarding the 2-dimensional dataset, the decision on which ear dimensions to collect was based on discussions with the designers of the user experience team and the mechanical engineers in the company environment and an understanding of the product (see next section). The 6 dimensions (5 linear, and 1 non-linear) that were retrieved during this phase are shown in Figure 3-5. These were namely: ear length; ear height; ear breadth; concha x; concha y; and circumference.

Figure 3-5 The 6 external-ear dimensions

3.5.2 Early product understanding

This section presents the initial stage of the ergonomic study. An early product understanding phase was undertaken prior to selecting the dimensions to extract from the 3D scans. All products mentioned in this study were objects seen as one object with stabile physical properties. Initially, product categories were created based on wearing style and fit. Five categories of external-ear worn products were defined for this study, as shown in Figure 3-6. At this stage, there was also the possibility of defining critical product components that touch upon critical areas of the human body. The interfaces would require a different treatment from a data collection point of view, such as the *ear gel* component in the “in the ear headsets” product category, which touches upon the in-the-ear area. However, this study did not focus on product components, as the main anthropometric area that this project focuses on was the external ear area and general head area. The researcher aimed to eliminate the possibility of having to treat in-the-ear data which would require different scanning techniques and has been much investigated in the hearing aid industry.

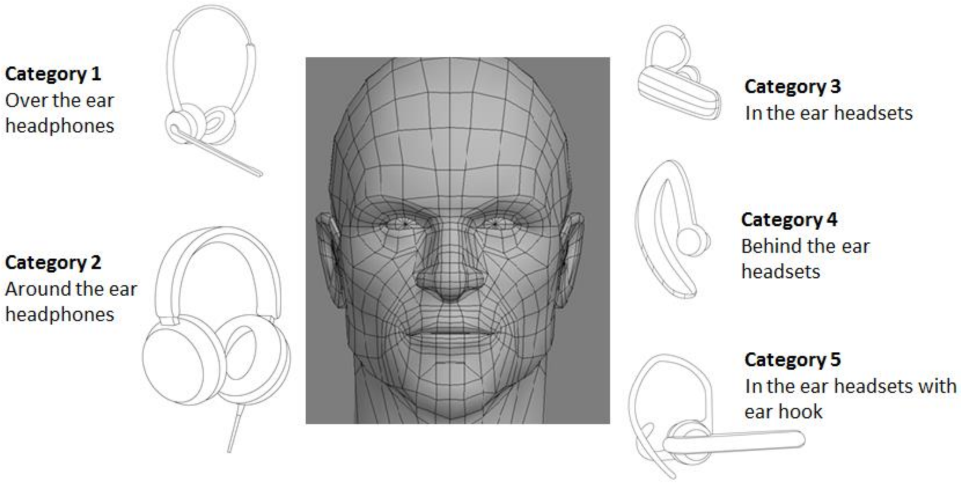


Figure 3-6 The 5 product families of external-ear worn products

In the next step, critical areas were defined on the human surface. These were selected based on the areas of physical contact between the human and the various product types. Once these areas were defined on the human head and ears, critical human dimensions were defined to describe as accurately as possible the critical area from a human-product interaction point of view, rather than a geometrical point of view. The associations between critical product areas and the determination of critical human dimensions, for product families 1 and 3 can be seen in figure 3-7.

Once the associations between critical areas of human-product interaction and human dimensions were completed, the researcher issued a table listing all critical human dimensions to be collected in order to achieve product and human body understanding. In total, 25 linear and non-linear human dimensions were identified in respect to the 5 product categories of ear-worn products.

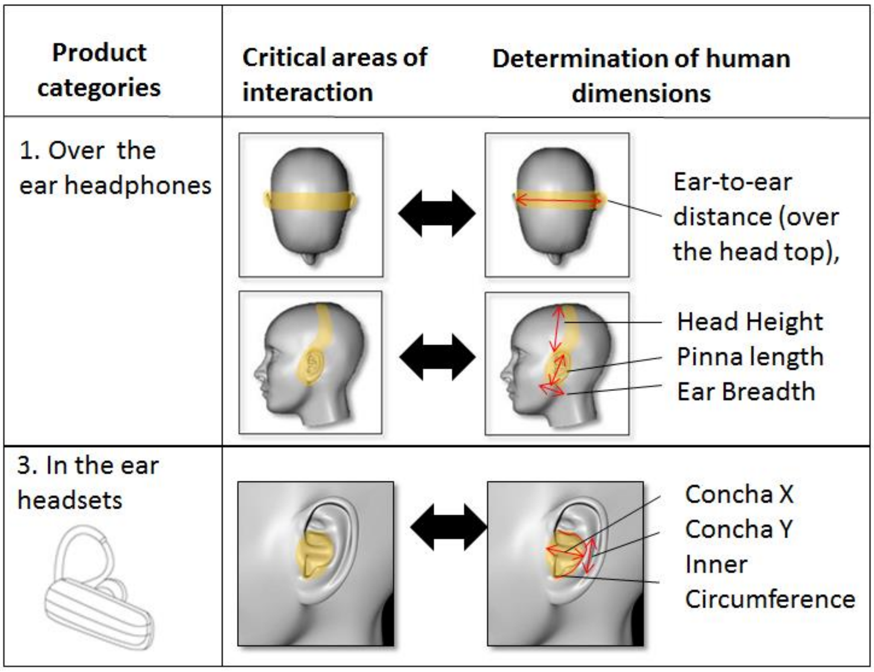


Figure 3-7 Matrix of associations for product categories 1 and 3

Once the critical human dimensions were determined, head and ear data was collected. The various steps of this process comprised of: (1) the selection of the population; (2) the definition of a representative user sample; and (3) the scanning of the population. The scanning process has been described earlier in this Chapter (section 3.5.1).

To ensure that the user sample was representative, a population with homogenous, ethnographic properties needed to be selected. The population of a country, which in this instance was Denmark, was selected for the execution of this study. To ensure that the user sample chosen to represent Denmark's population -which reached to approximately 5,500,000 persons- was representative, the statistical sample size of Denmark's population was calculated with the use of the following mathematical equation.

$$\text{Necessary Sample Size} = (\text{Z-score})^2 * \text{StdDev}*(1-\text{StdDev}) / (\text{margin of error})^2$$

In the case of Denmark, the sample size required was 196 people for a confidence level of 95%, confidence interval = 7 and population size = 5,500,00 people. This translated to the fact that if aproximately 200 people were randomly selected out of the 5,500,000, these could sufficiently represent statistically the population at hand from an anthropometric point of view. Hence, a randomized sample of 200 Danish people (100 men, 100 women) was chosen with ages ranging from 22 to 67 years to match the requirements of the calculated sample size for the scanning of the persons. More information on the demographics of the ergonomic study can be found in Chapter 3, Section 3.4, see Table 3-2.

3.5.3 Applications of 3-Dimensional Data for supporting design

This section presents the approaches towards different ways of applying the two datasets with the aim to support design decisions at the early stages of prototyping.

Once the scanning of the participants and the refinement of the scans was complete, a dataset of 196 human head scans was available. Three main approaches to utilising the data for supporting design were identified and performed in this paper. They were namely: (1) the basic and in-depth benchmarking between products and human factors; (2) the retrieval of critical dimensions through qualitative methods of data analysis (e.g. visualisations of 3D-Data); and (3) the creation of focus groups. The last approach is presented together with the 3rd study to ensure coherence of the thesis (refer to section 3.7). This is discussed together with the rest of the elements of the 3rd study on archetypes by utilising the archetype methodology described in depth in Stavrakos & Ahmed-Kristensen [2014] and summarised for this thesis in section 3.7.

For the basic benchmarking, the main step of this process concerned the selection of reference points and, the generation of a matrix of critical, linear human dimensions. In the basic benchmarking, the matrix of the associations between critical product areas and human dimensions was used, as shown in Figure 3-7.

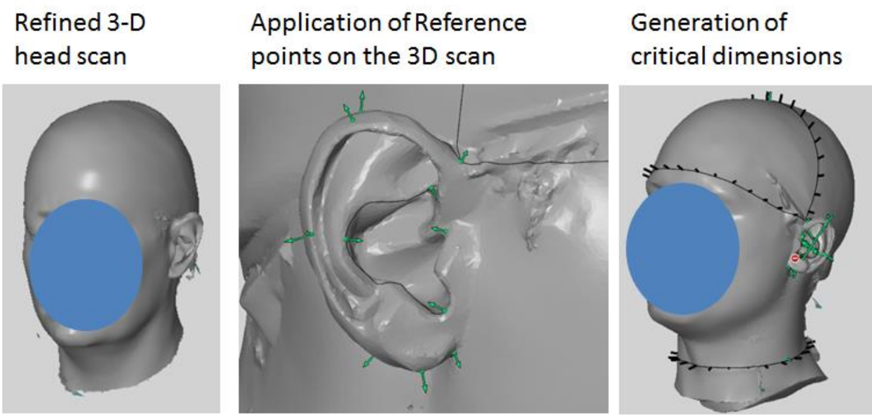


Figure 3-8 Generation of critical human dimensions

As stated in Table 3-2 of the characteristics of descriptive studies, 25 linear and non-linear human dimensions were first generated from the matrix. The 25 dimensions were identified on all 196 head scans by generating reference points for the linear dimensions (starting point – ending point) and by drawing the respective curves to reproduce the non-linear ones. After all reference points were applied, the dimensions between the starting and ending point for each one of the linear dimensions were calculated, as well as the non-linear ones, as shown in Figure 3-8. At this stage, 4,900 measurements were retrieved manually from the imaging software, utilising the G.O.M. Inspect 2.0 software.

The in-depth benchmarking comprised of: (1) a mathematical modelling of products, (2) selection of critical angles and through-the-mesh dimensions and, (3) application of geometrical elements on the 196 scans. For this research, it was important to facilitate the generation of additional human dimensions that could be retrieved by working *through* the mesh of points of the 3D scans, compared to the 25 dimensions which were identified *on* the surface of the human heads. For this purpose, 5 additional, through-the-mesh dimensions were defined. These can be seen in figure 3-9. The first two dimensions, Back Canal Top and Back Canal Bottom connected the top and bottom point of the ear canal to the middle point behind the ear. These dimensions were useful for the design of ear-product categories 4 and 5, as these were presented in Figure 3-6, which covers ear products worn behind the ear and products that include ear hooks.

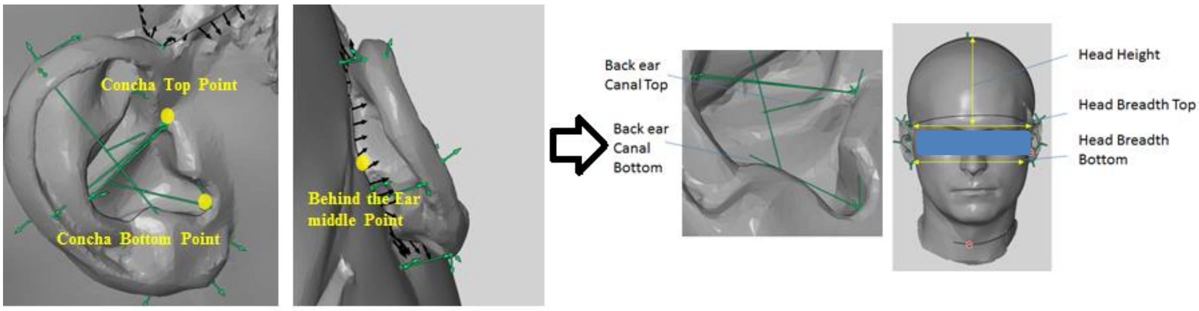


Figure 3-9 Presentation of critical points and additional ear and head dimensions

Calculating through-the-mesh dimensions, offered the possibility of generating three crucial dimensions for the design of headphones and products worn around the head. Figure 3-9 illustrates the dimensions of head height, head breadth top and head breadth bottom, which can inform the design of products in categories 1 and 2, as shown in Figure 3-6, i.e. headphones over and around the ears, respectively. Two more dimensions were also added to support product categories 1 and 2, i.e., the design of headphones. These were angles φ1 and φ2, as shown in figure 3-10. The angle φ1 was calculated as the angle formed (see Figure 3-10) between segment (BC) and the height of the trapeze (ABCD), which, in this case, was segment L3. Segments (AB) and (DC), which are contained in the trapeze, were the human dimensions Head Breadth Top and Head Breadth Bottom, respectively, which were identified earlier, as shown in Figure 3-9:

Calculation of the angle φ1 - $(\tan\varphi 1)^{-1} = ((AB) – (DC))/L3$

For the calculation of φ2, two planes were formed. Plane A was formed by the two ear connection points top and bottom, and point F, as shown in figure 3-10. Plane B was formed by the same ear connection points and the middle point along back circumference, i.e., the *behind the ear middle point*, as shown in figure 3-9.

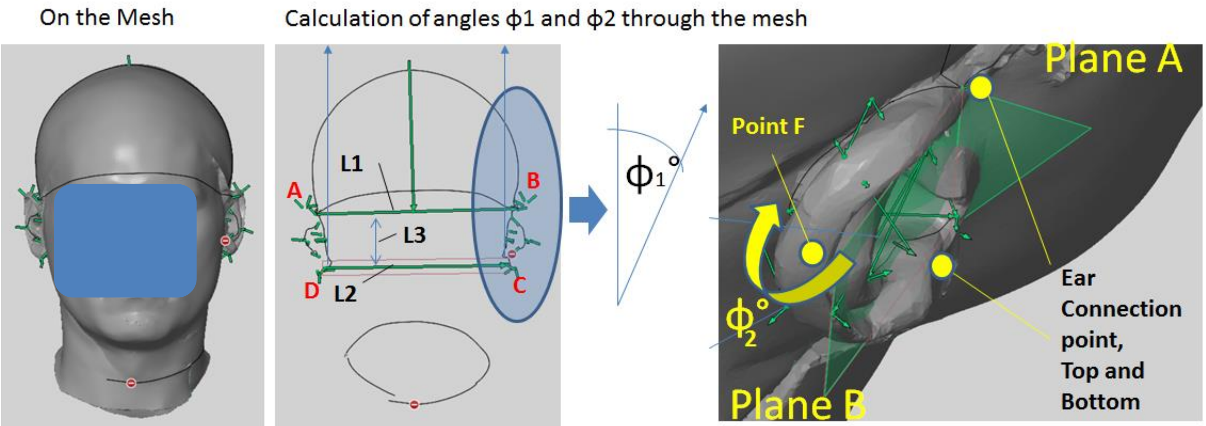


Figure 3-10 Presentation of angles φ1 and φ2

The angle φ2 was calculated in the G.O.M. Inspect software 2.0 as the angle between planes A and B for both left and right ear. Both angles were calculated for all 196 head scans. In total, 9 additional dimensions were added to the list of critical human dimensions (Back Ear Canal Top and Bottom for both right and left ear, Head height, Head Breadth Top, Head Breadth Bottom and angles φ1 and φ2). 1,764 additional measurements were executed.

The visualisation of data comprised of three approaches: (1) the selection of reference points and curved lines; (2) an overlay of geometry on the 196 scans; (3) and the calculation of product dimensions on the final image of the superimposed curves. An additional way to utilise the 3D data was to inform designers on the shape of product components and to generate human dimensions after a qualitative understanding of human geometry. In this study, additional human dimensions were generated through visualisation of 3D human data. Figure 3-11 shows a Bluetooth headset worn behind the ear. Initially two interfaces were identified, the one resting over the ear (green colour) and the other (red colour) resting behind the ear. An advanced knowledge of the area behind the ear is needed to inform the dimensions of the back product component.

Additionally, a joint movement, in the position where point A lies in figure 3-11, was identified with 3 degrees of freedom (dF=3). The mechanical model of the product components indicates that the back component rotates around point A, which lies on the frontal part of the ear area.

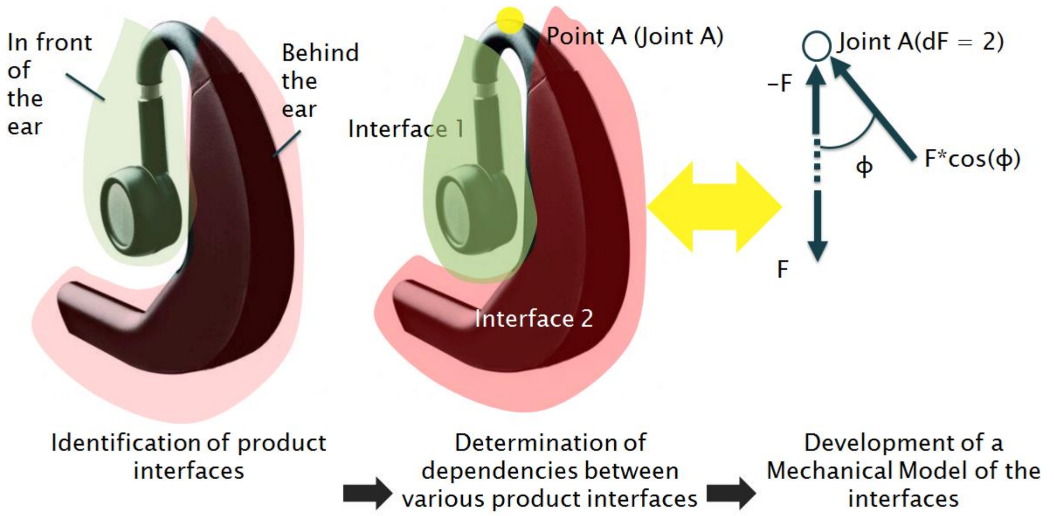


Figure 3-11 Mechanical model of a product worn behind the ear

Visualisation of the back ear area was executed with respect to point A. The back component of the bluetooth device was benchmarked against the back ear circumference which was calculated for all 196 headscans as one of the 25 ear dimensions identified during the basic benchmarking phase. The 196 curves were overlayed together in the same chart, maintaining a steady, reference point for all curves, which was the Ear Connection Point B, as shown in figure 3-12.

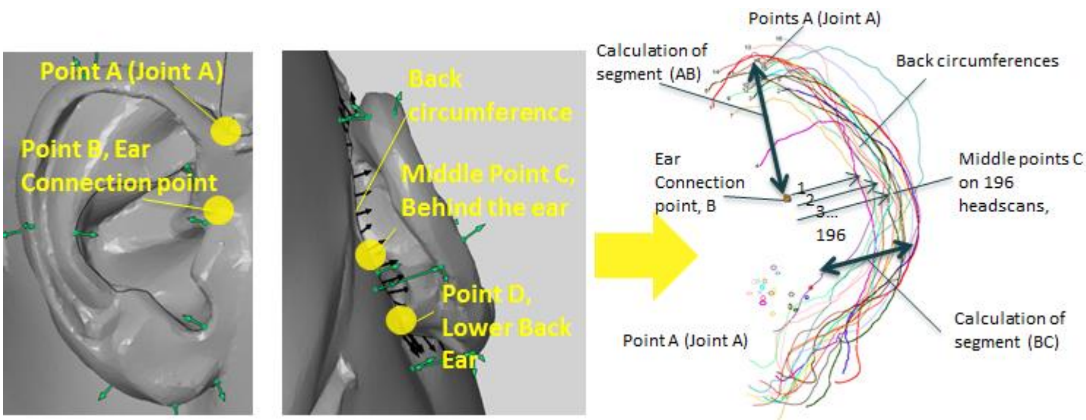


Figure 3-12 Mechanical model of a product worn behind the ear

Point A, linking to the respective point on the product, was identified earlier (see figure 3-11), as were C (middle point, behind the ear) and D (lower back ear) which were also determined on all the 196 head scans. Segments (AB) and (BC) were calculated for all head scans. The geometry of the 196 curves was also available to support the shaping of back component part.

3.5.4 Limitations of the Ergonomic study

In the majority of the ergonomic studies products are seen as a whole, homogenous object. In this research the product was also dealt with as a whole, due to product complexity and time limitations. The segmentation of the product into components would have resulted in the creation of various interfaces with different physical properties and reveal additional cases of critical dimensions and good fit.

This study was limited to one product type, that is, external-ear-worn products. The application of the methods on more product types would showcase additional issues of physical comfort and this would offer new knowledge in the comfort theory and methodology.

The collection of 3D data was limited to head physiology, as this was the only area of interest for the case study presented. Full body scans would offer the possibility to include additional body worn product types. Moreover, enriching the data with more scans would increase the dataset's reliability in terms of accuracy of the presented dimensions.

The selection of reference points on the 3D head scans were identified manually on the various heads, with the help of the 3D software, which added the potential of an experimental error in the calculation of the anthropometric dimensions.

For the visualisation of the data by overlaying the various curves, the assessment for each dimension required a series of manual management in the 3D software, which was time consuming. The use of image software or other software with integrated functions for superimposing geometric curves would save time in the execution of the method.

3.5.5 An ergonomic study: Analysis method

The 2-dimensional dataset was collected at an early phase in the project and was also utilised in the archetypes methodology study. All measurements from the 2-dimensional and the 3-dimensional datasets were inserted into a matrix and several statistical values were calculated, namely, minimum (MIN), maximum (MAX), median (MN) and average (AVE) values. The same values were also calculated for the dimensions retrieved from the visualisation of the data. Furthermore, tables of percentiles were calculated for all dimensions. The percentiles calculated covered a range from 5% to 90% with irregular steps of 5%, 10% and 20% to present different aspects of the data and satisfy the demand for different powers of coverage of the population sample. These are presented in the results section (refer to Chapter 4).

3.6 Study two: Comfort study on visual response

This section presents the second, descriptive study undertaken in this research. Parts of the comfort study can be found in Papers 4 and 5 (refer to Appendix 1).

A user study followed by a structural interview was conducted at this stage of the research. A controlled experiment assessing comfort in blind / non-blind conditions was executed, and followed by a structured interview including rating scaled questions on emotional comfort, physical comfort, product descriptors (words that people use to describe product attributes such as weight, size, etc.) and other physical comfort factors, such as heat, moisture and others. The part of the study which is relevant to this research concerned mostly the questions regarding emotional comfort and the product descriptors.

A rating scale is a psychometric scale commonly involved in research that employs questionnaires. It is the most widely used approach to scaling responses in survey research, such that the term is often used interchangeably with rating scale, or more accurately the Likert-type scale, even though the two are not synonymous. The scale is named after its inventor, psychologist Rensis Likert [Leikert, 1932]. Likert distinguished between a scale proper, which emerges from collective responses to a set of items (usually eight or more), and the format in which responses are scored along a range. When responding to a rate scaled questionnaire item, respondents specify their level of agreement or disagreement on a symmetric agree-disagree scale for a series of statements. Thus, the range captures the intensity of their feelings for a given item [Burns, 2008]. A scale can be created as the simple sum of questionnaire responses over the full range of the scale. In so doing, Likert scaling assumes that distances on each item are equal. Importantly, "All items are assumed to be replications of each other or in other words items are considered to be parallel instruments" [A. van Alphen *et al.* 1994].

A rate scale item is simply a statement which the respondent is asked to evaluate according to any kind of subjective or objective criteria; generally the level of agreement or disagreement is measured. It is considered symmetric or "balanced" because there are equal numbers of positive and negative positions [Burns *et al.* 2008]. Often five ordered response levels are used, although many psychometricians advocate using seven or nine levels; a recent empirical study [Dawes, 2008] found that items with five or seven levels may produce slightly higher mean scores relative to the highest possible attainable score, compared to those produced from the use of 10 levels, and this difference was statistically significant. In terms of the other data characteristics, there was very little difference among the scale formats in terms of variation about the mean, skewness or kurtosis.

The format of a typical five-level Likert item, for example, could be:

1. Strongly disagree,
2. Disagree
3. Neither agree nor disagree
4. Agree
5. Strongly agree

Rate scaling is a bipolar scaling method, measuring either positive or negative response to a statement. Sometimes an even-point scale is used, where the middle option of "Neither agree nor disagree" is not available. This is sometimes called a "forced choice" method, since the neutral option is removed [Allen, 2007]. The neutral option can be seen as an easy option to take when a respondent is unsure, and so whether it is a true neutral option is questionable. A 1987 study found negligible differences between the use of "undecided" and "neutral" as the middle option in a 5-point rate scale [Armstrong, 1987]. The use of rate scales for this research study is described in the following sections.

3.6.1 Comfort study on visual response: Description and Experimental set-up

This section presents the comfort study on visual response and the experimental set-up. Based on the findings of the literature review and drawing inspiration from Norman's [2004] approach on visceral response, the aim of the rate scale study on visual response was to investigate how the attractiveness during a human – product interaction affects the expectation and experience of comfort. It was hypothesized that:

- Hypothesis 1: In the case when the attractiveness of a product was perceived as positive the levels of comfort were also perceived as positive, whereas in the case when the attractiveness were perceived as negative the levels of comfort were perceived as negative.
- Hypothesis 2: Strong correlations between the levels of comfort and the product descriptors, that is, words which are commonly used to describe a product were expected. In the next section, the set of hypothesis are elaborated upon through the introduction of the metrics of this study.

The aims and hypothesis expressed here are framed in the context of products with a short time exposure, i.e. tasks involving interactions that are relatively short (2 – 3 minutes). The comfort study on visual response aims to advance the knowledge on the causal relationship between the attractiveness during a human – product interaction and the expectation and experience of comfort.

In addition this study aims to offer more information regarding the relationship between the expectation and assessment of comfort during a human – product interaction and words which are used to form a visual profile of a product.

The target population of this study consisted of 44 participants, who were men and women of similar age and social and professional background, as discussed in the section of characteristics of descriptive studies in Chapter 3, section 3.4 and presented in Table 3-2. All participants reported in advance a low or zero familiarity towards the products to-be-tested in order to avoid bias and eliminate the reflective responds to the products [Norman, 2004].

This study was conducted using two different set of products, whilst maintaining all other conditions as identical, to avoid bias against the product type. For the execution of the experiment two (2) groups i.e. two different product families, of three (3) products from the ear industry were selected, as shown in Figure 3-13 and 3-14, i.e., in total, 6 ear – products were used. The products which were Bluetooth headsets were all current models (i.e. in the market) during the study's execution time. The two product families were in-the-ear headsets and behind-the-ear headsets. All products were competitor products, that is, they belonged to the same product category (in–ear headsets or behind-the-ear headsets) i.e. they had a similar way of resting in the ear and consisted of similar parts with similar ways of use and belonged to the same price range. This was decided in order to keep the participants as unbiased as possible during their interaction with the products towards other potential influencing comfort factors (poor fit, high pressure levels, higher appreciation due to expensive materials, ownership effect, etc.). The products, however, were carefully selected in order to address the issue of diversity in terms of visual response and tactile interaction. Hence, they differentiated in shape, size, surface material, color, etc.

Figure 3-13 The three in - ear headsets

Figure 3-14 The three behind-the-ear headsets

A controlled experiment was carried out in two identical cycles. A total of 22 participants (11 men and 11 women) were involved in the first cycle and another 22 participants were involved in the second cycle. The experiment was realized in three different phases, as these are presented in the design study in Table 3-3, which summarises the study.

Collection of personal data	Name, Age,Gender, height
Cycle 1 (11men + 11 Women)	Each participant interacts with three in-ear products in a randomized order and answers the following questions
Phase A: No See and Yes(Touch & Wear) • Question on **actual** comfort	1) Please describe the overall feeling of comfort you experience towards the product
• Questions on physical comfort factors	2) How does it feel while touching and wearing the product? 3) Please describe the level of secure fit you experience towards the product 4) Please describe the level of easiness you experience when taking the product on and off
• Questions on product factors	5) Using the following list of adjectives, please select the closest description of the product you interacted with. (**Shape:** Bulky – Slim, Curvy –Flat, Round – Square, **Weight:** Light – Heavy, **Size:** Big – Little, Long – Short, **Surface material:** Rough – Soft, Slippery – Sticky, Pliant – Inflexible, Plastic-like – Velvety
Phase B: Yes(See & Touch) and No Wear • Question on attractiveness • Question on **expected** comfort	1) Please describe the attractiveness you experience towards the product 2) Please describe the overall feeling of expected comfort you experience towards the product
• Questions on physical comfort factors • Questions on product factors	Identical to Phase A
Phase C: Yes (See & Touch & Wear) • Question on **actual** comfort	1) Please describe the overall feeling of comfort you experience towards the product
• Questions on physical comfort factors • Questions on product factors	Identical to Phase A
Cycle 2 (11men + 11 Women)	A different set of 22 participants interacts with three behind-the-ear productsin a randomised order and runs an identical cycle of questions to the 1st cycle presented

Table 3-3 Design of the study

In the first phase (Phase A: No-See and Yes-Touch and Yes-Wear) each participant was given all three products and was asked to wear them one at a time. Each participant was allowed to wear and touch the products but not see them. For practical reasons the researcher hid the product from behind. In the first phase the researcher placed the products upon the participants' ears, hence the users were unable to see the products. The participants were not blindfolded, in order to minimize intrusiveness, and any discomfort developed due to this

In the second phase (Phase B: No-See and Yes-Touch and No wear) the users were given again the same products, only this time each participant was allowed to see and touch the products but not wear them.

In the third phase (Phase C: Yes (See and Touch and Wear)) the participants had a full physical interaction with the products by seeing, touching and wearing them. The participants were given the products in a randomized order, again, to eliminate bias.

The participants were given a questionnaire comprising of rate scaled questions and were asked to grade the products in terms of comfort and attractiveness and were also asked to describe the products from a list of opposite adjectives during each of the three phases. The participants were also asked about physical comfort factors such as the level of ease of wearing the products (on and off), the assessment of a good fit towards the product, etc. These findings are not part of this research, as this study mainly focused on emotional aspects of comfort. The participants were also asked to give feedback on pain and heat however, for short interaction periods, no pain or heat was reported hence this was not reported further.

In the first (No See and Touch and Wear) and third phase (See and Touch and Wear) the participants were asked to grade the products in terms of real comfort (comfort experienced whilst wearing the products), whereas in the second phase (See, Touch, No Wear), they were asked to grade them in terms of attractiveness and expected comfort, as shown in Table 3-3. For the product description part of the study which came at the end of each phase of the study, the participants were asked to describe the headsets in terms of shape, weight, size and surface material. For this task a list of paired adjectives was offered to the participants to choose among (bulky – slim, curvy – flat, round – square, light - heavy, big – little, long – short, rough – soft, slippery – sticky, pliant – inflexible, plastic-like – velvety), again, in the form of rated scaled questions. The various measures of the study are summarized in the following table. (See Table 3-4)

Study phases	**Description**	**Measures**		
		Real Comfort	**Expected Comfort**	**Attractiveness**
A	No see and Yes (Touch and Wear)	Ca	-	-
B	Yes(See and Touch) and No Wear	-	Cb	A
C	Yes(See and Touch and Wear)	Cc	-	-

Table 3-4 Presentation of the study measures

As when the attractiveness is high, comfort is also expected to be high, then the comfort when blind (Ca) is expected to be lower than when the participants can see the product (Cb). The final set of hypothesis based on the design of the study and the table of measures is presented below.

- H1: If the attractiveness (A) is positive (A > 0), then Ca < Cb
- H2: If the Attractiveness (A) is positive (A > 0), then Cb < Cc
- H3: If the Attractiveness (A) is positive (A > 0), then Ca < Cc
- H4: If the Attractiveness (A) is negative (A < 0), then Ca > Cb
- H5: If the Attractiveness (A) is negative (A < 0), then Cb > Cc
- H6: If the Attractiveness (A) is negative (A < 0), then Ca > Cc
- H7: Strong correlations are expected between comfort in all three phases (Ca, Cb, Cc) and the respective scores given to the lists of the opposite adjectives.

This study investigated only short–term effects. Hence the participants were asked to interact with the products for a short amount of time, i.e. approximately 2 – 3 minutes.

Data for the study was collected with a questionnaire consisting of two parts. Regarding the questions on actual and expected comfort and the attractiveness two directions, 24-point scaled questions (-12, +12) were provided to the participants in order to grade the comfort experience and the attractiveness, as shown in Figure 3-15.

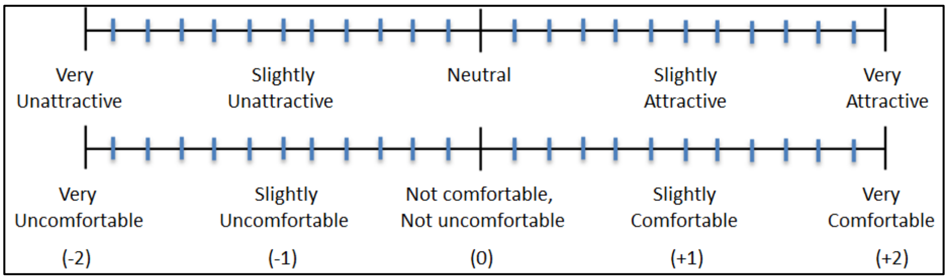


Figure 3-15 24-point Semantic scales and attributed scores for attractiveness and comfort

Regarding the questions on product factors the participants were asked to describe the products while wearing them. For the list of opposite adjectives a similar 24-point scaled question was used. The questions on product factors, as shown also in the design study table (refer to Table 3-3), regarded different product attributes, such as shape, size, weight and surface material. An example of the questions, as they were presented in the study, is shown in Figure 3-16.

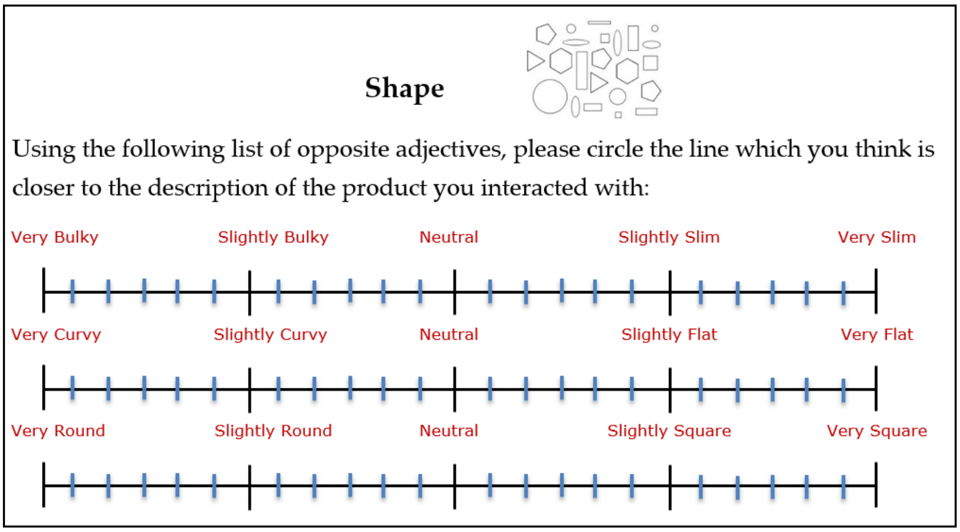


Figure 3-16 24-point scaled questions on product attributes (Example of the Shape attribute)

3.6.2 Limitations of the comfort study on visual response

This section presents the limitation of the comfort study on visual response. Rate scales may be subject to distortion from several causes. Respondents may avoid using extreme response categories (central tendency bias); agree with statements as presented (acquiescence bias); or try to portray themselves or their organization in a more favorable light (social desirability bias). Designing a scale with balanced keying (an equal number of positive and negative statements) can obliviate the problem of acquiescence bias, since acquiescence on positively keyed items will balance acquiescence on negatively keyed items, but central tendency and social desirability are more difficult to account for.

Regarding the set-up of this study, the inclusion of more participants would expand the age span and solidify the statistical significance of the results. This study would be expected to lead to different results for tasks over a longer period; however repeated exposure to short term tasks is expected to draw the same results.

Regarding the scaled questions on product factors, an element of bias may exist due to the subjective understanding of the meaning of the words used to describe a product. However, an effort was made to ensure that the descriptors were not ambiguous, and to adopt commonly used words.

3.6.3 Comfort study on visual response: Analysis method

In this section the various hypotheses and the method of analysis of the collected data are presented.

To test the hypothesis H1 (H1: If Attractiveness (A) is positive ($A > 0$), then $Ca \leq Cb$) and H2 (H2: If Attractiveness (A) is positive then $Cb \leq Cc$) and H3 (If Attractiveness (A) is positive ($A > 0$), then $Ca \leq Cc$) and H4 (If Attractiveness (A) is negative ($A < 0$), then $Ca \geq Cb$) and H5 (H5: If the Attractiveness (A) is negative ($A < 0$), then $Cb \geq Cc$) and H6 (If the Attractiveness (A) is negative ($A < 0$), then $Cb \geq Cc$) 6 paired two-sample t-tests were executed for each one of the hypothesis. In the case of positive and negative attractiveness, the null hypotheses were expressed as follows:

- **Null Hypothesis 1:** There is no mean difference between the scores of (Comfort a) and the scores of (Comfort b) for positive attractiveness ($A >0$).
- **Null Hypothesis 2:** There is no mean difference between the scores of (Comfort b) and the scores of (Comfort c) for positive attractiveness ($A >0$).
- **Null Hypothesis 3:** There is no mean difference between the scores of (Comfort a) and the scores of (Comfort c) for positive attractiveness ($A >0$).
- **Null hypothesis 4:** There is no mean difference between the scores of (Comfort a) and the scores of (Comfort b) for negative attractiveness ($A < 0$).
- **Null hypothesis 5:** There is no mean difference between the scores of (Comfort b) and the scores of (Comfort c) for negative attractiveness ($A < 0$).
- **Null hypothesis 6:** There is no mean difference between the scores of (Comfort a) and the scores of (Comfort c) for negative attractiveness ($A < 0$).

To test the seventh hypothesis (H_7: There are strong correlations between levels of comfort and the product descriptors), a correlational analysis using the Spearman's test was carried out between levels of comfort for each phase and the participants' responds to the list of descriptors for each product. Then, from the large matrix that was produced, only the strong and very strong dependencies are reported in this thesis. For the Spearman's correlation coefficient (r) values between 0.40 and 0.69 ($0.40 \leq r \leq 0.69$) indicate a strong positive relationship whereas values above 0.70 ($r \geq 0.70$) indicate a very strong positive relationship.

3.7 Study three: An archetypes study

This section presents the study of archetypes. The archetypes study is described in Papers 6 and 7 (refer to Appendix 1).

The concept of an archetype is found in areas relating to behavior, modern psychological theory, and literary analysis. An archetype can be a statement, pattern of behavior, or prototype which other statements, patterns of behavior, and objects copy or emulate; a Platonic philosophical idea referring to pure forms which embody the fundamental characteristics of a thing; a collectively-inherited unconscious idea, pattern of thought, image, etc., that is universally present in individual psyches, as in Jungian psychology; or a constantly recurring symbol or motif in literature, painting, or mythology (this usage of the term draws from both comparative anthropology and Jungian archetypal theory) [Brown, 2013].

Issuing archetypes in ergonomics is understood as the identification of archetype persons who are able to sufficiently represent a population at large from a mathematical and anthropometric point of view. There is, to the researcher's knowledge, no prior study where archetypes are formed with the aim to represent large populations.

A large number of participants is needed to build a reliable user group to represent large populations. The building of archetypes allows the selection of a smaller group of persons for user and focus groups, which will save time and resources, whilst being more representative of the data, rather than selecting the participants for the focus groups in random.

3.7.1 The archetypes study: Description and experimental set-up

In this section the archetypes study and the experiment conditions of the study are described.

The aim of this study was to issue archetypes that can be used to represent large populations and therefore streamline focus groups. A study was executed using an in-the-ear Bluetooth headset at an early prototype phase. The actual prototype cannot be presented in this study due to confidentiality reasons. However, the 3D printed headset resembled in shape and form to the product depicted in Figure 3-17. For the issuing of the archetypes, the 2-dimensional dataset which was used in the ergonomic study was also used for the archetype methodology study. The forming of the dataset is described in greater detail in this study.

Figure 3-17 An image of the prototype and respective the critical ear dimensions

An anthropometric data of ear dimensions was collected to represent the population of Denmark (= 5,500,000 people). The calculation of the sample size was executed with the use of the following mathematical equation.

$$\text{Necessary Sample Size} = (\text{Z-score})^2 * \text{StdDev}*(1-\text{StdDev}) / (\text{margin of error})^2 \quad (1)$$

In the case of Denmark, the sample size required is 196 people for a confidence level of 95%, confidence interval = 7 and population size = 5,500,00 people. Hence, a randomized sample of 200 Danish people (100 men, 100 women) was chosen with ages ranging from 22 to 67 years to match the requirements of the calculated sample size. A number of critical ear dimensions were defined and measured for both left and right ears of the 200 participants (see Figure 3-18). The linear dimensions (ear length, ear breadth, ear height, concha x and Concha y) were acquired with the use of a vernier caliper. The non-linear dimension (ear circumference) was acquired with the use of an elastic silicon tube that was positioned along the ear circumference curve, as shown on the right part of the image in Figure 3-17. In total 2,400 linear and non-linear ear measurements were collected.

	Participants					Left Ear					
	Surname	Name	Gender	Age	Height	Ear Length	Ear Breadth	Ear Height	ConchaX	ConchaY	Circumference
1			M	39	189	63,24	33,82	23,41	22,82	18,1	54,24
2			M	28	180	64,67	29,86	17,95	20,16	16,97	54,54
3			M	45	180	65,16	32,87	23,04	19,1	16,68	56,87
4			M	41	190	59,79	26,72	20,28	18,14	18,25	53,11
.			.	.	.	.	.	.	.	.	.
.			.	.	.	.	.	.	.	.	.
.			.	.	.	.	.	.	.	.	.
200			F	32	172	71,44	25,39	11,6	18,1	19,9	49,84

Figure 3-18 Part of the collected ear data

Three critical ear dimensions were chosen out of the six measured based on the areas of physical contact between the prototype and the human ear (see Figure 3-17). These were the Concha X, Concha Y and Circumference (Left ear). The data was clustered using the Ward's minimum variance method. The 200 participants were clustered based on the three selected ear dimensions. Hence, the data of ears was clustered in 9 meaningful clusters. Figure 3-19 shows an example of how the clusters were formed (of two out of 9 clusters). The numbers (also see first column from the left in Table 2) indicate the participants (out of 200) belonging to the clusters.

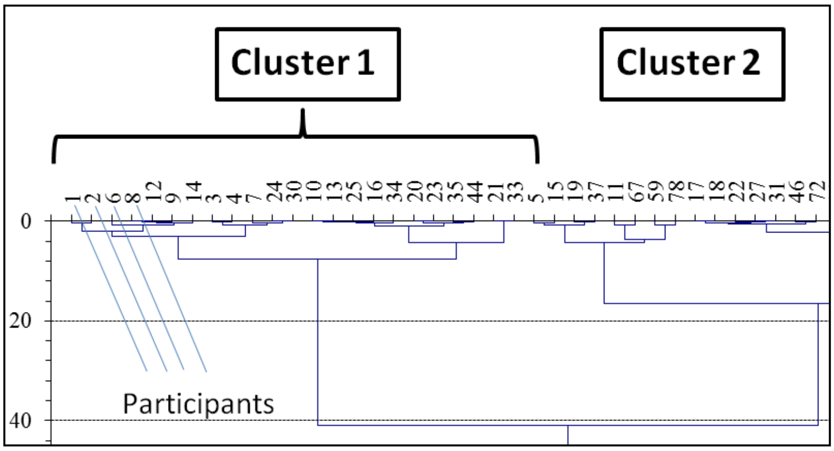


Figure 3-19 Part of the 9 groups - clusters as derived from Ward's minimum variance method

As shown in Figure 3-19, each group contained roughly 15 – 25 participants.

In the stage frequency diagrams were made for each ear dimension in each group, as shown in Figure 3-20 for Concha X, Group 1. This resulted in 3 frequency diagrams for each of the three ear dimensions within each group.

		Bin Limits		
MIN	12,27	0	12,27	1
MAX	17,61	1	13,03	0
AVG	15,85	2	13,80	0
	0,763	3	14,56	2
		4	15,32	2
		5	16,08	1
		6	16,85	7
		7	17,61	3

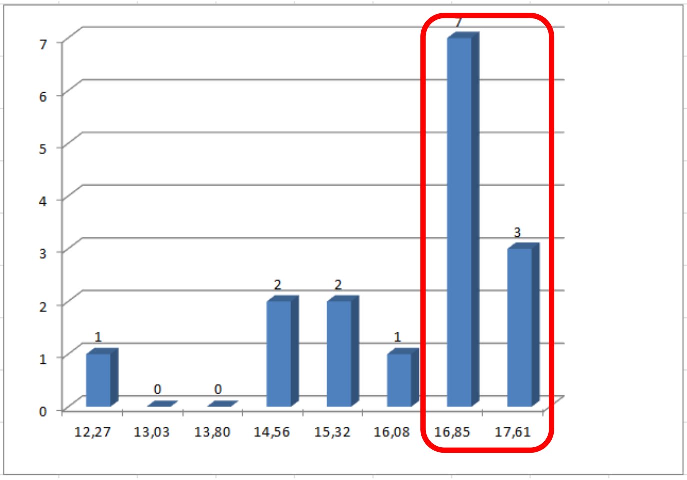


Figure 3-20 Frequency diagrams for concha X, Group 1

Popular intervals were chosen to include at least 60% of the participants for each group. In the case of Concha X in Figure 5 these intervals were interval 6 and 7. The archetype person was then selected based by identifying the person that belonged in all three popular intervals for all the three dimensions.

3.7.2 Limitations of the archetypes study

The limitations of the archetype study are presented in this section.

Ear data of 200 people was collected; this is the minimum number to ensure that the population is sufficiently represented from a statistical point of view. Including more participants in the data collection would generate more reliable archetypes and further solidify the findings of the second study.

The selection of more critical ear dimensions would provide with more accurate archetypes. The acquirement of additional measurements around the ear canal area would improve the predictions of fit since these measurements are linked to the ear gels of the headsets, which is a crucial product component for high scores of physical comfort.

A total of 9 archetypes were selected because of limitations in time and resources. There is, however the possibility to create more clusters, which will increase the number of archetypes, hence improve the understanding of the ear data and the prediction of physical comfort.

3.8 Conclusions

Several different approaches have been employed during the Description 1 Stage of this research. The research approach developed as the project proceeded. Each research approach had its limitations.

The ergonomic study provided an understanding of different methods to support design by various approaches to utilise 2-dimensional and 3-dimensional data with a focus on external-ear products. The appliance of the reference points on the head scans as well as the extraction of each dimension (repeated approximately 200 times for each one) were time consuming, and this is a lingering issue in the case that the designers at the company are in need for new dimensions to be included in the databases.

The comfort study on visual response provided an opportunity to compare the scores of the comfort variable against: (1) respective scores of attractiveness; and (2) rating scores of product descriptive words. The rating scales were useful in providing with an understanding on the causalitites between the three variables.

The archetypes study proposed a method to streamline focus groups and represent populations at large.

The total time spent on data collection during the Description 1 Stage of this research amounted to approximately 75 days, see Table 3-5.The additional time involved in collecting data for each of the three studies is useful in order to assess the effectiveness and efficiency of the research method. The additional time was used for: scanning the participants for the ergonomic study; travelling to meetings to arrange the data collection; extracting the 3-dimensional data from the 3D imaging software; issuing each of the 9 archetypes identified for the archetypes methodology study; setting up a method of analysis; and analyzing the data. All these activities required an additional time of 30 days. The extraction of the 3-dimensional data and the issuing of the archetypes were found to be the most time consuming and the study on visual response was the least.

The research methods together provided an insight into the identification of the influencing factors to comfort; and these factors (good fit and the visual response to a product) were of different nature (physical and psychological), which addresses the issue of the multidimensionality of comfort as well as the study of archetypes, primarily, shows the way to build methods to conduct more reliable comfort studies.

Time spent on data collection	Time in days
An ergonomic study	35 days
A comfort study on visual response	15 days
An archetypes study	15 days
Total Time	75 days

Table 3-5 Data collection for the Description 1 Stage

An evaluation of the proposed methods of support based upon the findings was also useful to validate the archetype study (described in Chapter 5). Methods of support regarding the other two studies are provided, mainly, in the form of methodological frameworks and documentation to be included as documents during the company's comfort standardization project which happened concurrently with this research project.

Chapter 4 Results

This chapter describes the results of the three studies at the Description 1 Stage. The threes studies were: (1) an ergonomic study; (2) a comfort study on visual response; and (3) an archetypes study. The three studies conducted are presented in Papers 2, 4 and 6 (refer to Appendix 1). This chapter presents an overview of the findings of all three studies and discusses their contribution to the main present project. The research methodology employed during the studies was discussed in Chapter 3. The results from each study influenced the direction of the subsequent studies. The ergonomic study was the first to be carried out. The results from the observations influenced mainly the use of the archetype methodology. The study of the rating scales and correlation analysis on visual response was conducted in parallel with both of these studies.

4.1 Study one: An ergonomic study

The results of the ergonomic study presented here can also be found in Paper 7 (refer to Appendix 1). For further details on the set-up of the ergonomic study, the presentation of the data and the method of analysis, refer to Chapter 3, section 3.5, or Paper 7. The findings from the 2-dimensional dataset are presented along with the findings of the two main applications of the 3D data, i.e. the basic and in-Depth benchmarking between products and human factors and, the visualisation of the 3-dimensional data. Due to confidentiality issues and data sensitivity only parts of the data will be presented. For more information on the total amount of data and the amount of measurements performed, see Chapter 3, Table 3-2.

4.1.1 Presentation of statistical values of the 2-dimensional dataset

This section presents statistical values derived for the critical ear dimensions of the 2-dimensional dataset; these dimensions, together with additional dimensions, were also extracted in the basic and in-depth benchmarking of the 3-dimensional dataset.

Statistical values and percentile diagrams are presented for 4 front left ear dimensions. These can be seen in Figure 4-1. Table 4-1 shows the respective dimensions retrieved from the manual measurement regarding the front ear dimensions and the statistical values of MIN, MAX, MEDIAN and AVERAGE values. Concha X ranges from a MIN= 12.27 mm to a MAX= 26.33 mm and Concha Y ranges from MIN= 12.29 mm to MAX= 21.40 mm. For the circumference dimension, the MIN= 37.76 mm and the MAX= 65.37. These dimensions can inform the product dimensions of the product categories 3, 4, 5, which were identified in the product understanding phase, which was described in Chapter 3, section 3.5.2 and can be seen in Figure 3-6.

	Statistical Values (mm)			
	MIN	**MAX**	**MEDIAN**	**AVERAGE**
Ear Height	4,29	27,25	15,16	15,99
Concha X	12,27	26,33	18,13	18,22
Concha Y	12,29	21,40	16,92	17,00
Circumference	37,76	65,37	50,20	50,64

Table 4-2. Statistical Values for front left ear dimensions

Table 4-3 presents the 5th, 10th, 20th, 40th, 50th, 70th, 80th and 90th percentile for four ear dimensions. The 80th percentile is a popular percentile for the design of external ear-worn products.

Ear dimensions	**Table of percentiles (mm)**							
	5%	**10%**	**20%**	**40%**	**50%**	**70%**	**80%**	**90%**
Ear height	9,77	10,21	11,58	13,56	15,16	19,26	20,76	22,95
Concha X	14,83	15,86	16,53	17,65	18,13	19,08	19,03	20,83
Concha Y	14,51	15,09	15,61	16,49	16,93	17,93	18,37	19,11
Circumference	43,98	44,96	46,98	49,28	50,32	53,09	54,35	55,90

Table 4-3 Percentiles for front ear dimensions

4.1.2 Basic and In-Depth benchmarking

This section presents statistical values regarding the critical ear dimensions. Due to confidentiality issues, instead the parts that influence confidentiality were omitted.

Figure 4-1 shows the selected critical ear dimensions and Table 2 shows the respective dimensions retrieved from the head scans regarding the front ear dimensions and the statistical values of MIN, MAX, MEDIAN and AVERAGE values. Concha X ranges from a MIN= 9,71 mm to a MAX= 27,21 mm and Concha Y ranges from MIN= 11,75 mm to MAX= 24,55 mm. For the circumference dimension, the MIN= 36,26 mm and the MAX= 62,04. These dimensions can inform the product dimensions of the product categories (3, 4, 5), i.e. the in-the-ear headsets, the behind-the-ear headsets and the in-the-ear headsets with ear-hook, which were described in Chapter 3, section 3.5.2

and can be seen in Figure 3-6. In particular, for the in-the-ear headsets the dimensions of the product part that rests inside the ear opening, can be benchmarked against the product dimensions, by consulting Table 4-1.

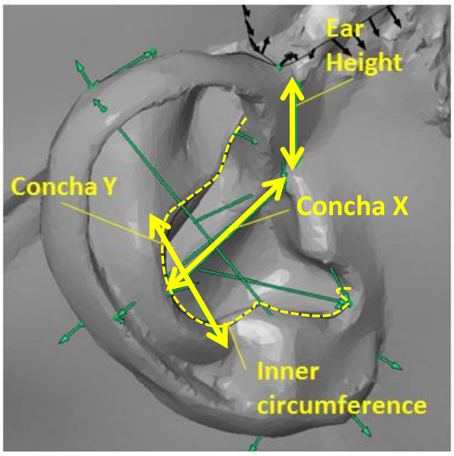


Figure 4-1 Front ear dimensions

	Statistical Values (mm)			
	MIN	**MAX**	**MEDIAN**	**AVERAGE**
Ear Height	9,71	28,78	19,47	51,11
Concha X	13,27	27,21	19,31	17,74
Concha Y	11,75	24,55	17,88	19,45
Circumference	36,26	62,04	50,44	93,11

Table 4-4 Statistical Values for front ear dimensions

Table 4-5 presents the 5th, 10th, 20th, 40th, 50th, 70th, 80th and 90th percentile for the previous dimensions.

Ear dimensions	**Table of percentiles (mm)**							
	5%	**10%**	**20%**	**40%**	**50%**	**70%**	**80%**	**90%**
Ear height	14,00	15,16	16,63	18,37	19,47	20,86	22,26	23,70
Concha X	15,95	16,49	17,42	18,60	19,34	20,78	21,32	22,65
Concha Y	14,61	15,03	15,88	17,32	17,89	18,80	19,52	20,41
Circumference	43,39	44,84	47,46	49,35	50,37	53,60	55,32	57,38

Table 4-5 Percentiles for front left ear dimensions

The additional dimensions calculated during the In-depth Benchmarking phase (refer to Figures 3-9 and 3-10) can be seen in Table 4-6. These dimensions can contribute in the design of product families 1 and 2, i.e., the design of headphones over and around the ear, as presented in Chapter 3, section 3.5.2 and can be seen in Figure 3-6; for example, the head height can be benchmarked against the height of the headband of the headphones.

	Statistical Values			
	MIN	**MAX**	**MEDIAN**	**AVERAGE**
Head breadth Top	135,76	175,26	154,51	135,76
Head Breadth Bottom	111,76	173,54	140,22	111,76
Head Height	111,77	163,18	124,74	11,77
φ1	0,28	40,23	19,22	0,28
φ2	7,74	26,49	154,48	7,74

Table 4-6 Statistical Values for head dimensions and angles φ1, φ2

The angles φ1 and φ2 can be used to define the degree of fluctuation of the ear cups of the headphones along different axis, as well as contribute to determine the pressure levels that the ear cups of the headphones exercise upon the head. These findings show that a product dimension can indeed be informed by human dimensions.

4.1.3 Visualisations of Data

Table 4-7 contains statistical values linking to the segments identified during the phase of Visualisation of 3D data as discussed in Chapter 3, section 3.5.3 and seen in Figure 3-12. Figure 4-2 shows the 2 segments in regard to a behind-the-ear Bluetooth headset product.

	Statistical Values			
	MIN	**MAX**	**MEDIAN**	**AVERAGE**
(AB)	10,71	29,78	19,72	19,94
(BC)	7,21	22,98	13,93	14,20

Table 4-7 Statistical Values for segments (AB) and (BC)

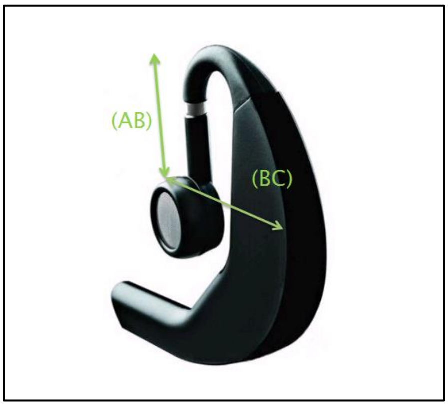


Figure 4-2 Benchmarking of segments (AB) and (BC)

The table of percentiles is presented here, as seen in Table 4-8.

	Table of percentiles							
	5%	**10%**	**20%**	**40%**	**50%**	**70%**	**80%**	**90%**
Segment (AB)	14,72	15,91	16,90	18,77	19,72	21,47	22,57	24,33
Segment (BC)	8,11	8,11	10,01	11,89	12,43	14,11	15,11	16,69

Table 4-8 Percentiles for segments (AB) and (BC)

The human dimensions presented were associated with product dimensions as seen in Figure 4-2. These findings prove that it is possible to predict product dimensions through qualitative methods of visualisation of human data. The potential of this method in addition to other approaches to supporting early conceptual design will be discussed in the method of support and preliminary evaluation, see Chapter 5.

4.1.4 Discussion

The resluts have clearly shown that by meaningful applications of 2-dimensional and 3-dimensional human data, it is possible to benchmark human dimensions against product dimensions with the aim to support product design, and that product dimensions can be predicted through qualitative methods of visualisation of human data.

These results can satisfy the demand for dimensioning of more complicated product parts in terms of shape and placement in the product geometry. In the Early Product Understanding phase the critical dimensions were defined and they were associated to respective human data. The various applications of the two datasets involved the benchmarking between human and product data and the visualisation of the data. These applications led to an increased understanding of human and product anatomy (providing 29 basic and 9 advanced human dimensions). These methods are expected to expand to other industries of body – worn products, such as helmets, etc., with the acquirement of respective human data.

The treatment of the 3-dimensional data, in particular, showcases the potential of having acquired such a powerful dataset, since the raw data of 3d head scans can be revisited and be reanalysed with the aim to produce additional dimensions to satisfy the need for designing new concepts of products and go beyond the context of headphones. The analysis of the 3-dimensional dataset provided 9 dimensions, that is, dimensions derived after a mathematical analysis of the shape and geometry of human physiology. The advantage of treating the 3d head scans in a 3-dimensional software offered the potential of calculating new geometrical shapes and values, curved lines and angles, respectively. Overall, the findings contributed to an increased understanding of human geometry and product complexity, achieving a more accurate benchmarking between humans and products.

Regarding the visualisation of the data the superimposed curves provided with a more qualitative approach towards the fitting of the ear products on the ear. The mathematical segments that were retrieved and the data that was extracted and analysed offered a more direct link to product dimensions, as the segments were more linked to product dimensions, rather than linking, first, to human dimensions, as seen in Figure 4-2.

These findings support the advancement of knowledge regarding *the good fit*, which, as discussed in the literature review (see Chapter 2, section 2.4), is an influential factor and a strong evaluative term for physical comfort.

4.2 Study two: A comfort study on visual response

This section presents the results of the comfort study on visual response. The results of this study are reported in Paper 4 and 5 (refer to Appendix 1). During the ergonomic study the different applications of 2-dimensional and 3-dimensional data offered information on possible ways of associating human dimensions with product dimensions with the aim to advance the knowledge of physical comfort in product design. Due to the multidimensional nature of comfort, as discussed in various parts of the thesis, in the comfort terminology section, of the literature review, (Chapter 2, section 2.1) in the section of the effect of emotional responses towards a product (Refer to Chapter 2, section 2.26) and in the section of the theoretical models of comfort (Refer to Chapter 2, section 2.3), comfort is linked to the aesthetic properties of the product , where the visceral response of a human towards a product is the first stage of the emotional process and is realised through the sensory inputs of the participant (appearance, touch and feel).

4.2.1 Attractiveness influences our perception of the products

To facilitate the reading and better understanding of the results of the rating scales study on visual response, the table of the presentation of the measures of this study (see Table 3-4), as well as, the list of hypotheses are presented again.

Study phases	**Description**	**Measures**		
		Real Comfort	**Expected Comfort**	**Attractiveness**
A	No see and Yes (Touch and Wear)	Ca	-	-
B	Yes (See and Touch) and No Wear	-	Cb	A
C	Yes (See and Touch and Wear)	Cc	-	-

Table 3-4 Presentation of the study measures

The final set of hypothesis based on the design of the study and the table of measures is presented below.

- H1: If the attractiveness (A) is positive (A > 0), then Ca < Cb
- H2: If the Attractiveness (A) is positive (A > 0), then Cb < Cc
- H3: If the Attractiveness (A) is positive (A > 0), then Ca < Cc
- H4: If the Attractiveness (A) is negative (A < 0), then Ca > Cb

- H5: If the Attractiveness (A) is negative (A < 0), then Cb > Cc
- H6: If the Attractiveness (A) is negative (A < 0), then Ca > Cc
- H7: Strong correlations are expected between comfort in all three phases (Ca, Cb, Cc) and the respective scores given to the lists of the opposite adjectives

As shown in Table 4-9, the means of the various comfort scores for each one of the phases of the study were compared against each other, first, in the case of positive attractiveness and then, in the case of negative attractiveness.

Positive Attractiveness		
	Ca	Cb
Mean	0.9636	3.7273
Variance	26.8875	17.7576
P(T<=t) two-tail	**6.20E-05**	
	Cb	Cc
Mean	3.7273	6.0364
Variance	17.7576	23.5912
P(T<=t) two-tail	**2.80E-04**	
	Ca	Cc
Mean	0.9636	6.0364
Variance	26.8875	23.5912
P(T<=t) two-tail	**6.11E-07**	

Table 4-9. T-tests for comfort scores for positive attractiveness

The two-tail probability value in the three different cases is for (Comfort a – Comfort b) equal to P(T<=t) two-tail = 6.2 E-05 and for (Comfort b – Comfort c) is P(T<=t) two-tail = 5.73 E-04 and for (Comfort a – Comfort c) is P(T<=t) two-tail = 6.1 E-07. In all three cases the probability value is less than α = 0.05 = 5%. This means that Null hypothesis 1,2 and 3 are rejected and therefore the alternative hypothesis are accepted, according to which the means of Comfort a ≠ Comfort b and Comfort b ≠ Comfort C and Comfort a ≠ Comfort c are significantly different to each other. In fact, after a look at the values of the means, it can be concluded that in the case when attractiveness is positive, then Cb > Ca, Cc > Cb and Cc > Ca. This means that in the case when the attractiveness towards the products was positive, the scores of comfort were enhanced from phase A (No see, Touch, Wear) to phase B (See, Touch, No Wear) and furthermore enhanced, as the experiment proceeded from phase B (See, Touch, No Wear) to phase C (See, Touch and Wear), i.e. the visual response to attractiveness enhances the perception of comfort.

In the following Table (see Table 4-10) the means of the various comfort scores for each one of the phases of the study are being compared against each other in the case of negative attractiveness. The two-tail probability value in the three different cases is for (Comfort a – Comfort b) equal to P(T<=t) two-tail = 4.31 E-08 and for (Comfort b – Comfort c) is P(T<=t) two-tail = 0.068 and for (Comfort a – Comfort c) is P(T<=t) two-tail = 2.69 E-07. In two out of the three cases the probability value is less than α = 0.05 = 5%.

Low Attractiveness		
	Ca	Cb
Mean	1.0217	-3.5217
Variance	44.3773	25.4995
P(T<=t) two-tail	**4,31E-08**	
	Cb	Cc
Mean	-3.5217	-4.6087
Variance	25.4995	26.1101
P(T<=t) two-tail	**0.06805**	
	Ca	Cc
Mean	1.0217	-4.6087
Variance	44.3773	26.1101
P(T<=t) two-tail	**2.69E-07**	

Table 4-10 T-tests for comfort scores for negative attractiveness

This means that the two Null hypothesis 4, 6 are rejected and therefore the alternative hypothesis are accepted, according to which the means of (Comfort a) ≠ (Comfort b) and (Comfort a) ≠ (Comfort C) are significantly different to each other, in fact, (Comfort a) > (Comfort b) and (Comfort a) > (Comfort C). In the case of the scores of comfort b compared to the ones of comfort c, the authors conclude that there is a low presumption against the null hypothesis and therefore it cannot be rejected. The mean sample value of the (Comfort C) scores is, however, larger than the respective (Comfort B) scores. This means that in the case when the attractiveness towards the products was negative, the scores of comfort were enhanced from phase A (No see, Yes (Touch, Wear)) to phase B (Yes(See, Touch), No Wear) but not enhanced, as the experiment proceeded from phase A (No see, Touch, Wear) to phase C (Yes(See, Touch and Wear)).

A visual representation of the data follows in order to increase the understanding of the association between the comfort levels and the attractiveness. The differences (Cb – Ca) were then plotted against the respective levels of attractiveness, as shown in Figure 4-3. With the exception of 9 outliers out of the 69 points the statistical results are confirmed regarding hypothesis 1 and 2 since for high levels of attractiveness the respective levels of comfort for each product increased, whereas for low levels of attractiveness the levels of comfort decreased. This means that the expected comfort is increased in comparison to the assessment of the product (Ca) when the appearance of the product being worn was not visible.

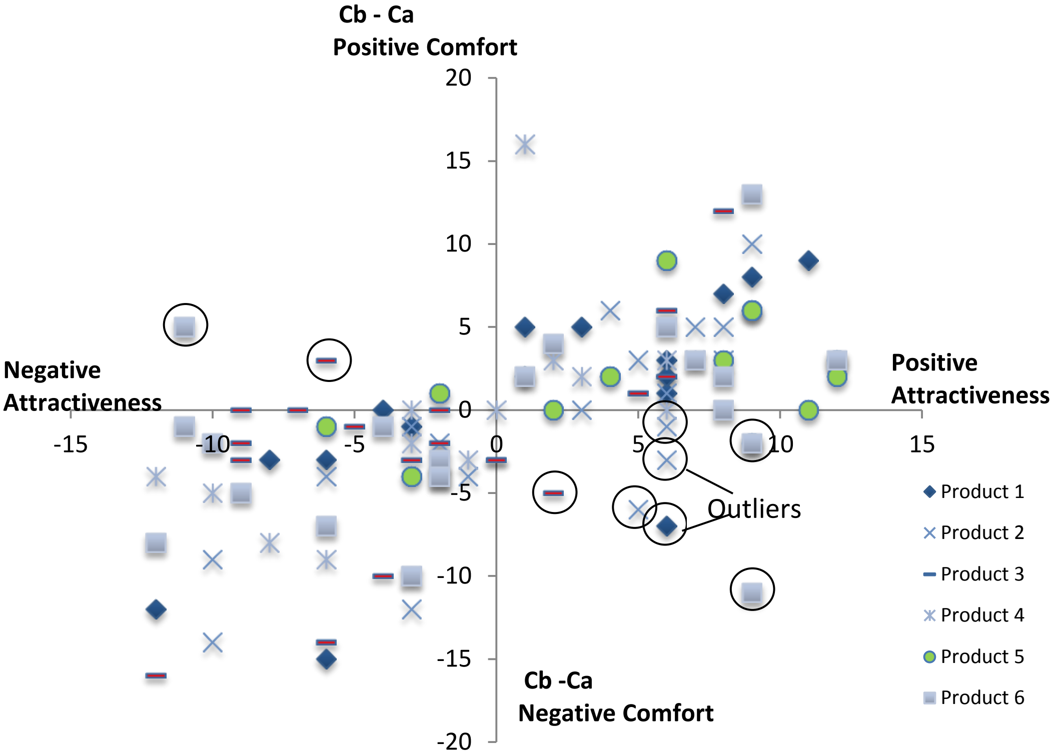


Figure 4-3 Differences of absolute means of comfort grades versus attractiveness scores for the first two phases (comfort a, comfort b)

The differences (Cc - Cb) were also plotted against the respective levels of attractiveness (see Figure 4-4). 13 outliers were found out of the 69 points as seen in Figure 4-4. The proof of the first hypothesis between attractiveness and the respective levels of comfort shows that the expectation of comfort during the second phase when the visual response comes to play was higher when the attractiveness towards the product was respectively high, whereas it was lower when the attractiveness was low. In the second diagram the comfort scores in the third phase (see, touch and wear) were either further enhanced or further reduced depending on the attractiveness levels. However there seemed to be a randomized increase or decrease, as well as, a greater number of outliers. The reason for this could be that in the third phase, where the participants engaged themselves in a full physical experience with the products, other influential factors contributed to the assessment of the comfort experience.

From the findings of Zhang *et al.* [1997], comfort is linked more to emotional factors and discomfort more to physical ones, the low scores of comfort found in this paper could derive not only from low attractiveness but also from physical factors that appear in the third phase.

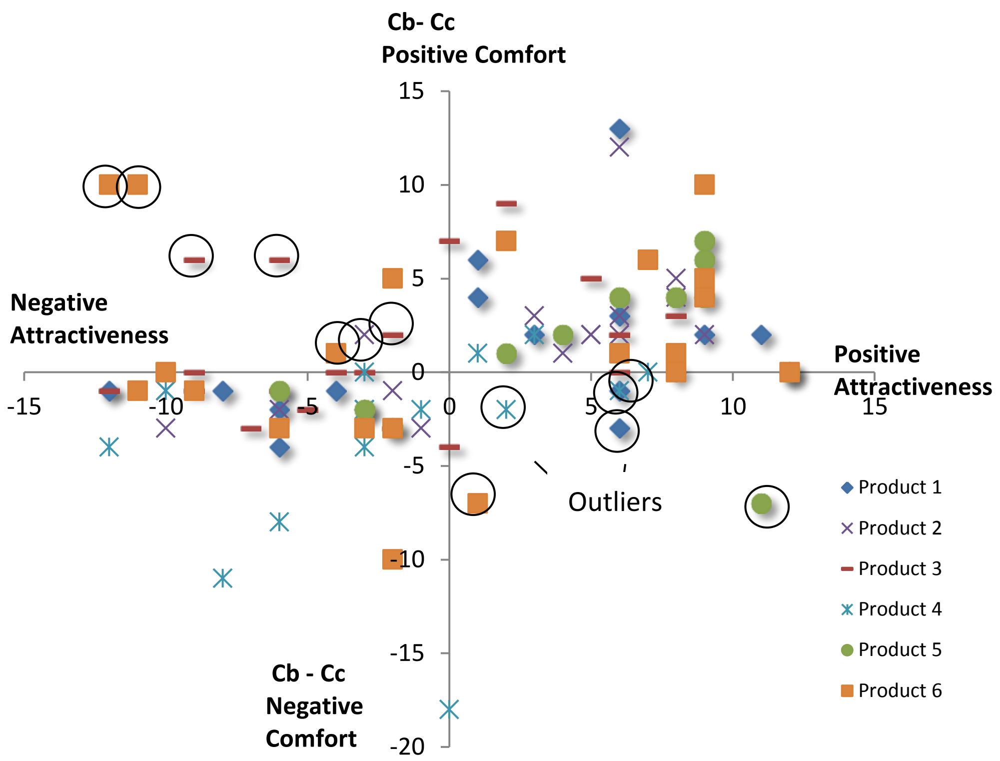


Figure 4-4 Differences of absolute means of comfort grades versus attractiveness scores for the last two phases

4.2.2 Developing the visual profile of a product through the influence of comfort

The correlation between the participants' responses on comfort versus their respective responses on product attributes by using the Spearman test was investigated. For the Spearman's correlation, coefficient (r) values between 0.40 and 0.69 ($0.40 \leq r \leq 0.69$) indicate a strong positive relationship whereas values above 0.70 ($r \geq 0.70$) indicate a very strong positive relationship. Table 3 shows only the part of the matrix that reveals the strong and very strong positive relationships observed between comfort scores and product descriptors. The summary of the coefficients in Table 4-11 show that there was a very strong positive relationship between comfort and the pairs of bulky –

slim (Phase A: 0.810, $p < 0,01$, Phase B: 0.821, $p < 0,01$, Phase C: 0.831, $p < 0,01$) and big – little (Phase A: 0.721, $p < 0,01$, Phase B: 0.645, $p < 0,01$, Phase C: 0.706, $p < 0,01$) in all three phases of the experiment. A weaker, yet considerably strong positive correlation was also observed between comfort and the rough – soft pair whereas there was a strong negative correlation between comfort scores and light – heavy in all phases.

Spearman Test	Bulky - Slim	Light - Heavy	Big - Little	Rough - Soft
Comfort a (Ca)	.810**	-.548**	.721**	.454**
P value	.000	.001	.000	.008
Sample Size	44	44	44	44
Comfort b (Cb)	.821**	-.583**	.645**	.368*
P value	.000	.000	.000	.035
Sample Size	44	44	44	44
Comfort c (Cc)	.831**	-.708**	.706**	.689**
P value	.000	.000	.000	.000
Sample Size	44	44	44	44

Table 4-11 Cumulative table of coefficients

The correlations observed from the cumulative table of coefficients led to the forming of associations between the concept of comfort of products, and the product descriptors. In this case, a slim and small (in size) headset with low weight made from a rather soft surface material was perceived as comfortable and vice versa. However, it must be made explicit that these associations were articulated in a context by the properties of the specific products which were in this case a Bluetooth in–ear and behind-the-ear headset. In the case of a different type of product, descriptors such as bulky or heavy could be linked to the concept of comfort instead, which did not occur in this study.

4.2.3 Discussion

This section presents the discussion of the results regarding the comfort study on visual response. The study of rating scales on visual response was conducted with the aim of investigating how the attractiveness during a human-product interaction affects the expectation and experience of comfort. The set of hypothesis proved in the previous section, i.e. in the case when the attractiveness of a product is perceived as high the levels of comfort are also perceived as high, whereas in the case where the attractiveness is perceived as low the levels of comfort are reduced, could also be explained by products that are designed for better comfort and also have a higher level of attractiveness. To ensure that this was not the case, the responses for each product were mapped (see Figure 4-3 and 4-4). If the products were scattered in all quadrants this would disapprove that it is the design -and hence is not an effect of all products that are best for comfort are also more attractive. Instead, the individual perception of a product with attractiveness increases the perception of comfort and that the individual perception of products varies, i.e. the same products are not perceived by all participants as attractive or with a high level of comfort. This can be confirmed by observing that the perception of all 6 products varies, i.e. the products are scattered in the graphs (Refer to Figures 4-3 and 4-4), rather than one or two products falling in a quadrant where there is both high attractiveness and high comfort (or low attractiveness and low comfort). This observation confirms that attractiveness is an important influencing comfort factor and a strong evaluative term for comfort.

The results of this study highlighted the relationship between attractiveness and comfort. The main findings showed that the comfort experience was amplified by the attractiveness during a human – product interaction i.e. that emotional design does influence the comfort assessment of a product. When the levels of attractiveness were low the comfort scores reduced from phase A (No See and Yes(Touch and Wear)) to phase B (Yes(See and Touch) and No Wear) and from phase B to phase C (Yes(See and Touch and Wear)). The opposite case occurred for high levels of attractiveness. The findings showcased that an individual perception of the attractiveness of a product influences the level of comfort perceived of a product, i.e. attractive products do interact better at least for short term interactions.

4.3 Study three: The archetypes study

The section presents a generalised framework of the different steps of the execution of the archetypes methodology to generate the archetypes. A more detailed analysis of this section can be found in Papers 6 and 7 (see Appendix 1).

4.3.1 Designing a comfort study to evaluate products based on a reliable user panel

Based on the description of the study, as this was presented in Chapter 3, section 3.7.1, the following methodological framework to create a reliable representative user panel of a large population is proposed, see Figure 4-5, where this is summarised. In the same figure, the example of executing the methodology is shown, as it was described in the above sections.

The method is dependent on the attributes of the product, hence the product definition precedes most of the phases of the framework to ensure that these are identified early on and used to create the correct clusters and select the appropriate archetype. Once the product is defined it is necessary to execute preliminary interactions involving users in order to identify relevant dimensions. This will provide a reliable set of critical product dimensions that highlight the anthropometric data that needs to be collected. Once the archetypes have been defined these can be used in two ways. The first way is to use the archetype people's dimensions in order to design comfort studies where the researcher could make inquiries on physical properties of comfort towards new prototypes. However selecting prototypes with similar attributes (e.g. similar manner of use, similar geometry, etc.) to the product used at the beginning of the method is important in order to ensure the validity of the archetypes. The second way is to define test panels based on the generated archetypes to select participants that should be part of the panel. These panels can be used for both quantitative and qualitative studies.

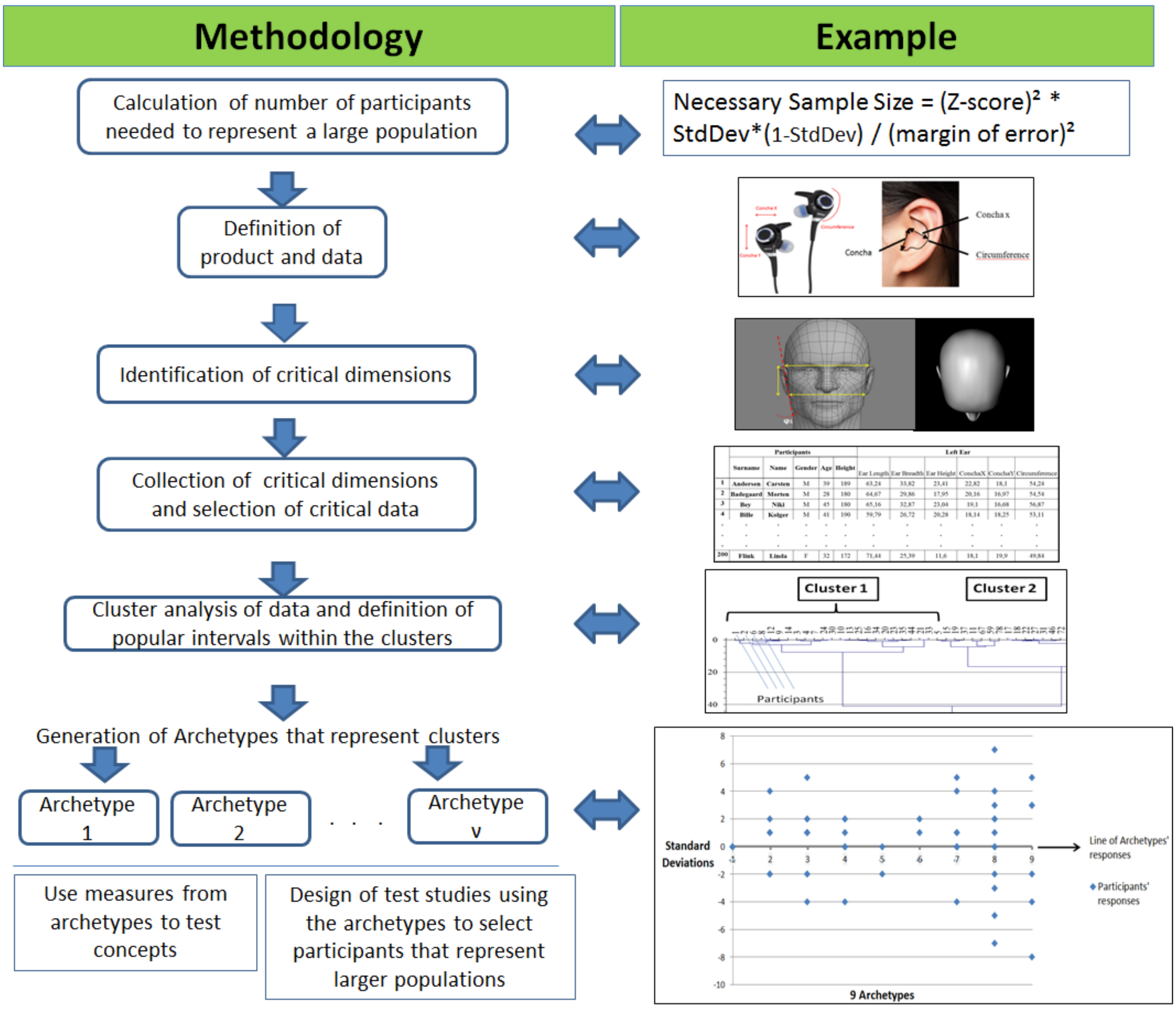


Figure 4-5 Proposed methodological framework to represent large populations

4.3.2 Discussion

This section introduces the discussion of the findings of the study on archetypes.

The archetypes study proposed a new user test approach taking the specific problem of comfort and great variability of ears (sizes, angles) into account. Instead of selecting test panels at random with little considerations for whether the selected individuals are representative for a population at large and relying on anecdotal knowledge of specific users exhibiting unusual ear geometry, with the archetypes study a general methodology was developed to streamline this process, by identifying archetypes ears,(and hence, the participants for user test panels) and creating computational support to evaluate product designs (in this case headsets) to identify comfort areas.

The archetypes study contributed to the general area of user involvement, whereas with this study it is not expected to replace the role of users, but to focus the users' involvement and support the selection of the user.

It is expected that the methodology employed could be transferred to user involvement research with other products and dimensions.

4.4 Conclusions

The findings from the three studies contributed to the advancement of knowledge regarding the dependencies between the physical and psychological dimensions of comfort and provided with a methodological framework which improves the reliability of user testing for the testing of users to be included in the comfort studies conducted at the early conceptual phase of the design process.

In the ergonomic study, the incorporation of anthropometry in the design of products was examined. Different methods were presented to support applications of 2-dimensional and 3-dimensional head and ear data with a focus on external ear products. External-ear worn products were assigned to 5 product categories based on function and physical fit. A total of 200 persons representing the Danish population were scanned, and once the 3D data was collected,, it was refined and analyzed. The main findings generated a matrix of 29 anthropometric dimensions in alliance with respective product dimensions. An increased understanding of human geometry and product complexity, as well as the execution of data visualization provided with a secondary matrix, including an additional number of 9, advanced dimensions, from a geometrical viewpoint. These methods contributed to an increased understanding of human geometry and product complexity, achieving a more accurate association between humans and products and leading to the execution of more reliable comfort studies.

Regarding the comfort study on visual response, comfort was assessed in three phases versus the levels of attractiveness for two sets of products with 44 participants. The results of this study highlighted the relationship between attractiveness and comfort, hence showing the benefit for companies to invest more in products where emotional comfort for short tasks is important. The main findings showed that the comfort experience was amplified by the attractiveness during a human – product interaction i.e. that emotional design does influence the comfort assessment of a product. When the levels of attractiveness were low the comfort scores reduced from phase A (No See and Touch and Wear) to phase B (See and Touch and No Wear) and from phase B to phase C (See and Touch and Wear). The opposite case occurred for high levels of attractiveness.

The findings concluded that an individual perception of the attractiveness of a product influences the level of comfort perceived of a product, i.e. attractive products do interact better, at least in the context this study was restricted to, that is, for short term interactions. Additional findings revealed very strong (or strong) correlations between expected and real comfort scores and the bulky – slim, light – heavy, big – little and rough – soft pairs of product descriptors. These results inscribe the visual image of a product; hence, support designers in predicting the visual information that leads to products being perceived as comfortable by the user. These findings not only stress the need to focus on the emotional dimension of comfort but they can be seen as guidelines for product designers. Emotional design is a viable strategy for areas where comfort is significant and where short tasks are dominant. Consequently designers should focus more on improving the visual response that the products create to the users when striving for comfort, as this improves the perception of comfort.

In the archetypes study, anthropometric data was collected from 200 participants. The participants were distributed into 9 clusters and archetypes were generated to represent each cluster. Based on the proposed method, a methodological framework to develop a representative user panel for the execution of comfort studies in the ear industry was presented. By using an early prototype as the main case study, the methodological framework was able to be tested, and archetypes were generated out of the clusters of the ear data, which was collected. The method adopted the approach of identifying an archetype from clusters analysis on a large set of data, which can then be used to identify participants for a test panel. This method contributed in the reduction of cost and time by providing guidance on the selection of participants as an alternative to statistical approach, which would require a large number of users. In Chapter 5, a method of support with the form of guidelines is provided, and a preliminary evaluation of the first set of archetypes which were identified in the archetypes study is presented.

The findings from the ergonomic study and the comfort study on visual response indicated that both physical and psychological aspects of comfort should be considered at the early stages of concept development. The framework presented in the archetypes study proposed a reliable way for user testing. A similar need exists for a methodological framework to support the execution of ergonomic and psychological studies to evaluate comfort at the early stages of conceptual development. These methods of support are presented in the following section of methods of support and preliminary evaluation (Refer to Chapter 5, section 5.2.1).

Chapter 5 Method of Support and Evaluation

5.1 Introduction

This chapter describes the Prescriptive Stage (methods of support) and the initial part of the Descriptive 2 Stage (evaluation of methods) of the overall research methodology (Design Research Methodology). This methodology is described in Chapter 3, section 3.1.

This chapter outlines:

- The prescriptive stage: proposed methods of support for the assessment of comfort and the execution of comfort studies at the early stages of conceptual development in the context of product design.
- The description 2 Stage: preliminary evaluations of the proposed methods and the research method employed.
- The preliminary implementation of the method.

5.2 Development of methods of support

As stated elsewhere, due to the multidimensionality of comfort, different methods of support were developed to address the different aspects of comfort, linking the descriptive studies presented in Chapters 3 and 4 and their findings (presented and discussed in Chapter 4). For each of the issues raised in the respective descriptive studies, various approaches towards the developed methods of support to address these issues were considered.

After considering the findings of each study, these main issues were identified as important, prior to creating methods and tools that can be adopted by the industry:

- For the execution of ergonomic studies on comfort in the industry (linking to the Ergonomic study of this research), the methods of applications of data need to be summarised and presented in a way that they can be adopted by user experience designers in the industry, with the aim to reproduce the methods if necessary, or extract the already retrieved dimensions.

- For the assessment of comfort at the early stages of the product development process (linking to the Comfort study on visual response), physical comfort is already addressed early in the pre conceptual development. There is a need to address psychological comfort too at this stage to achieve overall comfort of the prototypes at the early stages of the design process.

- For the improvement of user testing for the comfort studies executed in the industry, the Archetypes study was presented. This was only applied in one product family, namely, the in-the-ear headsets. There is a need to generate archetypes for the remaining product families, i.e. the behind-the-ear headsets, the in-the-ear headsets with an ear hook, the over-the-ear headphones and the around-the-ear headphones, to support the issuing of reliable user panels for comfort studies.

  Additionally, a preliminary evaluation of the first batch of archetypes generated during the archetypes study would verify the study on archetypes and show the way to expanding its contribution by generating the rest of the groups of archetypes.

In accordance to these issues, the main contributions of the thesis for methods of support were the following two areas:

1) A methodological framework including all applications of the 3-dimensional data was created. The framework aims to include all the activities performed during the ergonomic study with the aim to reproduce the method if necessary.

2) A new matrix of additional groups of archetypes was developed to facilitate the selection of a representative sample for the comfort studies executed. A preliminary evaluation of the first group of archetypes presented in the archetypes study was conducted in the form of an empirical study, including 20 participants.

However, in addition, the findings also led to a contribution, to a lesser extent, in redesigning the product development process to include activities that address the assessment of psychological comfort. These are presented in the following sections.

5.3 A methodological framework to perform ergonomic studies for physical comfort

The methodological framework of the various applications of 3-D data that were executed in the ergonomic study is presented in this section, in Figure 5-1. The methodology is expected to be applied to different context and products that are in physical interaction with the human body. The methodology consists of three main phases; (1) the Early Product Understanding phase; (2) the 3-dimensional Data collection phase and; (3) the various Applications of the 3-dimensional Data phase. These phases, and the various steps they consist of, are described in turn below and are summarised in Figure 5-1.

5.3.1 Provision of guidelines for support regarding the methodological framework

Each of the three phases are now described further in detail. To facilitate the understanding of the different phases of the methodological framework, refer to Chaper 3, sections 3.5.1, 3.5.2 and 3.5.3, as the experimental set-up and the applications of the datasets in the Ergonomic study were generalised for the development of the framework proposed in this section.

1) In the Early Product Understanding phase (first column in Figure 5-1), the critical dimensions are defined and these are associated to respective human data. The product categories were defined during the study of data applications based on fit, for more information on the product categories, see Chapter 3, section 3.5.2. Additional physical and physiological comfort factors can also be used at this stage, such as pressure, pain, etc. In this phase, it is advisable to use a high number of dimensions in order to cover as much of the complexity of the products as possible. In the case that product components interact with different body areas, a matrix of product components versus critical dimensions (instead of product categories versus human dimensions) is created to make more direct associations between human data and products.

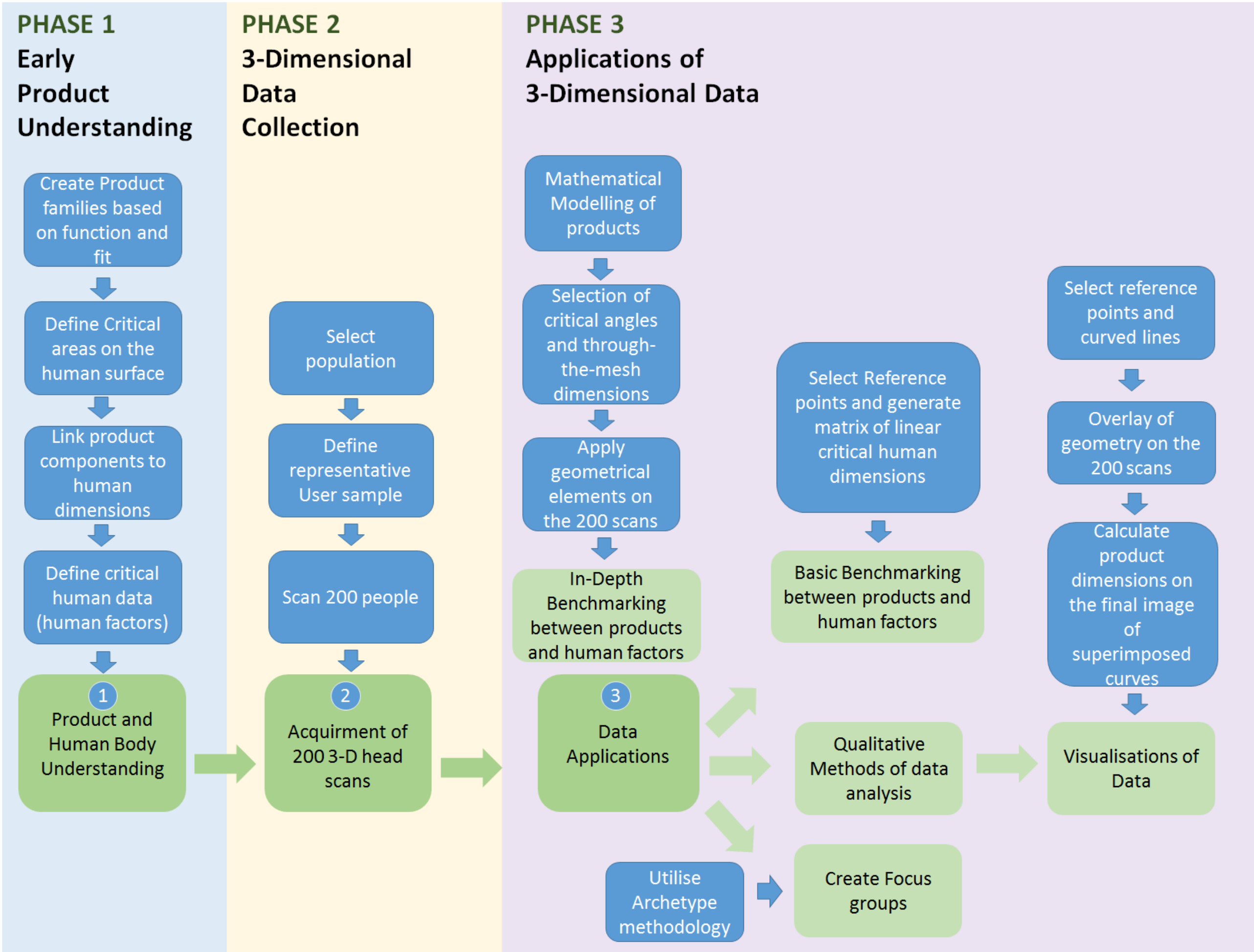


Figure 5-1 Methodological framework of 3D applications

2) In the Collection of 3-dimensional Data phase (second column in Figure 5-1), the importance of a homogenous dataset, in terms of origin of the population , was recognised in order to achieve a representative sample, for example, the Danish population, used in the Ergonomic study. The selected population should also be linked to the customer pool, which the products address to.

3) In the Applications of 3-Dimensional data phase (third column in Figure 5-1), these can be applied in different phases of the design process. The applications of the data are discussed here. Associations between product and human dimensions, where human data informs basic product dimensions, could be utilised in the early prototyping phase where basic issues of shaping and contour are still at stake. The in-depth benchmarking can be used in the refinement of prototypes, where mechatronic components are added into the prototype. In this phase, issues of slight alterations in the dimensioning of the prototype may arise, to fit the various components inside the

basic prototype casing. The visualisation of data can contribute both in early and later stages of the design process, as the method can provide defining dimensions of the basic prototype (e.g. the *head circumference* dimension, which is measured from top ear to top ear, over the head, informs the length of the headband of a headphone product) as well as give an impression of more complicated dimensions, the need for which is high in later stages of the product development (e.g. segments (AB) and (BC) in the example provided in the presentation of Visualisations of data in section 3.5).

5.4 The expansion of the Archetypes study

The second method of support is presented in this section. 4 groups of archetypes were developed covering for the remaining 4 product categories, which were identified in the Product Understanding phase, during the Ergonomic study (see first column in Figure 5-1). For the in-the ear headsets, archetypes were developed during the archetypes study, see Chapter 3, section 3.7.1. The remaining product families identified were namely: 1) the behind-the-ear headsets; the in-the-ear headsets with an ear hook; the over-the-ear headphones; and the around-the-ear headphones (see Figure 5-2). The Archetypes study was executed four times to cover the span of the product categories. The archetypes matrix (see Table 5-3) has been delivered to the designers of the user experience team at the company, where it has been applied to.

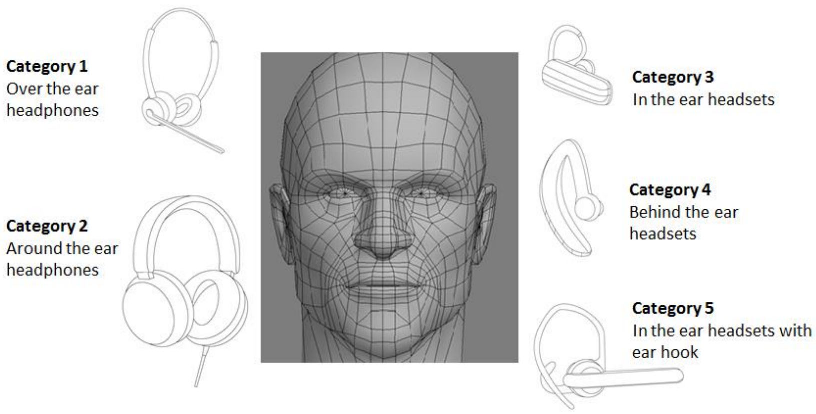
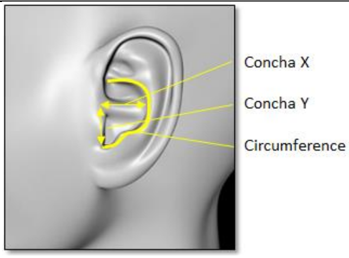
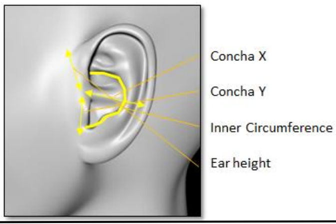
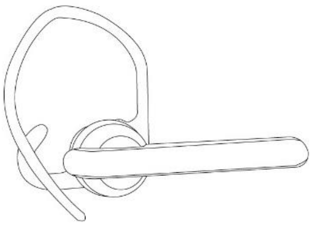
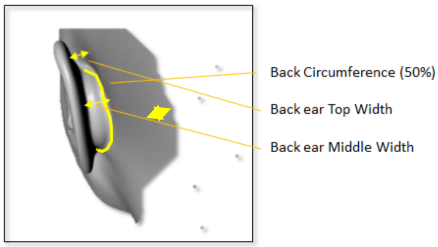
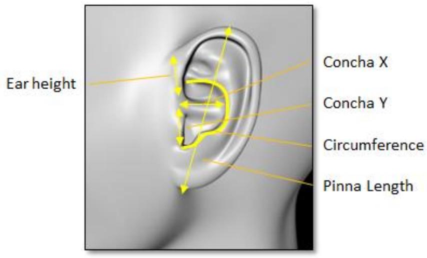
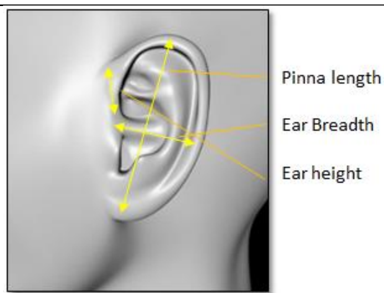
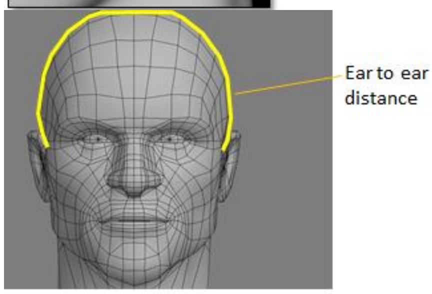


Figure 5-2 The 5 product families of external-ear worn products

PRODUCT CATEGORIES	CRITICAL EAR DIMENSIONS

<table>
<tr>
<td>In the Ear Headsets
</td>
<td>Concha X,
Concha Y,
Inner circumference</td>
<td>
</td>
</tr>
<tr>
<td>Behind the
Ear headsets
</td>
<td>Concha X,
Concha Y,
Inner circumference,
Ear height</td>
<td>
</td>
</tr>
<tr>
<td>In the ear headsets with ear hook
</td>
<td>Concha X,
Concha Y,
Inner Circumference,
Pinna Length</td>
<td>


</td>
</tr>
<tr>
<td>Over the ear Headphones
</td>
<td>Pinna length,
Ear Breadth,
Head Height,
Ear-to-ear distance</td>
<td>


</td>
</tr>
</table>

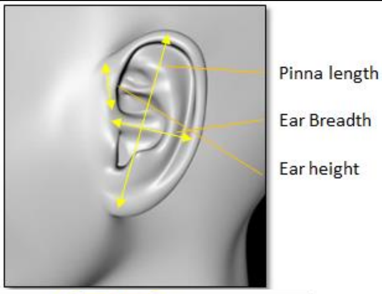
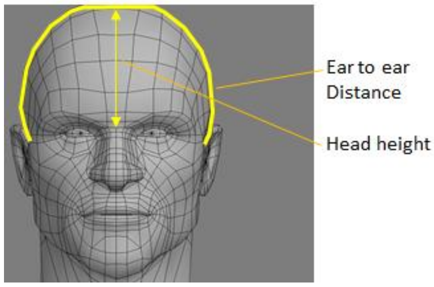
Around the Ear Headphones 	Pinna length, Ear Breadth, Ear- to – Ear distance, Head Height,	 

Figure 5-3 Archetype Matrix based on the product families

Finally, a document was created, including a summarised description of the archetypes study and the methodological framework that was proposed during the archetypes study in Chapter 4, section 4.3.1. The document includes a list of the steps of the archetypes generation process so that the methodology can be easily reproduced by the designers of the User Experience team in the company.

5.4.1 A preliminary evaluation of the first batch of archetypes

Prior to the extension of the archetypes to more product categories, a preliminary evaluation study was executed to evaluate the data from the archetypes that were generated during the Archetype study. This was done performed in order to check the validity of the archetypes.

20 individuals participated in the evaluation study. The aim of the study was to test if it is possible to predict the perception of good fit based on the use of archetypes. For this goal, the same dataset (2-dimensional data) of the 200 participants was used, similar to the one used in the Archetype study. 20 participants were randomly selected from the 200 people, but had to cover all 9 clusters, which were generated during the archetypes study by using cluster analysis (see Chapter 3, section 3.7.1). These 20 participants along with the 9 archetype persons (who were defined in the archetypes study) participated in an empirical study where they interacted with two groups of three external – ear products. Each of the participants interacted with three different external headsets (out of a possible six), see Figure 5-3. All participants were asked whether they were familiar with

the products that were tested in advance, in order to avoid bias towards one or more products. All participants were unfamiliar with the products the interacted with. During the interaction, the researcher placed the products upon the subjects' ears; hence the users were unable to see the products. The participants were not blindfolded, in order to minimize intrusiveness.

Figure 5-3 The groups of behind - the - ear and in - the - ear bluetooth headsets

Data for this study was collected with a questionnaire consisting of a question on physical fit. The question was provided in a 24 point double sided form. The participants were asked to evaluate the products in terms of good fit, see figure 5-4.

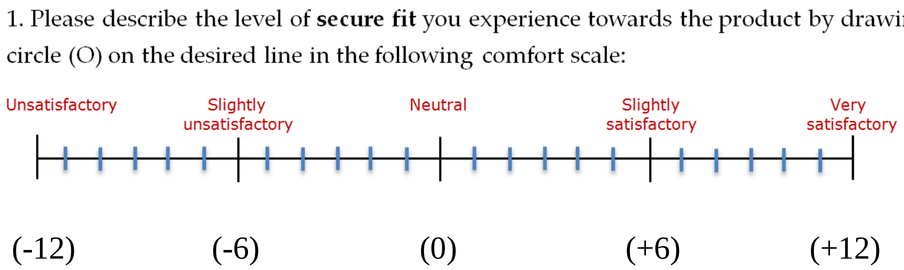


Figure 5-4 Semantic scale and attributed scores for physical fit

There were a total of 9 archetypes representing 9 clusters. The archetype person's scores were benchmarked against the respective scores of the participants who belonged in the same cluster. Deviations were calculated for all the 20 participants' responses against the 9 archetype persons' responses, to understand if the archetype person could represent the cluster (group of participants), to which the archetype belonged.

5.4.2 Predicting physical comfort based on the notion of archetypes

The aim of this study was to validate that the archetype persons can indeed represent the population from an anthropometric point of view. In this section it is shown that physical factors of comfort can be predicted based on the notion of archetypes.

In total, 29 people participated in the questionnaire including the 9 archetype persons. The participants assessed their fit factor, that is, how securely the product is placed on their ear, during their interaction with the 3 Bluetooth headsets. As shown in Table 5-1, each of the participants was categorised to his or her cluster from a total of 9 clusters derived from the 200 participants based upon the ear dimensions. A condition for the validity of the study was that each participant and the archetype from the same cluster interacted with the same group of products. Therefore care was taken to ensure that this was the case. Hence, the responses of the participants could be compared against the responses of the archetype person. Once the responses were retrieved the deviations of the participants' responses were calculated against their archetypes' responses. In total there were a total of 60 data points generated (three per person), which were compared to 27 data points (nine archetype persons x three products), see Table 5-1.

										Total Number of responses
9 Archetype people	**1st**	**2nd**	**3rd**	**4th**	**5th**	**6th**	**7th**	**8th**	**9th**	**9 People x 3 Products = 27 responses**
20 Participants	2	1	3	4	2	1	3	3	1	**20 People x 3 products = 60 responses**
Product type (In-the ear / Behind-the-ear)	In the ear	Behind the ear	In the ear	Behind the ear	Behind the ear	In the ear	Behind the ear	In the ear	Behind the ear	

Table 5-1 Distribution of participants to the 9 clusters

As shown in Figure 5-5, the deviations of the 20 participants were plotted against the scores of their archetypes. Not all 60 points can be seen clearly in the graph, due to overlapping of points with similar responses. The *zero* x axis is called the line of archetypes and it represents the responses of the archetypes (ArchRes). Each of the 60 points in the graph (see Figure 5-5) represents the deviation of the participant of the same cluster response (PartResp) against the archetype response (ArchRes). Hence, each point represents the mathematical difference (ArchRes – PartRes). A close deviation, would mean that the answers of the cluster members were almost similar to the ones of the archetypes', indicating that the archetypes can indeed represent their group. If all the points are as close to the horizontal axis as possible, this would indicate a close match of the participants' response to that of the archetype person.

The scale of the deviations on the y axis followed the attributed scores of a 24 point scale, from the question on physical fit which was presented earlier, that is, from -12 to +12. With the exception of 7 responses (out of a total of 60) close deviations were observed. This indicates that it is possible to predict people's perceptions of physical properties of comfort based on anthropometric data, through the use of clusters and archetypes as representatives of these clusters.

This finding forms a link between perception and human factors and can be seen in this instance as a prediction of users' perception of fit based on the anthropometric properties of the archetypes that represent them. For the archetypes 7 and 9, where a larger deviation is observed the second group of the behind–the–ear products was used for the interaction with the participants.

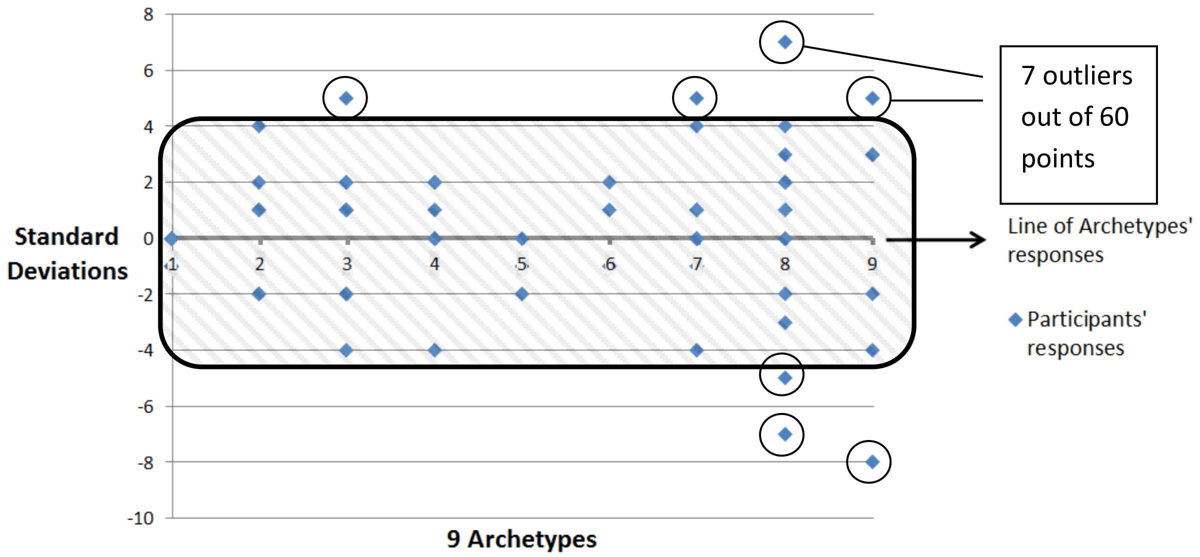


Figure 5-5 The chart of standard deviations

The use of these products may have been the reason for wider deviations since these products have different attributes to the prototypes upon which the archetypes were developed. These attributes concern product geometry, the manner of wearing the product, etc. and this issue is elaborated upon in the section of the limitations of the study.

5.4.3 Limitations of the study

Although a participant number of 20 were sufficient to demonstrate the method, a larger number of participants would ensure that there are a significant number of participants distributed among the clusters. This is planned as part of further work in order to gain a better knowledge of the link between perception of physical comfort and anthropometry, see Chapter 6, section 6.5. Finally, the choice of behind-the-ears products may have resulted in wider deviations due to the fact that the products may have required a slightly different set of human factors, that is, a different set of anthropometric ear dimensions than the product (in-the-ear) for which the dataset was collected. This points to the need for more ear measurements needed to increase the applicability to a wider range of ear products.

5.4.4 The archetypes study: Applications to industry

The archetypes study was applied on the design of a sensor integrated headphone, the Jabra Sport Pulse™ Wireless headset, designed to measure heart rate for fitness purposes. The prototype version of this product was used in the Archetypes study (see Chapter 3, section 3.7.1). The Jabra Sport Pulse™ won the Design and Innovation Showstoppers award for best headphone at the IFA Design Fair in Berlin, 2014. Comfort was highlighted as one of the key features for the success of the product, however, the success of this cannot be contributed to the use of the methodology alone, but this influenced the design, in particular, when considering comfort.

At this point, it should be mentioned that a series of comfort tests, strongly influenced by the findings of the research's project on good fit and visual response, had been conducted from early stages of the development cycles.

5.5 Contributions to the inclusion of comfort in the product development process

Part of the project's aims, as these were defined in Chapter 1, section 1.2, was to allow the assessment of physical and psychological comfort as soon as possible in the PD process. This led to a redesign of the process, described in this section.

A standardization of various aspects of the design process in the company took place over a period of 10 months, starting, roughly, in the middle of this research project. The general Product Development (PD) model of the design process was updated and the various steps of the comfort assessment of products were aligned with the phases of the PD process. The researchers of this project assisted the comfort specialist and the designers, who executed the standardization process, with intellectual contributions through regular meetings and through writing of sections of the standardized documents produced at this stage to support the execution of the various phases of the

PD model. Figure 5-6 shows part of the PD process of the company, linking to the first two phases of the pre-conceptual phase, these were namely: product definition (-2); and concept design (-1). Under these phases, the respective design activities were added. In the same figure, some of the main elements of this research project, namely: the *comfort theory;* the *ergonomic study*; the *comfort study on visual response*; and the *archetypes study* were included in the design process of the company. This was performed to show the level of dissemination of the knowledge produced by this project.

As seen in Figure 5-6, the definition of a comfort test panel and the generation of archetypes are expected to occur as some of the first activities during the pre-conceptual phase. These steps were introduced as part of the archetypes methodological framework during the archetypes study.

Under the same phase (product definition) of the product development model, *benchmark* product tests are expected to be executed, linking to the association between human data and product data, as this was performed and presented in various applications during the ergonomic study.

The literature review on comfort definitions and comfort methodologies, (the main conclusions of which were presented in Chapter 2, section 2.5), influenced the *product specific research* activity and the *comfort evaluation* activity, as seen in Figure 5-6. The new comfort terminology, linking to physical, physiological and psychological comfort, was used throughout the PD company's model, that is, where comfort and its dimensions needed to be addressed.

Finally, comfort studies are performed in two phases (expected comfort, real comfort) in the execution of the *comfort id evaluation* activity. The separation of these studies into two phases, with the aim to assess both expected and real comfort, links to the design of the controlled experiment study on visual response, as this was presented in Chapter 3, section 3.6.1, see Figure 3-3.

Additional elements of this project influenced also other phases of the company's PD model, where *comfort validation* tests are required in order to verify if the product design matches the intended comfort targets. However, this has not been examined thoroughly, as the focus of this project was to assess comfort at the earlier stages of the conceptual development.

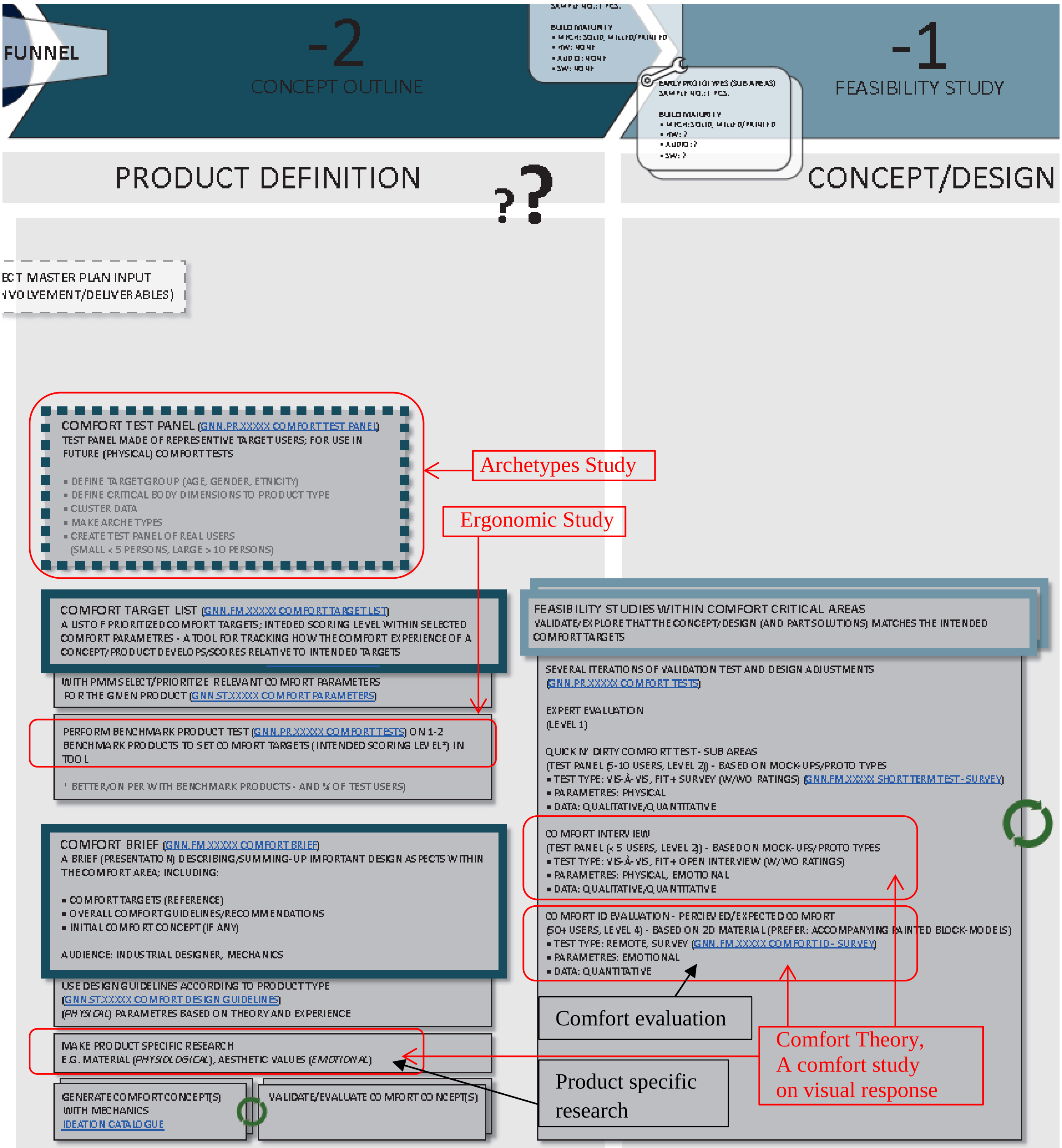


Figure 5-6 Reflections of the project elements on the company's design model

These revisions to the PD process, although shown in-depth with the collaborating company, can also be applied to other companies working with products where comfort is important, in particular, body-worn products.

5.6 Conclusions

The different methods of support were created (and evaluated) based upon the findings presented in Chapter 4. A methodological framework was developed summarizing all the phases of the ergonomic study presented in Chapter 3, including the various methods of applications of data. In terms of impact to industry, these can be adopted by the User Experience team in the company (and other companies), with the aim to reproduce the methodology if necessary, or extract the already retrieved dimensions, which were presented in the findings, in Chapter 4.

The reflections of the result of this project influence on the product development model of the company, showed clearly that the company's current product development model was heavily influenced by the new, theoretical knowledge acquired and the main contributions from the execution of the descriptive studies performed, leading to new activities added. The multidimensionality of comfort was addressed at the earliest stages of the conceptual development of the company's PD model, as well as most of the proposed methods, which were developed during the three main studies of the project.

A matrix including 4 new sets of archetypes was issued as a method of support towards faster user testing and the selection of more representative user panels for the execution of user studies. The identification of more groups of archetypes covering the number of the product families, aims to provide with faster development cycles.

The first batch of archetypes that was generated during the execution of the archetypes study was evaluated with a study to test 20 participants' responses against the archetypes' during their interaction with in-the-ear and behind-the-ear products to identify how well they represent their clusters with promising results. By executing the second study, where participants' responses were compared to the respective responses of the archetypes, it was shown that perceived physical comfort can be predicted based on the knowledge of anthropometry and human factors, hence verifying the approach and the archetypes methodology.

Chapter 6 Conclusions

This chapter presents the main conclusions drawn from this research, including the literature review the research approach, the findings, and the proposed methods of support. Suggestions for further research are also presented (refer to section 6.5).

This thesis is a paper-based thesis with a total of seven papers (these can be found in Appendix 1). Four papers were published in the proceedings of various design conferences and three papers are at different stages of review within journals of design and ergonomics. To summarise, three studies were conducted for this research, these were: (1) an ergonomic study; (2) a comfort study on visual response; and (3) an archetypes study. Two methods of support were developed together with a series of guidelines, leading in the advancement of the areas under investigation. These methods and the guidelines are described below.

A review on comfort terminology confirmed the debate on comfort definitions. It was assessed that a division or discontinuity exists between comfort and discomfort scales. Comfort is defined as a discontinued, dual concept entailing both comfort and discomfort. Comfort, in the context of this thesis was described as “a pleasant state or relaxed feeling of a human being in reaction to its environment” and “discomfort is seen as an unpleasant state of the human body in reaction to its physical environment”. From the review, it was clear that comfort is affected by factors of various nature, i.e., physical, psychological and physiological.

The research has reviewed relevant literature in the field of comfort theory and the factors that influence comfort. The review found that there is a strong connection between discomfort and human physical dimensions, such as the pressure load, discomfort and the type of task during the interaction between the human and the product. A review on a number of comfort studies revealed that discomfort is influenced by product attributes, such as neighboring interfaces to the product under investigation, the product material and the product form. Reviewing the different methods of collecting anthropometric data confirmed that *good fit* is one of the dominating factors of physical comfort. Regarding comfort, the review on influential factors found that comfort is influenced by cognitive and psychological factors, such as the memory of past interactions to similar products, as well as the impact on the senses.

The review on the impact of the emotional parameters of a product on the assessment of comfort revealed that the attractiveness towards a product is strongly linked to visceral responses realized by the individual’s senses and it can be considered as a strong evaluative term for comfort.

The review of comfort models confirmed some of the early findings of the review of comfort definitions. It concluded that comfort is linked more to feelings of well - being and relaxedness whereas discomfort is strongly linked to a more physical dimension. Although the role of aesthetics is acknowledged, the emotional dimension of comfort needed to be investigated as this aspect appeared to be underdeveloped in the existing models.

Reviewing the different studies on comfort indicated that these primarily focused upon the acquirement of anthropometric data, and that there is a lack of a validated methodological framework to link ear dimensions to design and a lack of methodologies to define a reliable user group and focus groups for user studies.

The literature review identified a need to understand further how comfort is perceived by individuals during a human – product interaction and, in particular, how emotional factors and the streamlining of user testing affect the assessment of comfort. This understanding could then provide the basis of a tool or the providing of guidelines to reduce the time of the development cycles and design more comfortable products.

6.1 Data Collection

Empirical research in the industry of external ear worn products and in the laboratory was carried out to understand the dependencies between comfort and the influential physical and psychological factors, as well as, to investigate methods to improve user testing for comfort. Three different research approaches were employed: (1) an ergonomic study; (2) a comfort study on visual response; and (3) an archetypes study. Each research approach had its own advantages and limitations.

The ergonomic study provided an understanding of different methods to support design by various applications of 2-dimensional and 3-dimensional data with a focus on external-ear products.

The comfort study on visual response provided an opportunity to compare the assessment of comfort by participants against: (1) respective scores of attractiveness; and (2) rating scores of product descriptive words. The subsequent analyses provided an understanding on the causalities between the three variables.

The archetypes methodology proposed a method to streamline focus groups and represent populations at large through selecting participants who are representative of clusters, and ensure all clusters are represented.

The total time spent on data collection during the Description 1 Stage of this research amounted to approximately 75 days. In addition to conducting the studies, time was used for: scanning the participants for the ergonomic study; travelling to meetings to arrange the data collection; extracting the 3-dimensional data from the 3D imaging software; issuing each of the 9 archetypes identified for the archetypes methodology study; setting up a method of analysis; and analyzing the data.

The research methods together provided an insight into the identification of the influencing factors to comfort; and these factors (good fit and the visual response to a product) were of a different nature (physical and psychological), which addresses the issue of the multidimensionality of comfort. In addition, the study of archetypes shows the way to build methods to conduct more reliable comfort studies, as does the methodological framework presented in Chapter 5, section 5.3.

6.2 Main findings

The findings from the three studies conducted identified dependencies between comfort and physical and psychological factors, and the findings also identified an approach to improve user testing for comfort. The findings focused mainly on:

- Physical comfort, and the various applications of 2-d and 3-d data to support design decisions at the early conceptual stage.
- Psychological comfort, and the dependency between comfort and visual response, expressed as the attractiveness towards a product, and
- Comfort and the issuing of a representative sample to streamline user testing for comfort.

Each of the three studies contributed in its own way towards identifying the dependencies between comfort and its influencing factors and investigating methods to improve user testing. The ergonomic study focused upon various applications of 2-d and 3-d data to allow evaluations of product designs through benchmarking between human dimensions and product dimensions. The comfort study on visual response was useful in identifying a relationship between comfort and the attractiveness towards a product. The archetypes study focused upon the issuing of a representative sample of users for the execution of more reliable user studies. A summary of the main findings for each of the studies is presented in the following paragraphs.

The findings from the three studies contributed to the advancement of knowledge regarding the dependencies between the physical and psychological dimensions of comfort and provided with a methodological framework which improves the reliability of user testing for the testing of users to be included in the comfort studies conducted at the early conceptual phase of the design process.

In the ergonomic study, the main findings generated a matrix of 29 basic anthropometric dimensions in alliance with respective product dimensions. An increased understanding of human geometry and product complexity, as well as the execution of data visualization provided with a secondary matrix, including an additional number of 9, advanced dimensions from a geometrical viewpoint. These methods contributed to an increased understanding of human geometry and product complexity, achieving a more accurate benchmarking between humans and products and leading to the execution of more reliable comfort studies.

Regarding the comfort study on visual response, comfort was assessed by 44 participants in three phases versus the levels of attractiveness for two sets of products. The findings of this study showcased the relationship between attractiveness and comfort, that is, the comfort experience was amplified by the attractiveness during a human – product interaction. An individual perception of the attractiveness of a product influences the level of comfort perceived of a product, i.e. attractive products do interact better. The findings showed the benefit for companies to invest more on products where emotional comfort, especially for short tasks, is of high importance. Additional descriptors were assessed, i.e. terms describing the products. These findings revealed very strong (or strong) correlations between expected and real comfort scores and the bulky-slim, light-heavy, big-little and rough-soft pairs of product descriptors. These findings help designers predict the visual information that leads to products being perceived as comfortable by the user.

In the archetypes study, 9 archetypes were generated from an anthropometric dataset of ear dimensions to represent each cluster. A methodological framework was proposed to develop a representative user panel for the execution of comfort studies in the ear industry was presented. These findings suggested that it is possible to represent a population at large, based on the generation of archetype persons by providing guidance on the selection of participants as an alternative to statistical approach, which would require a large number of users.

The findings from the ergonomic study and the comfort study on visual response indicated that both physical and psychological aspects of comfort should be taken into consideration at the early stages of concept development. The framework presented in the archetypes study contributed to a more reliable way for user testing providing an approach to a similar method for the execution of ergonomic and psychological studies to evaluate comfort at the early stages of conceptual development in other context.

The findings suggest that there is a need to disseminate the methods of benchmarking between human data and product data. Designers require support in the assessment of physical and psychological comfort at early stages of the conceptual development and in the issuing of representative user panels regarding all product families identified.

6.3 Method of support

Different methods of support and preliminary evaluation were based upon the findings presented in Chapter 4. A methodological framework was proposed summarizing all the phases of the ergonomic study presented in Chapter 3, including the various methods of applications of data. The framework aims to assist in the reproducibility of the various applications of 2-d and 3-d data, which were presented in the findings, in Chapter 4.

A matrix including 4 new sets of archetypes was developed as a method of support towards faster user testing and the issuing of more representative user panels for the execution of user studies. The identification of more groups of archetypes covering the number of the product families, aims to provide with faster development cycles.

A preliminary evaluation of the archetypes method has been carried out. The first group of archetypes linking to in-the-ear Bluetooth headsets was evaluated with a study to test 20 participants' responses against the archetypes' to identify how well they represent their clusters with promising results. It was shown that perceived physical comfort can be predicted based on the knowledge of anthropometry and human factors.

The observations of the reflections of this project's different elements on the product development model of the company showed clearly that the company's current product development model was heavily influenced by the new, theoretical knowledge acquired demonstrating the impact to industry.

The multidimensionality of comfort was addressed at the earliest stages of the conceptual development of the collaborating company's PD model, as well as most of the proposed methods, which were developed during the three main studies of the project. The company has initially implemented the archetypes methodology with positive feedback on comfort from the market of external ear products and the design community, as discussed in Chapter 5. Although the industrial contributions focused on the case company, these could be applied to other body-worn devices in other contexts.

The research has contributed towards understanding the nature of comfort in product design at the early stages of the design process and the factors that influence the different dimensions of comfort (physical, physiological and psychological). A method to help designers in creating a representative user panel for the various comfort studies has been developed and ergonomic guidelines for the achievement of physical comfort are also provided based upon the findings of the research.

Stage of overall research methodology	Study	No. of days	No. of participants
Description 1 Stage	An ergonomic study	35 days	398
	A comfort study on visual response	15 days	44
	An archetypes methodology	15 days	200
Description 2 Stage	Evaluation	15 days	20
Total		80 days	662

Table 6-1 Breakdown of time spent on data collection and analysis

This research has been carried out in industry and controlled experiments and differs from previous studies in that the findings have been used overall with the intention to contribute to a methodology for assessing comfort. The results are relevant to both industry and advancing comfort theory. The total time for data collection and analysis during the research amounted to 80 days and is broken down in Table 6-1. Many issues need to be considered when carrying out empirical research in industry and the laboratory, e.g. the bias effect of the participants to products during their interaction.

The research has found that comfort is influenced by both physical factors, such as the *physical fit,* and psychological factors, such as the *visual response* (or attractiveness) towards a product, at least for short-term interactions, lasting approximately between 2 – 3 minutes. Designers should therefore consider comfort from the early stages of the life cycle of a product, that is, the early conceptual development of a product. Methods and guidelines to assist designers to assess comfort have been proposed. The overall conclusions suggest moving the assessment of both physical and physiological comfort as early as possible in the design process.

6.4 Limitations

This research was realized in one company. The expansion of the research in other companies and other contexts of products would have facilitated the generalisability of the results. However, the focus on one company offered an in-depth analysis of the elements of this research, achieving deep knowledge of the researched areas, and allowed for the collection of reliable datasets, as it was possible to revisit the participants, whose dimensions were measured. Although this research focused solely on external-ear body worn products, the possibility of working closely to the collaborating firm offered the ability to interact with a big variety of external-ear devices, covering the full span of the overall genre of products, i.e. external-ear, body worn, devices for commercial use.

6.5 Further work

The research has begun to understand the influential factors of comfort in the industry of external ear products for commercial use. The following areas have been identified for further research:

- The focus of this research has been mainly on the physical and psychological dimensions of comfort and this has been ensured by limiting the human - product interaction to a couple of minutes. It would be useful to reproduce some of the methods of this project in a different context, i.e. including long - term interactions with the aim to assess physiological comfort.

- This research has assumed that a product is perceived as one object with homogenous physical properties. It would be useful to break - down the product in components and assess the comfort of components with the aim to draw more fruitful conclusions on influencing factors of comfort with respect to product attributes.

- Further research is required to understand the effect of additional emotional and psychological factors of comfort.

- The literature review established that a series of factors affect the comfort assessment. A correlational study could perhaps standardize these dependencies and provide with mathematical relationships between comfort and these factors.

- The second part of the comfort study on visual response defined the visual profile of a product which leads to positive comfort. Expanding this study to other product families of external - ear products would enable the creation of a visual profiles database to define the aesthetics of a *comfortable* product.

Bibliography

Aarts, E. and B. de Ruyter *"New research perspectives on Ambient Intelligence."* Journal of Ambient Intelligence and Smart Environments 1(1): 5-14, 2009

Achiche, S. & Ahmed, S., *"Mapping Shape Geometry and Emotions Using Fuzzy Logic"*, ASME 639 International Design Engineering Technical Conferences Computers & Information in Engineering 640 Conference, Brooklyn, New York, USA, 2008

Allen, I., A. Seaman. *"Likert scales and data analyses."* Quality Progress 40, (7), Pages 64-65, 2007.

Armstrong, Robert L., *"The midpoint on a five-point Likert-type scale"*, Perceptual and Motor Skills 64(2), Pages 359-362, 1987

Armstrong, T. J., P. Buckle, *"A conceptual model for work-related neck and upper-limb musculoskeletal disorders."* Scandinavian Journal of Work Environment and Health 19(2): 73-84, 1993

A. Ruiz, *"An anthropometric study of the ear in an adult population"*, International Journal Of Anthropology, Volume 1, Number 2, 135-143, 1986

Alphen, A., Halfens, R., Hasman, A., Imbos, T., *"Likert or Rasch? Nothing is more applicable than good theory"*, Journal of Advanced Nursing, 20, (1), pages 196–201, 1994

Bishu, R. R., M. S. Hallbeck, *"Seating comfort and its relationship to spinal profile: A pilot study."* International Journal of Industrial Ergonomics 8(1): 89-101, 1981

Blessing LTM., Chakrabarti, A., *"DRM, A design research methodology"*, Springer, 2009

Branton, P. *"Behavior, body mechanics and discomfort"*, Ergonomics 12(2): 316-&, 1969

Brown, M., L., McDonald,S., Smith., F., *"Jungian archetypes and dreams of social enterprise"*, Journal of Organizational Change Management 26, (4) Pages 670-688, 2013

Burns K, Duffett, M., Kho, M., O. Meade, M., Adhikari, N., Sinuff, T., Cook, J.,D., *"A guide for the design and conduct of self-administered surveys of clinicians"*,179(3), 2008

Chao, A., A. J. Kumar, *"An ergonomic evaluation of Cleco pliers"*, Proceedings of the XIVth Triennial Congress of the International Ergonomics Association and 44th Annual Meeting of the Human Factors and Ergonomics Association, 'Ergonomics for the New Millennium': 441-442, 2000

Cole, R. J., J. Robinson, *"Re-contextualizing the notion of comfort"*, Building Research and Information 36(4): 323-336, 2008

Cook, D. J., W. Song *"Ambient intelligence and wearable computing: Sensors on the body, in the home, and beyond"*, Journal of Ambient Intelligence and Smart Environments 1(2): 83-86, 2009

Dawes, J., *"Do data characteristics change according to the number of scale points used"*, International Journal of Market Research, 50 (1), pages 61-77, 2008

De Korte, E. M., M. A. Huysmans, *"Effects of four types of non-obtrusive feedback on computer behaviour, task performance and comfort"*, Applied Ergonomics 43(2): 344-353, 2009

Desmet, P., K. Overbeeke, *"Designing products with added emotional value: Development and application of an approach for research through design"*, Design Journal - Aldershot- 4(1): 32-47, 2001

Desmet, P. 2010, *"Three Levels of Product Emotion"*, The Proceedings of the Kansei Engineering and Emotion Research (KEER) International Conference, pp. 238, 2010

Ellegast, R. P., K. Kraft, *"Comparison of four specific dynamic office chairs with a conventional office chair: Impact upon muscle activation, physical activity and posture"* Applied Ergonomics 43(2): 296-307, 2012

Fellows, G. L., A. Freivalds, *"Ergonomics evaluation of a foam rubber grip for tool handles"*, Applied Ergonomics 22(4): 225-230, 1991

Floyd, W. F., D. F. Roberts, *"Anatomical and physiological principles in chair and table design"*, Ergonomics 2(1-4): 1-16, 1958

Franz, M., A. Durt, *"Comfort effects of a new car headrest with neck support"*, Applied Ergonomics 43(2): 336-343, 2012

Ghoddousi, H., R. Edler, *"Comparison of three methods of facial measurement"*, International Journal of 563 Oral and Maxillofacial Surgery, Vol. 36(3, 2007), pp 250-258, 2006

Gouvali, M.K., Boudolos, K., *"Match between school furniture dimensions and children's anthropometry", Applied Ergonomics, 37(6), pages 765-773, 2006*

Greenbaum J, Kyng M, "Design at work: cooperative design of computer systems", Lawrence Erlbaum Associates, Inc. Mahwah, NJ, USA, 1991

Groenesteijn, L., R. P. Ellegast, *"Office task effects on comfort and body dynamics in five dynamic office chairs"* Applied Ergonomics 43(2): 320-328, 2012

Habsburg, S., Middendorf, L., *"What Really Connects in Seating Comfort?-Studies of Correlates of Static Seat Comfort"*, SAE Technical Paper 770247, 1977

Helander, M. G., L. Zhang,*,"Field studies of comfort and discomfort in sitting"*, Ergonomics 40(9): 895-915, 1997

Hennessy, R. J., A. Kinsella, *"3D laser surface scanning and geometric morphometric analysis of 566 craniofacial shape as an index of cerebro-craniofacial morphogenesis: initial application to sexual dimorphism"*, 567 Biological Psychiatry, Vol. 51(6), pp 507-514, 2007

Hekkert, P. , *"Design aesthetics: Principles of pleasure in design"*, Psychology science, vol. 48, no. 2, pp. 157, 2006

Hertzberg, H.T.E. Annotated Bibliography of applied physical anthropology in human engineering, Report No. WADC-TR-56-30, Wright-Patterson Air Force Base. OH: Aero-Medical library, 1958

Hibaru and Watanabe, *"A procedure for allocating chairs to school children"*, Hard facts about soft machines, 570 London, 1994

Hitchings, R., *"Studying thermal comfort in context"*, Building Research & Information 37(1): 89-94, 2009

Jaffari, S. D., B. Matthews, *"From occupying to inhabiting - a change in conceptualising comfort"*, Beyond Kyoto: Addressing the challenges of climate change – Science meets industry, policy and public 8, 2009

Jensen, C., Borg, V., Finsen, L., Hansen, K., Juul-Kristensen, B., Christensen, H., *"Job demands, muscle activity and musculoskeletal symptoms in relation to work with the computer mouse"*, Scandinavian Journal of Work Environment and Health 24, 2009

Jianghong, Z., T. Long, *"An evaluation of comfort of a bus seat"*, Applied Ergonomics 25(6): 386-392, 1994

Jordan, P., *"The Four Pleasures. In Designing Pleasurable Products"*, CRC Press , pp. 11-57, 2000

Jung Hwa S., Hyung-Shik Jung, *"Surveying the dimensions and characteristics of Korean ears for the ergonomic design of ear-related products"*, International Journal of Industrial Ergonomics, 31(6): 361-373, 2001

Kamijo, K., Tsujimara, H., Obara, H., Katsumatu, M., *"Evaluation of seating comfort"*, SAE Technical Paper Series 820761 (Troy, MI: Society of Automotive Engineers), 1 – 6, 1982

Kamp, I., *"The influence of car-seat design on its character experience"*, Applied Ergonomics 43(2): 329-335, 2012

Kee, D., I. Lee, *"Relationships between subjective and objective measures in assessing postural stresses"*, Applied Ergonomics 43(2): 277-282, 2012

Klamklaya, Angoon Sungkhaponga, Nantakrit Yodpijitb, Patrick E. Pattersonc, *"Anthropometry of the southern 579 Thai population"*, International Journal of Industrial Ergonomics, Vol. 38(1), pp 111–118, 2002

Kleeman, W., *"The challenge of Interior design"*, (Boston, MA: CBI), 1981

Knight, J. F., Baber, C., Schwirtz, A., Bristow, H. W. *"The Comfort Assessment of Wearable Computers"*, In Proceedings of the International Symposium of Wearable Computers (IEEE ISWC), 65-72, 2002

Kuijt-Evers, L. Groenesteijn, M.P. de Looze, P. Vink. *"Identifying factors in using hand tools"*, Applied Ergonomics, 35(2004), 453-458, 2004

Likert, R., "A technique for the measurement of attitudes", Archives of Psychology, (22), page 140, 1932

Leuder, R. K., *"Seat comfort: A review of the construct in the office environment"*, Human Factors 25(6): 701-711, 1983

Liljan Zhang. *"Identifying Factors of Comfort and Discomfort in Sitting"*, Human Factors, 38(3), 377-389, 1996

Merllié, M., Paoli, P., *"Working Conditions in the European Union"*, Dublin: European Foundation for the Improvement of Living and Working Conditions, 2002

Mijnwoordenboek (3rd ed., rev. 2012)

Moes, N. C. C. M., *"Analysis of sitting discomfort, A review"*, Contemporary Ergonomics 2005: 200-204, 2005

Muñoz Roussy, A.G., *"Sociological Considerations on Sentiments and Emotions. Thoughts on Possibilities of A New Sociological Approach"*, World Journal of Social Sciences, vol. Vol. 1. No. 2, no. 2/18/2012, pp. Pp. 66 - 82, 2011

Myers, D. (ed), *"Theories of Emotion"*, Seventh Edition edn, Worth Publishers: New York, 2004
Norman, D.A., *"Emotional Design: Why We Love (or Hate) Everyday Things"*, New York: basic Books, 2004

Ortony, A., Turner, T.J., *"What's basic about basic emotions?"*, Psychological Review, 97 (3), 315–331, 1990

Parcells, C., M. Stommel, R.P. Hubbard, *"Mismatch of classroom furniture and student body dimensions: empirical findings and health implications"*, Health, Vol. 24 (4), pp. 265–273, 1999

Paul, R. D., "*Nurturing and pampering paradigm for office ergonomics",* Proceedings of the Human Factors and Ergonomics Society 1: 519-523, 1997

Picard, R.W., *"Affective Computing",* Cambridge, MA: MIT Press, 2006

Redström, J., *"Towards User Design? On the shift from object to user as the subject of design"*, Design Studies, Vol. 27, No. 2, pp 123-139, 2006

Richards, L. G., *"On the psychology of passenger comfort"*, Human Factors in Transport Research (Based on the Proceedings of the International Conference on Ergonomics and Transport), Volume 2: User Factors: Comfort, The Environment and Behavior: 15-23, 1980

Russell, J.A., *"A circumplex model of affect",* Journal of Personality and Social Psychology 39, 1980

Sanders E., *"Design Research",* in Design Research Quarterly, Vol. 1:1, 2006

Sanders, M.S., McCormick, E.J., *"Human Factors in Engineering and Design",* (seventh ed), McGraw-Hill, New York, 1993

Slater, K., *"Comfort properties of textiles",* Textile progress, 9(4), 1977

Stavrakos, S-K , Ahmed-Kristensen S., Goldman, T, 2014, *"Using archetypes to create user panels for comfort studies"* in Design 2014 - International Design Conference. Design Society, pp. 2157-2166, 2014

Stavrakos, S-K , Ahmed-Kristensen,S., *"Assessment of anthropometric methods in headset design"*, in Design 2012 - International Design Conference. Design Society, pp. 1123-1132, 2012

The Oxford Dictionary of English (2nd ed., rev. 2005)

Ulrich, K.T., "*Chp 5: Aesthetics in design"* in Design: Creation of artifacts in society, Pontifica Press, 2006

Vink, P., "*Comfort and design: principles and good practice",* Boca Raton, CRC Pres, 2005

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

Webster's Dictionary (2nd ed., rev. 2008)

Weinberg, Naidoo, Govier, Martin, Kane, Marazita, *"Anthropometric Precision and Accuracy of Digital Three-603 Dimensional Photogrammetry"*, Journal of Craniofacial Surgery, Vol. 17(3), pp 477-483, 2006

Wilder, D., M. L. Magnusson, "*The effect of posture and seat suspension design on discomfort and back muscle fatigue during simulated truck driving"*, Applied Ergonomics 25(2): 66-76, 1994

Yin, R.,B., "Case study research: Design and methods", SAGE Publications, 2014

Zenk, R., M. Franz, *"Technical note: Spine loading in automotive seating"*, Applied Ergonomics 43(2): 290-295, 2011

Zhang, L., M. G. Helander, *"Identifying factors of comfort and discomfort in sitting"*, Human Factors 38(3): 377-389, 1996

APPENDIX 1

PAPER 1 Definition of comfort in design and key aspects- A literature review

Reference: Ahmed-Kristensen, S., Stavrakos, S., *"Definition of comfort in design and key aspects-A literature review"*, in NORDDESIGN Conference, 2012.

PAPER 2 Methods of 3D data manipulations to inform design decisions for physical comfort

Status: Submitted in the special issue of the Journal in Environmental design

PAPER 3 Assessment of anthropometric methods in headset design

Reference: Stavrakos, S-K., and Saeema Ahmed-Kristensen. *"Assessment of anthropometric methods in headset design"*, DS 70: Proceedings of DESIGN 2012, the 12th International Design Conference, Dubrovnik, Croatia, 2012.

PAPER 4 Investigating the role of aesthetics for interaction design

Reference: Stavrakos, Konstantinos Stavros, and Saeema Ahmed-Kristensen. *"Investigating the role of aesthetics for interaction design."* DS 75-7: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol. 7: Human Behavior in Design, Seoul, Korea, 2013.

PAPER 5 Do attractive things, Interact better – the role of emotional design on the 2 assessment of comfort of consumer products

Status: Submitted in the Journal of Design Studies

PAPER 6 Using archetypes to create user panels for comfort studies

Reference: Stavrakos, K., Ahmed-Kristensen,S., Goldman, J.,T., *"Using Archetypes To Create User Panels For Comfort Studies*." DS 77: Proceedings of the DESIGN 2014 13th International Design Conference, 2014.

PAPER 7 Using archetypes to create user panels for comfort studies: Streamlining focus groups and user studies

Status: Submitted in the Journal of Applied Ergonomics