Advanced Aircraft Passenger Seat:

A Qualitative and Quantitative Study of Comfort

by

Narmada

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ABSTRACT

This thesis describes work performed during a project in the Master of Engineering degree program in the Department of Aeronautics and Astronautics of the Massachusetts Institute of Technology. The project was to design, build and evaluate improved aircraft passenger seats. The main focus was comfort.

Two surveys were used to assess passenger needs for a more comfortable seat: in-flight activities and physical effects were the primary factors under considerations. The combination of these needs, airline needs and seat manufacturing constraints was integrated into a design tool, Quality Function Deployment, to end up with two new concepts of aircraft economy seats. The first concept used a webbed back instead of a conventional cushion back, the second concept had a back which reclined as the seat slid forward.

Prototypes were built and then tested in two different ways. Subjects were asked to simulate a flight during three hours in each of three seats: the prototypes and one conventional aircraft seat. Questionnaires were distributed at periodic intervals during each test to evaluate the level of comfort in specific areas of the subjects' bodies. In addition, maps of the pressure distribution on the bottom and back of the seats were taken in an attempt to quantify comfort. Dynamic pressure maps of volunteers were then recorded over ninety minutes.

It was concluded that both concepts were comparable or better than the baseline seat. No statistical correlation between pressure distribution and comfort was derived. But distribution patterns were found to describe comfort in a qualitative way.

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This thesis symbolizes the crowning achievement of my year of study at MIT. It is not only the result of four months of work, it is what I will show to all people who will ask me : "what did you do there?" So this is definitely the place to write everything that I have always thought ... or almost everything!

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INTRODUCTION

Long-haul flights are uncomfortable in economy class. Spending four hours or more in an airplane, without being able to rest properly leads to fatigue and physical pain. So the purpose of the project referred to in this thesis was to find ways of improving comfort for passengers during long-haul flights.

It was a team effort: during a little more than four months, five Master of Engineering students worked on designing aircraft passenger seats that would help improve comfort during long-haul flights. All were international students and thus were deeply concerned about any improvements that could be made to aircraft seats.

Apart from comfort, there are several other factors to account for in the design of an aircraft seat: FAA regulations, price, etc. The part of the project this thesis particularly focuses on is human factors. *"Human factors discovers and applies information about human behavior, limitations, and other characteristics to the design of tools, machines, systems, tasks, jobs, and environments for productive, safe, comfortable, and effective human use."* (Sanders & McCormick, 1993).

As far as the project is concerned, this relates to the study of comfort in an aircraft seat and to the ways of improving it. Once prototypes of new concepts were built, comparison between them was made on the basis of their comfort. This comfort was assessed in a subjective way and using quantitative measurements related to comfort. This thesis develops one of these measurements, namely pressure distribution, and presents its importance in the project.

1 BACKGROUND

1.1 Comfort

1.1.1 Definition

A major keyword in the team's goal is "comfort." The team's efforts were aimed at improving the comfort of the passenger in all his activities during the flight. A definition of comfort is: "a feeling of well-being." [1]

Many parameters affect comfort, but there are two important ones through which one can really improve or create comfort:

- ✓ **Physical**: Discomfort is almost always characterized by pain, be it small or completely unbearable. These pains may come, for example, from a poor posture, which causes undesirable tensions in muscles. So the body must be kept as often as possible in the most unstressed position where tension on any part of the body is avoided.

- ✓ **Psychological**: One can also keep the mind away from the feeling of discomfort. If a person focuses on something in particular, then this person forgets for a while the feeling of discomfort, providing that the physical tension or pressure is not too severe. These psychological effects are described in more detail in section 2.2.2.

1.1.2 Measurements

Although the notion of comfort is commonly used, it is hard to characterize quantitatively. Since it influences our everyday life in an important way, many studies concerning comfort (in a car, at work...) have been written [2, 3, 4].

Studying comfort involves trying to measure the feeling of comfort experienced by a subject in a particular environment. This raises a problem of objectivity because comfort is intrinsically subjective. Each person is different from another, and two people may not feel the same way in the same conditions. Of course it is not possible to put aside all qualitative data, but it is possible to minimize the bias introduced by personal judgment. Indeed, instead of just asking for the general feeling of comfort, one can focus on specific areas on the body and introduce a scale of comfort that is the same for every subject. It is then easier to process the data, if everybody gives comparable answers.

But to enhance qualitative results, quantitative measurements can be implemented. By analyzing together quantitative and qualitative data, an objective measurement of comfort can be obtained.

Some of these quantitative measures are the following:

- ✓ **EMG (electromyography)**: EMG measures the electrical activity of the muscle action potential. The degree of muscle activity of a certain posture represents the bodily tension needed to maintain that posture. Thus, this measures the degree of muscle fatigue.

- ✓ **Pressure mapping**. Pressure mapping represents the pressure distribution exerted by a body on a surface. In this case it measures the pressure of the human body on the seat. Pressure pads are put on a seat, and the subject sits on them. Then the experimenter can take a mapping of the pressure distribution exerted by the subject on the pad. This pad is thin enough to not influence the distribution significantly, so that the obtained pressure distribution represents accurately what is happening to the seat. No study has yet demonstrated a complete correlation between comfort and pressure distribution. Usually, experimenters try to link pressure with data given by subjects in order to emphasize results, which eventually drives post-design modifications [2]. Some sources suggest that comfort goes with a uniform low-pressure distribution.

According to Herman Miller [5], there are two facts that can be used to compare pressure distribution and comfort. First, high pressure points are usually associated with discomfort because surface pressure constricts blood vessels and thus blood flow is restricted. However, there are two particular areas of the body which can withstand high pressure: ischial tuberosities (sitting bones) and the lumbar area away from spine. The skin and fat tissues under the sitting bones are less sensitive to pressure than surrounding tissues. Figure 1 and Figure 2 represent pressure maps associated with a comfortable and an uncomfortable chair. Picture top-halves of the show the back of a person, while the bottom-half represents the sitting bones and thighs. As can be seen in Figure 1, pressure on the back is distributed away from the spine, and on the sitting bones, contrary to what happens in Figure 2.

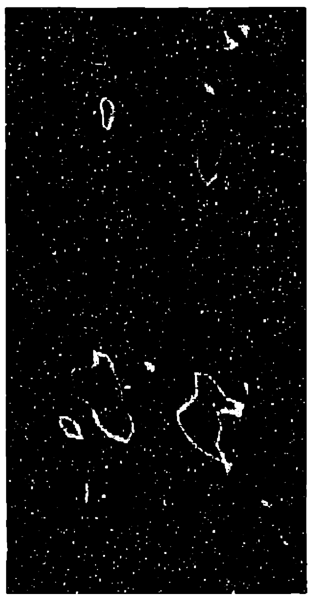


Figure 1: Comfort

Figure 2: Discomfort

(Source: http://www.hermanmiller.com/research/essays)

Pressure maps alone are not sufficient to measure comfort and must be linked with qualitative observations provided by the subject, as mentioned previously. For the moment, no rule is known to go from quantitative measures of muscle activity or pressure distribution to a quantitative measurement of comfort. So both types of data (qualitative and quantitative) are useful.

Pressure mapping is what the team used to quantify comfort. The measurement system will be detailed in Appendix 7.

1.2 Ergonomics

1.2.1 Definition

"Ergonomics" is derived from two Greek words: "erg" (work) and "nomas" (natural laws). It is the study of human capabilities in relationship to work demands. Indeed, certain tasks require specific parts of the body to act more than others; these parts can be so taxed that negative physical effects are induced on them. So ergonomics is aimed at releasing the body from the pain usually experienced when holding the same position for a long period of time.

The main focus of ergonomics is to make the human body adopt the most unstressed posture, to minimize forces acting on the body. So an important consideration is: how can a human body be described in a useful way? In this matter, anthropometry is useful. Anthropometry is the measure of the human body. The human population is divided into several categories, according to height of people. Thus, in matters that are related to anthropometry, authors usually refer to three specific categories: the 5^{th} percentile which represents the smallest Chinese female (59 inches), the 50^{th} percentile (69.1" for men and 64" for women) and the 95^{th} percentile, which represents the North-American male (72.6"). Anthropometry describes many details of each dimension of the human body in different situations (standing, lying down, sitting…) [6].

Ergonomics is a major issue in work life. Workers (either in front of a computer or with tools) suffer from RSI (Repetitive Stress Injury) because of bad postures. In order to alleviate those pains, which eventually cost industries time and money, industry managers now focus on more comfortable work environments. This includes finding seats which help support sensitive parts of the body (neck, back, lumbar, arms…).

Figure 3 shows an example of an ergonomic chair.

Figure 3: Example of an ergonomic chair

Many web sites discuss ergonomics: this proves the interest directed towards this science. There are even computer-based tools that simulate and analyze postures and their effects on humans in the workplace, especially in terms of task injury (e.g., DENEB [7]).

1.2.2 Sitting position

Sitting on a chair

There are several ways of sitting on a chair, depending on the person who is considered [8]. But they can be separated into two main categories: a correct sitting position or a slumped one. While standing or lying down puts little pressure on the lower back vertebrae, sitting correctly more than doubles the pressure to the spine, and sitting in a slumped position increases it four times. A slumped posture also stretches the ligaments and muscles and extends the back.

This stretched position causes back extensor muscles to be chronically active. There is then a low-level of activity that can cause a decrease in blood circulation to the working muscles. Alteration in circulation can cause pain.

So in any sitting position, correct posture with the back straight should be adopted. And even in that case, pain will eventually be experienced because the human body is not meant to be in a sitting position for extended periods of time.

An ideal sitting posture exists: the main ideas are that feet should be flat on the floor, knee angle must be of 90° or slightly more, back of knees should be 2" to 3" forward of the seat's front edge. Nevertheless, this ideal sitting position is not valid forever. The body needs to move and cannot adopt the same posture indefinitely. For more details, see Ref. [9].

Neutral position

Another idea of ideal sitting posture has arisen lately, following studies of NASA astronauts in a zero-gravity environment [10]. In the most relaxed case in micro-gravity, the body assumes a trunk-to-thigh angle of 128 degrees. This is called the neutral position (Figure 4).

Figure 4: Astronaut in neutral position

Independent studies have been made, revealing that if the body is approximately in this position in a 1-g environment, tension is relieved in key muscle groups (lower back, neck, shoulder, forearm) by as much as 75%. So this position should be very safe for the body and comfortable.

Nevertheless, it is not very practical. The last drawing of Figure 5 [8] shows how a neutral position seat would look like. As can be seen, somebody sitting on such a chair would easily slide on the seat. There must be belts to prevent that. No seat has yet been designed according to this theory, and it seems to take too much space to be considered for aircraft use.

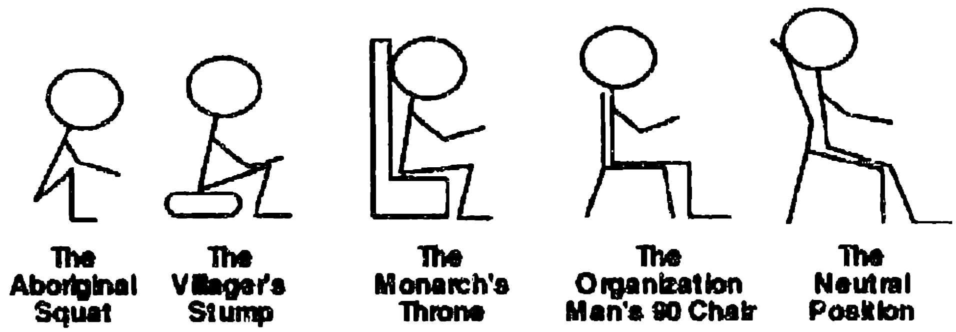


Figure 5: Evolution of seating

1.2.3 Use of ergonomics

Although better work posture is not what the team focused on, it generally helps in understanding better sitting postures. Thanks to studies on human postures, data on the best sitting postures have been found, for working or just simply sitting on a chair.

Passengers in an airplane are not always working or sitting. They try to sleep, eat, talk, etc. Actually they adopt many different postures during their flight. As confirmed by a second survey presented in section 2.1.3. So data on a particular posture do not provide the solution to the question of comfort in an aircraft, but they give leads to follow on how to improve it. This is the reason why the team has done research on ergonomics as well as anthropometry (the measure of human body) and comfort. This research is presented in section 2.2.1.

1.3 Aircraft seat design considerations

1.3.1 Parameters

When manufacturers sell their aircraft to airlines, they do not provide the interior equipment such as seats or carpet. Airlines have specific suppliers for all this equipment. So aircraft seat manufacturing is a complete industry.

There are many parameters to account for in the design of an aircraft seat. The team decided to focus on a few of them.

Below are the most important design parameters (Source: private communication with B/E Aerospace, January 1999).

- ✓ **Aircraft model and airline**: The type of the aircraft and of course the needs of the airline are the basis for the design. Dimensions of seats are constrained by the aircraft dimensions and the airline which determines the seat pitch, the number of rows and the arrangement in the aircraft. Besides, the airline may have specifications for the shape of the seat and the seat manufacturer must adapt to them. These specifications also include the implementation of special features, like headrests, footrests, or personal entertainment systems.

- ✓ **Travel class**: An important parameter is whether the seat is designed for economy, business, or first class. The higher a seat is in this hierarchy, the more additional features there are, and the larger it is. At the end, a first class seat will cost significantly more than an economy class one, in terms of money (from $1,000 to $3,000 for an economy class seat and from $15,000 to $50,000 for a first class seat) and will weigh at least twice as much.

- ✓ **Weight**: Weight is a key factor. Aircraft load capacity is limited, and the less empty weight there is in the cabin, the more additional freight the company can carry. So a seat must be as light as possible. Nowadays, a tourist class seat weighs approximately thirty pounds.

- ✓ **Budget**: The budget allowed by the airline must not be exceeded. A seat must be competitively priced.

- ✓ **FAA regulations**: There are several stringent FAA regulations the seat has to fulfill. The whole procedure for the approval of the seat can take more than one year. It must be started over for every small change in the seat (for example a change of cushion). There are two major points of interest for the FAA:
  - Flammability properties of materials. Here is an example of criteria on seat cushions [11]: " *Seat cushions must be self-extinguishing when tested vertically. The average burn length may not exceed 8 inches. and the average flame time after removal of the flame source may not exceed 15 seconds. Drippings from the test specimen may not continue to flame for more than an average of 5 seconds after falling.*" Flammability requirements also apply to any type of materials in compartment interiors: (panels, decorative surfaces, trays, plastic windows, or electrical components).
  - Crash-test. One must ensure chances of survival in case of accident. Seat manufacturers perform several types of crash-tests before they have the seats approved. Tests are performed with a 170-pound anthropometric dummy attached to the seat. Those tests reproduce as accurately as possible several possible crashes that can occur. Inside the dummy, there are sensors that measure the forces and accelerations on the limbs, muscles and spine. Using these sensors, experimenters can estimate the degree of injury that would have been incurred to a real passenger in this situation, and ultimately if the passenger can survive the crash.
- ✓ **Population fit**: The seat must fit from the 5^{th} percentile to the 95^{th} percentile of the human population in terms of height.

1.3.2 Materials

A seat is composed of many parts made of different materials. An economy class seat is almost never manufactured alone, but along with the row it belongs too. The frame that carries this row is aluminum. The back of the seat fiberglass. A cushion for the back is put on it. At the back of this fiberglass frame, the tray is attached.

The cushion for the bottom can be of flotation foam or not. This depends on the airline's choice: FAA regulations impose all airplanes to be equipped for each passenger's safety in case of emergencies in water. This can be done either with flotation cushions on the bottom of the seat or with life vests which are more expensive.

The armrest contains the control for the recline of the seat, the plug for the headphones and a panel control for entertainment (this includes volume, and channel control either for the screens or for personal entertainment in some cases). Also, there are often buttons for light and calling stewardess (although these could also be on the ceiling).

Figure 6 shows an example of an economy aircraft seat

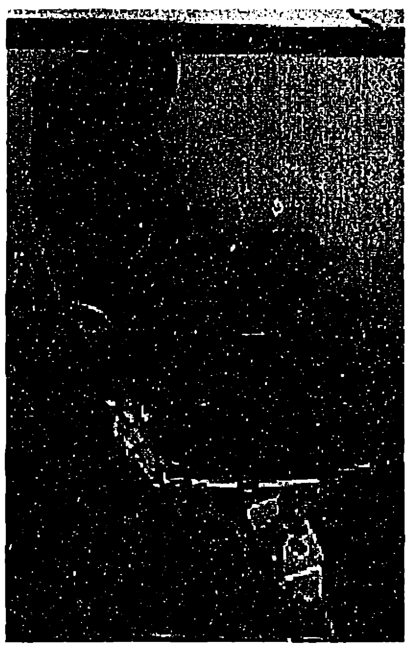


Figure 6: Example of an aircraft seat

(Source: B/E Aerospace)

2 SEAT DESIGN

There are three major points the team investigated to derive prototype designs.

✓ The first point was to get an overview of the customer needs.

✓ The second was to do research on particular areas of importance to the design of a seat: ergonomics and the ideal sitting position, anthropometry, cushioning and physical design concepts.

✓ The third was to list all features that can be implemented in the design, and then organize and prioritize them.

All these points as well as a detail of the design concepts are described in this section.

2.1 Understanding customer needs

The design of any new concept, namely aircraft seats, first goes through the assessment of who the customers are and what they expect.

As far as this project goes, there are two types of customers: the passengers who will be traveling and the airline company that will be buying the seat. Indeed the first concern of the team was to design and develop a more comfortable seat for travelers but this must be done in such a way that it will also be attractive to airlines.

2.1.1 Evaluation of passenger needs: surveys

Two surveys were issued to assess what passengers expect from an aircraft seat and how they rate current seats. The first survey requested ratings of current seats and of possible features that could be implemented in a new seat. The second survey focused on in-flight activities.

2.1.2 Results from survey I

The first survey requested personal data and had ten questions divided into four categories: flying habits, opinions on the need of changing seat design, physical effects at the end of the flight, and seat aspects (rating of actual seats and of possible new features). The actual survey can be found in Appendix 1.

The survey was sent to friends, relatives of team members, and the faculty members in the MIT Aero/Astro Department. The response rate of the survey was very high: for the first set of surveys which have been sent, there were 122 responses from the 350 surveys sent out (35 %). Response rates are typically 10%. This demonstrates the interest raised regarding comfort in an airplane.

Detailed results class by class are presented in Appendix 2.

Biographical data

Table 1 presents the personal data:

Data	Average	Standard deviation
Age	34 years	12 years
Height	172 cm / 5'8"	13 cm / 5"
Weight	70 kg / 154 lb.	18 kg / 39 lb.

Table 1: Personal data from survey I

Flying habits

Respondents fly an average of 2 to 5 times a year; the length of the flight is mostly 3 to 5 hours (42% of the respondents) but 33% of the respondents also fly from 6 to 10 hours.

85% of the people who responded travel in economy class, 12% in business and 3% in first class. The percentage of people who fly in economy class is a little higher than the average number of seats per class in an airplane. Of course this depends on the company and the aircraft model but, for Air France or Lufthansa, the number of economy class seats is no more than 76% of the total number of seats. But there are usually no more than 4% of first class seats.

Opinions

To the question "do you think the current seats can be improved?," 2% responded no. This may come from the fact that they think current seats are the best they can be, considering environmental constraints. Those 2% were traveling in economy class.

But the other 98% of the respondents all responded yes! This is a very high score and there are not many surveys which make so many people agree on the same point! Respondents were self-selected in the sense that if they had not been interested in changing aircraft seats, they would not have responded. But this response is still significant.

Although they think seats can and must be improved, 68% were not willing to pay more than 5% of the ticket price for improvements. Actually, some explicitly wrote in their surveys that they would accept no increase of the price at all. Most passengers probably think the airlines owe them comfort, especially considering ticket prices. But this leaves 32% who would agree to spend more than 5% of the price to have some improvement, which is non-negligible, considering that flight tickets are still expensive.

Results from this survey reinforce the team conviction that any improvement must be done at very little expense.

Improvements

As shown in Figure 7, respondents indicated that the aspect of the seat which requires the most improvement is personal space, followed by back support and headrest.

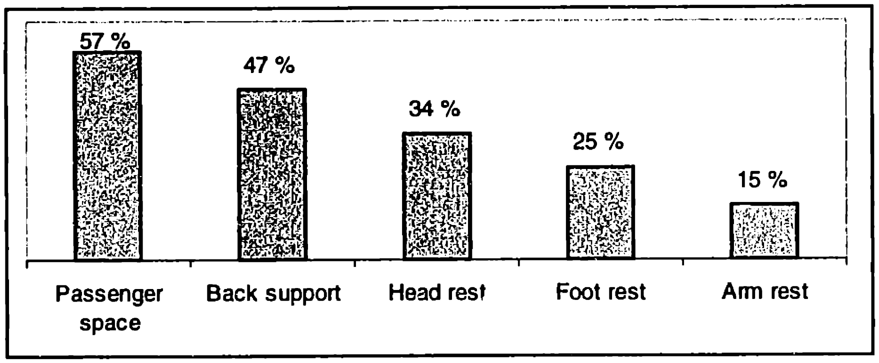


Figure 7: Aspects of the seats requiring the most improvement

Another question was to rate specific functionalities on a scale of one to five, one being excellent and five mediocre. Responses state that headroom is considered to be adequate but back support (average of 3.6) and functionality for slumber (average of 3.8) were rated as poor.

Physical effects at the end of the flight

Another question was to describe pains at the end of the flight. According to the responses, most people feel pains all over their body. The most sensitive parts are head, neck, back and legs. Legs as well as joints are either stiff or numb and muscles are often sore: lack of space make passengers feel uncomfortable in the legs which are then painful; tall people are particularly concerned with this effect. Knees suffer a lot too. Extremities are swollen. Lack of proper neck rest causes neck aches. The back is not well supported either, and hurts. All these points, combined together, prevent proper rest and eventually lead to headache and fatigue. Figure 8 illustrates this point.

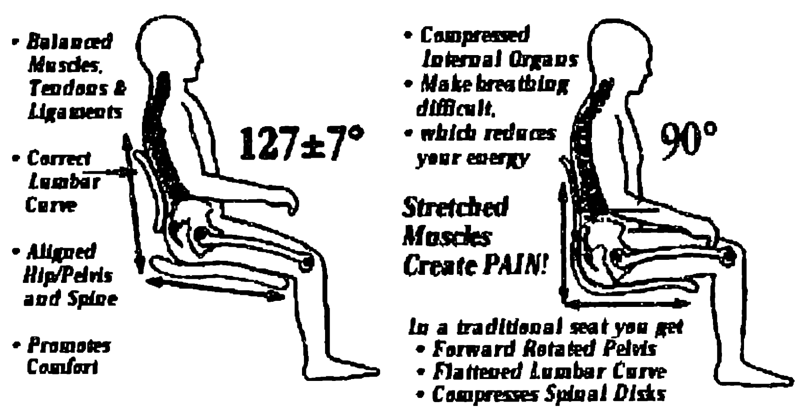


Figure 8: Effect of sitting positions on spine [8]

Additional comments

It is interesting to note that even people traveling in first class complained about their seats and about pains at the end of the flight. But on a scale of one to five (one meaning excellent comfort and five mediocre), seats in first class scored on average one point less than in economy class, which means they are considered more comfortable. However, there were only four people traveling in first class so any comment on those seats may not be representative. Besides, seats vary from one airline company to another, which introduces another parameter that has not been accounted for.

2.1.3 Results from survey II

In order to refine the analysis of passenger needs, the team a second survey. This survey focused on in-flight activities. There were four parts: a biographical data inquiry, flying habits, a part related to identifying flight activities and rating their comfort, and finally preferences on questions concerning the recline position. The actual survey can be found in Appendix 3.

This survey was sent to 700 faculty members at MIT. 135 responded, which is a 19% response rate. This population does not represent the average human population, and there are also differences between results from this survey and results from the first survey (mainly for personal data, class of travel) because only faculty members were surveyed. Detailed results can be found in Appendix 4.

Biographical data

Personal data are presented in Table 2.

Data	Average	Standard deviation
Age	47 years	13 years
Height	177 cm / 6'10"	4"
Weight	77 kg / 169 lb.	38 lb.

Table 2: Personal data from survey II

Flying habits

For this population, the number of flights per year is mostly greater than 10 (47% of the respondents), and the length of the flight between 2 and 5 hours (for 68% of the respondents). 94% travel in economy class.

These results differ considerably from the first survey due to differences in the surveyed population.

Flight activities

One question was to rate the comfort experienced while performing specific activities stated in the questionnaire, and also to give the percentage of time spent on each of these activities. These activities, rated in the order of decreasing amount of time spent doing them, are reading, working, sleeping, eating and chatting, as is shown in Figure 9.

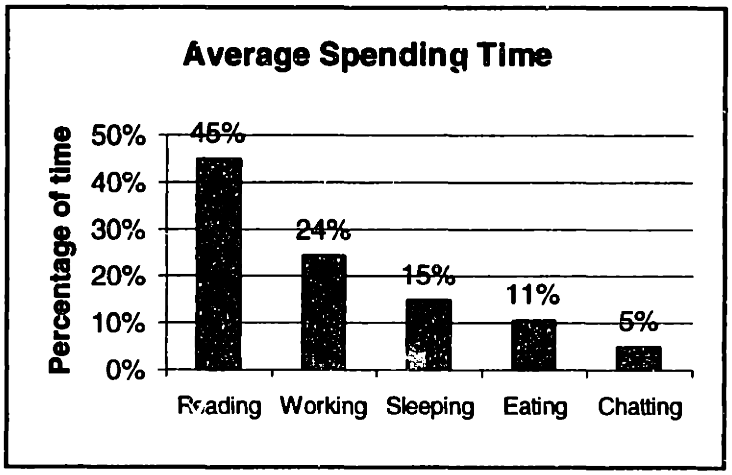


Figure 9: Tasks performed during a flight

Another question was to rate the ease with which these tasks can be performed. It turned out that performing them is rather difficult, as Figure 10 shows for sleeping (details for other tasks are in Appendix 4).

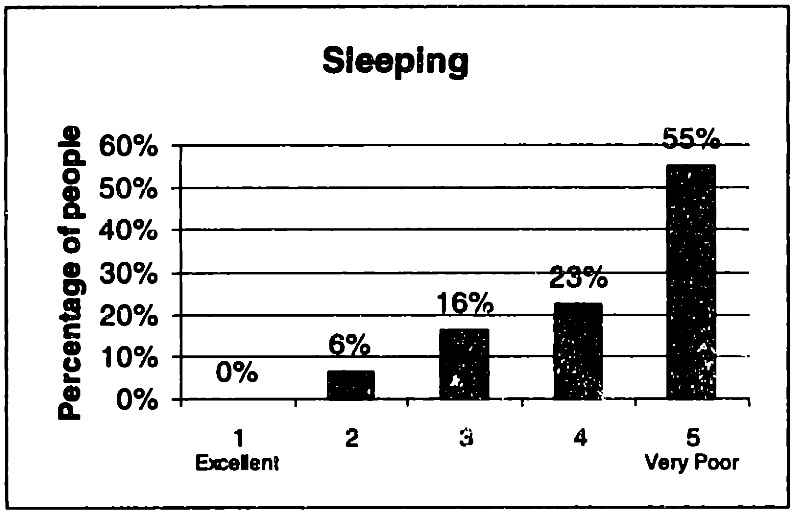


Figure 10: Rate of ease for sleeping position

Conclusion

Looking at the results (details in Appendix 4), the important points that we can get from this survey are:

- ✓ It is difficult to get out of the seat, when one needs to go to the bathroom or simply to take a walk or to stretch legs. This is the case wherever the seat is placed on the row, but it is especially difficult for a passenger sitting on the window seat, with the front seat reclined (57% of the respondents rated this phase poor to very poor).

- ✓ Sleeping is not easy (poor to very poor for 78% of the respondents), and neither is working (59%) probably because the tray is not adjustable.

- ✓ Having the seat in front reclined is very disturbing, and influences significantly the feeling of discomfort for 68% of the respondents.

- ✓ 47% of the respondents agree with the idea of trading of the recline feature of the seat with an adjustable lumbar support.

2.1.4 Airline needs

Airlines have different objectives concerning seats. What they are interested in concerns more the manufacturing process and the maintenance, although physical comfort of the passenger is also important, because it eventually contributes to the airline reputation.

Airlines need a seat to be as light as possible (for the reasons discussed previously). It must be robust, to pass FAA tests, and must have highly reliable parts. The cost of ownership must be as low as possible. Indeed, when the airline buys seats, it does not equip its aircraft with those seats right away. They often have to be stored, and storage costs a lot of money. So seats must be manufactured in such a way that they do not cost too much in ownership. Seats should be easily maintained, and ideally they should be compatible with the whole fleet. They also should be easily upgradable. Last, they must fit a large spectrum of human sizes.

2.1.5 Conclusions of needs evaluation

The survey identifies points to focus on to help increase the comfort of a seat. What passengers are expecting is more space, better conditions for sleeping, and also more back support.

The team had to think about ways to satisfy those needs as well as airlines needs, which may at first seem incompatible. More space could be found by raising the seat pitch for example, but this is not a decision an airline would want to take.

All this puts many constraints in the design of the seat. The team could not just focus on finding the best seat in general and apply it to an aircraft.

Features and concepts had to be determined in order to respect those constraints. One way to account for constraints in the choice of a design is to enter them in Quality Function Diagram (QFD) matrices. This is presented in the next section.

2.2 Design considerations

Design considerations were determined during a research phase: its goal was to increase the knowledge of the most important points concerning the seat design.

2.2.1 Recommendations on the sitting position

Several recommendations can be made to achieve a good sitting posture [8].

First, adjustability is an important feature for such parts as the backrest and headrest. The backrest should be tiltable and height-adjustable: this helps achieve a proper spinal alignment. The headrest should also be adjustable: if it is placed in the right place, it helps reduce most neck tension.

Another good point is having tilt adjustments: it helps create a slight rocking motion that enhances the feeling of comfort. It also allows the person to lean forward if he/she wishes while keeping support on his/her back.

Although there has been an argument as to the use of a lumbar support (some people claim it is bad for the back), a proper lumbar support is crucial: it acts on the curvature of an individual's spine and makes this curvature unique. The best approach to an adequate lumbar support is to make it adjustable in height, thickness, and curvature.

Contoured seats are advised. The idea is to replace a flat bottom and a flat back by shaped forms (cambered for the back, a little hollowed out for the bottom). This helps improve weight distribution, and reduces high pressure points, which are linked to pain as mentioned previously. Besides, shaped forms improve blood circulation to the lower extremities. Nevertheless, contoured seats will not fit a wide range of the population and are therefore rather unsuitable for an aircraft seat.

An ergonomic seat should have its front part sloping down slightly. This allows a fist size gap between the leg and the knee joint, which reduces the pressure at the back of the thighs. Once again the idea is to have as little pressure as possible on the body.

One last point to mention is the fabric. A good fabric is important for comfort: it must be pleasant to see, touch, and feel. It must also last a long time. Grade nylon based fabric fulfills these constraints of highest quality in aesthetics, comfort and durability.

2.2.2 Other findings

The team focused on four different areas: anthropometry, cushioning, psychology and physical design concepts.

- ✓ **Anthropometry**: This concerns data on the ideal sitting position. It has been presented in section 1.2.2.
- ✓ **Cushioning**: A good cushion should have a number of properties. For example, it should be comfortable (which is assessed by the pressure distribution), economical, easy to process and to maintain, and it should not give off poisonous gas. And in some cases, it should also provide flotation (once again, this depends on whether the airline chooses a life-vest or a flotation cushion in the eventuality of crash). Finally, a very good cushion is a sandwich cushion made of different layers of foam, thinly cut, which are then put one upon another. For more details, see Ref. [12].
- ✓ **Psychology**: There are psychological considerations that could help improve the feeling of comfort.
  - The first point is colors: some colors have a tendency to excite (like red hues), while others tend to calm down (blue hues). Green is neutral. Some colors (short wavelength: violet, blue...) appear to be retiring and others (longer wavelength: yellow, orange...) are advancing.
  - The second point is the feeling of privacy, which is linked to the field of vision: if no one can be seen in the field of vision, then one feels more comfortable. The last point is logos and patterns, which could draw attention and distract the passenger from any interference. However all these effects are valid only for a limited period of time. For more details, see Ref. [13].
- ✓ **Physical design concepts**: Anthropometry and a seat's optimal dimensions are closely related. This is an important factor for the proper design for working:

height of the tray, tray inclination, and inclination of seat bottom. For more details, see Ref. [14].

2.3 QFD matrices

2.3.1 General points on QFD

A description of the Quality Function Deployment (QFD) process and matrices that were helpful to the team is included in Appendix 5. The purpose of such a tool was to help the team prioritize technical requirements found to fulfill customer needs, and then do the same task for features that can be implemented to satisfy these technical requirements.

2.3.2 Technical Requirement matrix

Presentation of the results

The complete matrix is presented in Figure 11. Rows represent customer needs and columns represent technical requirements that fulfill those needs. At the intersection between rows and columns, numbers indicate the degree of fulfillment of the corresponding need by the corresponding requirement. The scale is: 0 (no influence on the need), 1 (small influence), 3 (influences the need) and 9 (completely fulfills the need). At the top of the matrix, conflicts between technical requirements are identified.

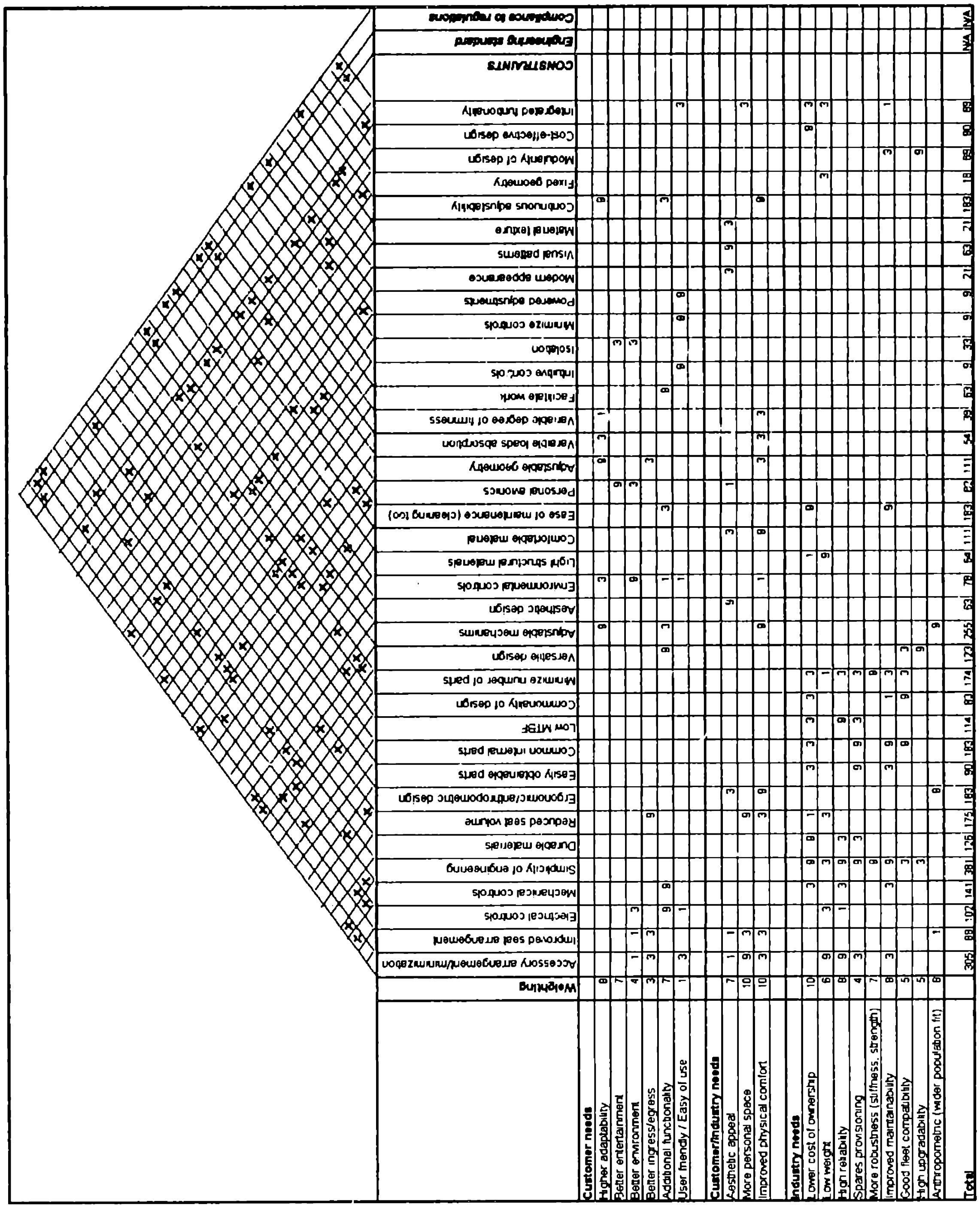


Figure 11: Technical requirements matrix

Customer and airline needs were separated in three different categories: customer needs only, industry needs only and common needs.

Weightings (from 1 to 10) were allocated from the results based on the survey and the answers from industry advisors.

The team came up with 37 technical requirements. There are three really important ones, which score higher than the others:

- ✓ **Simplicity of engineering:** (381 points). The design of the seat must be as simple as possible, in order to make the seat easily manufactured and maintained. This requirement fulfills every industry need with high ranking, except anthropometry. But it conflicts with ergonomic/anthropometric design, continuous adjustability, and adjustable mechanisms.

- ✓ **Accessory arrangement/minimization:** (305 points). Every accessory in the seat must be arranged so as to take as little room as possible and there should be a minimum number of accessories. In terms of scores, the most important needs it fulfills are low weight, high reliability and more personal space. It conflicts with adjustable mechanisms.

- ✓ **Adjustable mechanisms:** (255 points). There should be adjustable mechanisms on the seat (for example an adjustable headrest or footrest...). It fulfills higher adaptability, additional functionality, improved physical comfort, and anthropometry. It conflicts with ease of maintenance, simplicity of engineering and accessory arrangement/minimization.

After these, four technical requirements come with the same scoring (183 points): ergonomic/anthropometric design, common internal parts, ease of maintenance, and continuous adjustability (as opposed to adjustability in steps).

<u>*Conclusions*</u>

The purpose of this QFD matrix is not to take only the first three or more technical requirements and ignore the others. There are several points to consider:

- ✓ First of all, are the most important technical requirements compatible with each other? Do they fulfill many of needs? For example, the first three technical requirements do not fulfill all the needs, they even fulfill more industry needs than passenger needs. So the other requirements cannot be forgotten.

- ✓ QFD does not give an absolute answer to the question: "how are we going to design the seats?" Indeed, technical requirements are found but the next step is to find features to implement them. It is rather a tool to help think about what to do next.

But this matrix provides very useful guidelines to derive the following matrix: the product design matrix.

2.3.3 Product Design matrix

Presentation of the results

Surveys provided the team with more information to design features for the new seat. Indeed, the team's goal was to improve static comfort (i.e. comfort when the passenger is quietly sitting) as well as dynamic comfort, that is comfort during all the passenger's activities over a certain period of time. Those activities were identified and prioritized in the second survey.

A product Design QFD matrix was derived from all these results as well as from the research presented in previous sections. This matrix ranks features found to fulfill the technical requirements from the first matrix.

Some requirements were added to those in the first matrix, on the basis of the results mentioned from the second survey and other research. A copy of this matrix can be found in Figure 12 in the next two pages.

#	Technical Requirements	Weighting	1 Patterns on fabric that give feeling of greater space	2 Aesthetically pleasing patterns of fabric	3 Colors that are pleasing to the eyes	4 Light colors to convey better sense of depth	5 Dark colors to make stains less visible	6 Space-age colors	7 "Slides" at the back of trays depicting sunset, mountain, etc. (selectable)	8 Logo/symbol on seat back to draw attention away from peripheral vision	9 Soft and comfortable fabric (nice to the touch)	10 Smooth fabric	11 Textured fabric	12 Durable and longlasting fabric	13 Zip-up seat covers (to facilitate cleaning)	14 Protruding seat edges to symbolically mark personal boundaries	15 Protruding head rest edges for more privacy	16 Retractable screens that block other passengers from field of vision	17 Seats arranged diagonally	18 Middle seats offset backwards to facilitate 3-way/4-way conversation	19 Theatre-style seating	20 Sliding trays	21 Tiltable trays	22 Height-adjustable trays	23 Height-adjustable arm rests	24 Inflatable arm rests	25 Arm rests that swing out to facilitate conversation (when seats are offset)	26 Width adjustable arm rest	27 Cup holder on arm rest	28 Cushioned arm rest	29 Sinkable (all the way) arm rest (instead of upwards rotation)	30 Contour head rest	31 Height-adjustable head/neck rest (mechanical)	32 Inflatable head rests	33 "Wings" to rest head on	34 Foldable head rest to facilitate front-back conversation
1	Simplicity of engineering	20	9	9	9	9	9	9	3	9	3	9	9	3	9	3	3	3				3	3	1	1	3	3	3	9	9		3	1	1	3	
2	Accessory arrangement/minimization	16																													3					
3	Adjustable mechanisms	13							3									9				9	9	9	9	9	9	9			3		9	9	9	9
4	Ergonomic/anthropometric design	10																				9	9	9	9	3		3		3		9	9	3	1	
5	Ease of maintainance	10	3	3	3	3	9	3	1	3		3		9	9	3	3												9	1		9				
6	Continuous adjustability	10																9				9	9	3	3	3	9	3			3		3	3	9	9
7	Common internal parts	10																																		
8	Reduced seat volume	9																																		
9	Minimize number of parts	9																														1				
10	Mechanical controls	7							1									9				9	9	9	9	1	9	3			3		9	1	3	3
11	Durable materials	7											1	9																						
12	Versatile design	6	3	3	3	3	3	3	3	3						3	3		3	9							9		9		9				9	9
13	Low MTBF	6					1							9																		3				
14	Comfortable materials	6	3	3	3	3				3	9																			1						
15	Adjustable geometry	6																							1	3	1	9			9		1	3		9
16	Electrical controls	5																																		
17	Easily obtainable parts	5	3	3	3	3				3	1	1	1						1	1		1	1	1	1		1		1	1			1		1	
18	Cost-effective design	5	3	3	3	3	3	1		3	1	3	3	1																					1	
19	Integrated functionality	5	1	1	1	1	1	1	1	1	1			1		1	1					3	3	9	3	1	1	3	9	1	1		3	3		
20	Improved seat arrangement	5																	9	9	3															
21	Commonality of design	4																																		
22	Personal avionics	4																																		
23	Environmental controls	4																																		
24	Modularity of design	4	1	1	1	1	1	1		1	1			1																						
25	Light structural materials	3																																		
26	Visual patterns	3	9	9						3			3																							
27	Aesthetic design	3	3	9	9	3	3	3	9	3											3		1							3		3			3	
28	Facilitate work (laptops included)	3														1	3			1		9	9	9	3	3	1		3	1						1
29	Variable loads absorption	3																								3				3				3		
30	Variable degree of firmness	2																								3								3		
31	Isolation	2							1	3						3	3	9	3													1			3	
32	Modern appearance	1		3	1			9	3	1	1							3	1	3	3		3			3	1			1	1	1	1	3	9	
33	Material texture	1									9	3	9																	3						
34	Fixed geometry	1														1	3															9				
	TOTAL:		331	352	323	304	337	270	181	320	153	243	235	291	280	133	141	361	85	120	37	477	483	407	365	304	414	337	393	271	262	298	357	265	396	349

35	Adjustable foot rest	3		9	9		9				9					1		1																		441
36	Adjustable leg rest			9	9		9				9					1																	3			379
37	Vertically adjustable seat back			9	9		3				9					9				9																409
38	Horizontally adjustable backrest			9	3		3				9					1				3									9							298
39	Flat seat back	9				9			3					3				3	9																9	394
40	Contoured seat back	3			9	9				1				3						3								3					9		9	319
41	Concave contouring	3			9	9																						1					3		3	259
42	Edge contouring	1			9	9			3																			1					9		3	252
43	Pillow secured to the seat with velcro (position adjustable)	9	1	3	3	3							1	3				9	1						1					3				1		393
44	Electronic massage pillows			3	3												9											1					3			130
45	Adjustable lumbar support (mechanical)			9	9		3				9					1		1		1																326
46	Adjustable lumbar support (electrical)			9	9		9									1	9			1																363
47	Inflatable lumbar support			9	9		3				1					1				1										3	3		3			283
48	Pelvic support	3			9									3						9													3		9	235
49	Adjustable seat height (mechanical)			9	9		3				9					1				3									3							340
50	Inflatable seat bottom			9	3		3				1					3				1										3	3		3			235
51	Tiltable seat bottom (entire)			9	3		9				9					3				1								9	9				1			388
52	Downward foldable seat bottom (front edge) to facilitate ingress/egress			3	1		3		1		3		9			9																				227
53	Tiltable seat bottom (front edge)			9	3		9				9					3				3									3							352
54	Sliding-out seats			9	1		9				9					3												9	9							362
55	Foldable seat bottom			3	1		3		1		3		9			9				1																232
56	Flip-over seat bottom	3		3									3							1											1					134
57	Lower seat bottoms (no luggage space)	9			1															1															9	214
58	Sideways rocking seat bottom			1	1		9						3																				3			144
59	Non-reclinable seats	9	9			9				9				9				9	9			9			9				9						9	757
60	Thin diaphragm seats without cushions	3	9			9		1	9	3		9		3					1							9									3	529
61	Webbing as cushioning substitute	9	9			9			9			9		3					1	1						9									3	626
62	Sandwich structure in the cushion																									3				9	3					52
63	Store hand items below seat (remove front pocket)	9	9						3																											361
64	Bag/pocket hanging from seat bottom edge (remove front pocket)	9	9						3																											361
65	Knee cushions	9			1	1									1			1												3				3		233
66	Seat to diagonal bed transformation			9	1		3				9		9			9				1										1			3			349
67	Personal entertainment system			3									9				9			9			3					9				9	9			283
68	Variable light intensity			9			9																	9					9							280
69	Confor foam														3															9	9					73
70	Conventional foams	9				3						3						9	9			9			1	1										374
71	One type of foam	9				3		9										1	9			9			3											327
72	One type of structural material	9				3		9										1	9			9			3											327
73	One-type adjustment mechanisms (inflatable)		1	9	9	1	3	9			1					3			1			3														324
74	One-type adjustment mechanisms (mechanical)			9	9	1	3	9			9					1		1	1			3														357
75	One-type adjustment mechanisms (pneumatic/hydraulic)			9	9	1	9	9			3					1		1	1			3														375
76	One-type adjustment mechanisms (electrical)		3	9	9	1	9	9								1	9					3														437

Figure 12: Product Design matrix

Weightings of technical requirements (from 1 to 20) came from the scores in the first QFD matrix.

The team came up with 76 design features or design specifications. As it was done in the Technical Requirement matrix, the degree to which the features fulfilled the technical requirements was ranked, as either 0, 1, 3, or 9. Another scoring was done, in order to integrate results from the research phase. Thus by averaging scores from the matrix and scores from the research, the team was able to rank all these features as objectively as possible. But as in the first QFD matrix, the two or three most important features are not the only ones that should be considered under the pretext that they score more than others: less important features in terms of scoring are to be kept in mind as well.

Final designs of the seat can then come from a proper "mixing" of some of those features. The top five features are presented next. The detail of all the features and their scoring is presented in Figure 13.

Concept #	Provide more space	Facilitate in-flight activities	Provide better support	Score
1	- Non-reclinable seat	- Sliding-out seat - Cushioned armrest	- Adjustable lumbar support - Winged headrest	2472
2	- Non-reclinable seat	- Height-adjustable armrest - Cushioned armrest	- Adjustable seat height - Pillow secured to seat with velcro	2446
3	- Non-reclinable seat	- Foldable head rest - Cup holder on armrest	- Adjustable lumbar support - Winged headrest	2491
4	**- Non-reclinable seat**	**- Height-adjustable tray**	**- Inflatable lumbar support** **- Height-adjustable headrest** **- Winged headrest**	**2670**
5	- Non-reclinable seat - Webbing	- Sliding-out seat - Cup holder on armrest	- Adjustable foot rest	2789
6	- Webbing	- Height-adjustable armrest	- Adjustable leg rest - Adjustable foot rest	2141
7	**- Webbing**	**- Height-adjustable tray**	**- Height-adjustable headrest** **- Winged headrest**	**2146**
8	- Webbing	- Height-adjustable armrest	- Seat to diagonal bed transformation - Adjustable foot rest	2051
9	- Webbing	- Tiltable seat bottom - Cup holder on armrest	- Height-adjustable headrest	2034
10	- Webbing	- Height-adjustable tray - Inflatable armrest	-Adjustable lumbar support	2083

Figure 13: Scoring of features

Design features

The top five design features are:

✓ Non-reclinable seats (to improve room for the passenger behind the seat)

✓ Webbing as cushioning substitute

- ✓ Sliding tray
- ✓ Height adjustable tray
- ✓ Adjustable footrest

Now concepts can be derived from these features.

2.4 Final concepts

2.4.1 Seat concepts

Considering the fact that all the features are different and have different properties, the team decided it should implement two concepts instead of one. In each concept, the team included several features found in the matrix, with one feature being the key of the concept. Additional features were not chosen arbitrarily. Rather, design features were divided into three categories, derived from passenger needs given by the surveys. Those categories were:

- ✓ Provide more space
- ✓ Facilitate in-flight activities
- ✓ Provide better support

At least one feature was chosen in each of these categories. The team limited the total number of features to five: too many features may take too long to implement, and too few may not create any improvement.

Two major concepts were developed:

- ✓ **Forward-sliding seat**: The recline of this seat is obtained by sliding the back forward, with the result that the seat seems to be non-reclinable for the passenger who is behind. The fact that the seat is "non-reclinable" provides more space to the passenger behind. The recline would work comfortably only for the 50th percentile of the population, since a tall person would already have his knees on the back of the front seat and would not be able to slide forward. But at least this passenger would not have his knees hurt by the recline of the front seat. Figure 14 is a sketch of the forward-sliding seat. Also the team added a height-adjustable headrest with wings and an inflatable and height adjustable lumbar support. A sandwich cushion bottom provided more comfort as well as durability: it was made of different very thin layers of a special kind of foam, which distributes weight evenly on its surface. Finally, a height-adjustable tray facilitated in-flight activities seat. Technical requirements that a non-recline feature fulfills are simplicity of engineering, accessory arrangement and minimization, ease of maintenance and minimize number of parts.

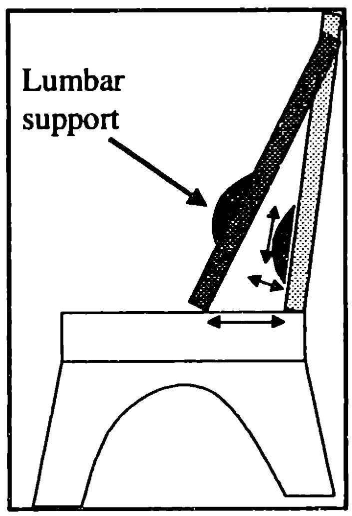


Figure 14: Concept 1: Forward-sliding seat [14]

✓ **Webbing seat**: The main feature of this concept is to use webbing instead of cushioning. This saves space: a cushion is particularly thick and reduces the available seat depth. The headrest was a simple headrest and there was also a height-adjustable tray. The web feature satisfies simplicity of engineering, accessory arrangement/minimization, reduced seat volume and effective cost design.

Figure 15: Concept 2: Example of a webbed back

2.4.2 Design parameters

The design of an aircraft seat should obey specific rules which have been mentioned partly in section 1.3.1. Through these two concepts the team took some of the design parameters into account. Features were chosen so as to reduce seat weight. The baseline structure for these seats was a conventional seat row B/E Aerospace kindly gave to the team, so the seats will fit the correct percentiles of the population.

Other considerations like FAA regulations were kept in mind, but compliance to these regulations was not the focus of the team. Another point is price: the concepts are likely to reduce the overall price of the seat (including the cost of operations). But the team did not try to study cost: a prototype costs more than a mass production seat.

3 SEAT FABRICATION

3.1 Summary of features

3.1.1 Forward-sliding seat

Main features of the forward-sliding seat are:

- ✓ A forward-sliding back.
- ✓ A height-adjustable inflatable lumbar support.
- ✓ A height-adjustable headrest with wings on its sides.
- ✓ A height-adjustable tray.

3.1.2 Webbed-back seat

Main features are:

- ✓ A webbed back.
- ✓ A height-adjustable tray.
- ✓ A sandwich seat cushion.

3.2 Details of construction

The baseline seat for the prototypes was a row of conventional seats that B/E Aerospace gave to the team.

3.2.1 Webbed back

The team had two possibilities to implement the webbed back.

- ✓ The first one, which was the one the team chose for the prototype, was to use an office chair with a webbed back, the Aeron chair from Herman Miller, and to place the back directly on the frame. The mechanism to recline the seat was preserved in the baseline. Thus the webbed back could be attached so as to retain the seat recline capability.

- ✓ The second one was made possible thanks to Milliken and Co, a company which specializes in ergonomic office chairs and which already worked with B/E Aerospace on webbed aircraft seats (on these prototypes, the web was covered). Milliken and Co agreed to manufacture a webbed seat on the basis of one of the fiberglass backs the team possessed.

3.2.2 Height-adjustable tray

The height-adjustable tray is held by two arms which are connected to the frame of the seat. To achieve the height-adjustability, these arms are cut slightly above the lower extremities (the ones which are attached to the frame). Then a guide encloses each of the arms and the upper part of each arm is free to move up and down inside the guide. Holes in the guides and pins ensure retention of the tray at the desired height. Figure 16 illustrates the design:

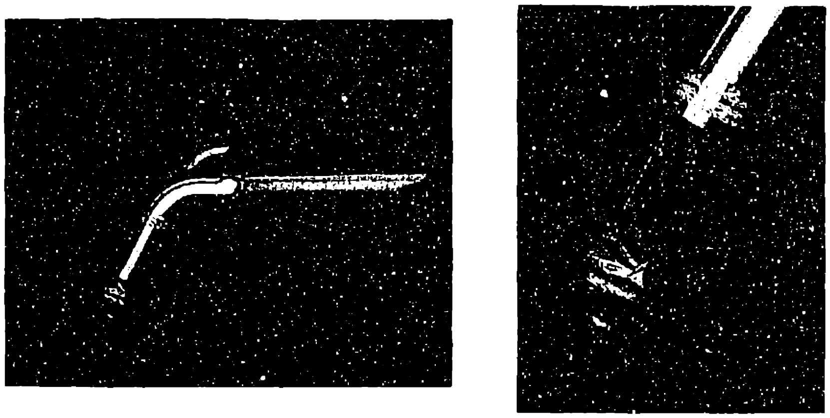


Figure 16: Height-adjustable tray

3.2.3 Lumbar support

The inflatable lumbar support is made from a blood pressure measuring device similar to the ones used by doctors. A pump inflates the blood pressure cuff. This part (with the pump still attached) was taken from the device and wrapped up in a piece of fabric.

To make it height-adjustable, Velcro was sewed on the back, and on the lumbar support. The ideal height of a lumbar support varies from 7" to 11.5" measured from the bottom of the back seat to the middle of the lumbar support as shown in Figure 17 [6]:

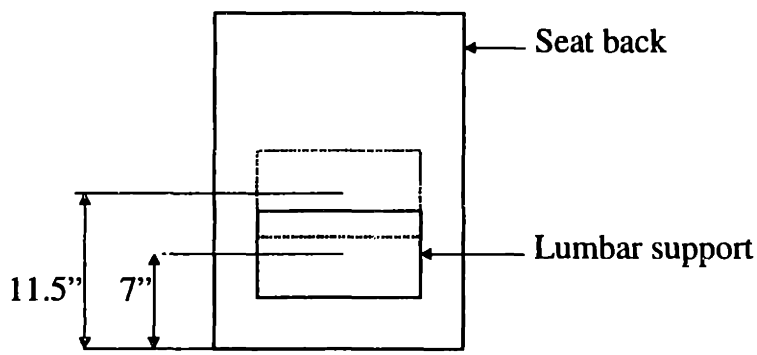


Figure 17: Ideal position of lumbar support

On the part of the back cushion where the lumbar support can move, a little thickness of foam was removed; otherwise, at its uninflated position, the lumbar support causes an uncomfortable bump.

3.2.4 Forward-sliding seat

The back of the baseline seat was removed and replaced by a flat wood back. Adjustment handles attached to the back allowed the back to be pulled forward or pushed backwards. Desired position was maintained with screws placed aligned with the desired position notch.

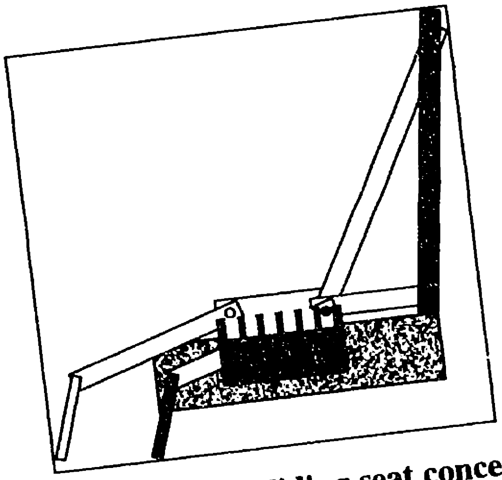


Figure 18: Forward-sliding seat concept [14]

3.2.5 Sandwich cushion

The sandwich cushion was kindly manufactured by Oregon Aero and was made of four difference materials:

- ✓ Confor foam: multi-density open-cell polyurethane foam.
- ✓ Upholstery foam: used to protect the confor foam.
- ✓ Plastazote: semi-rigid, light-weight material.

✓ Upholstery: flame-retardant, meets flammability specifications.

For more details on the sandwich cushion, see Ref. [12].

3.2.6 Height-adjustable, wing headrest

B/E Aerospace offered a height-adjustable wing headrest to the team. Wings that are movable on both sides of the headrest can maintain the head and prevent it from sliding to the right or to the left. The team added a layer of cushion to move the edge of the headrest forward, in order to have it at the same position as in an actual aircraft seat.

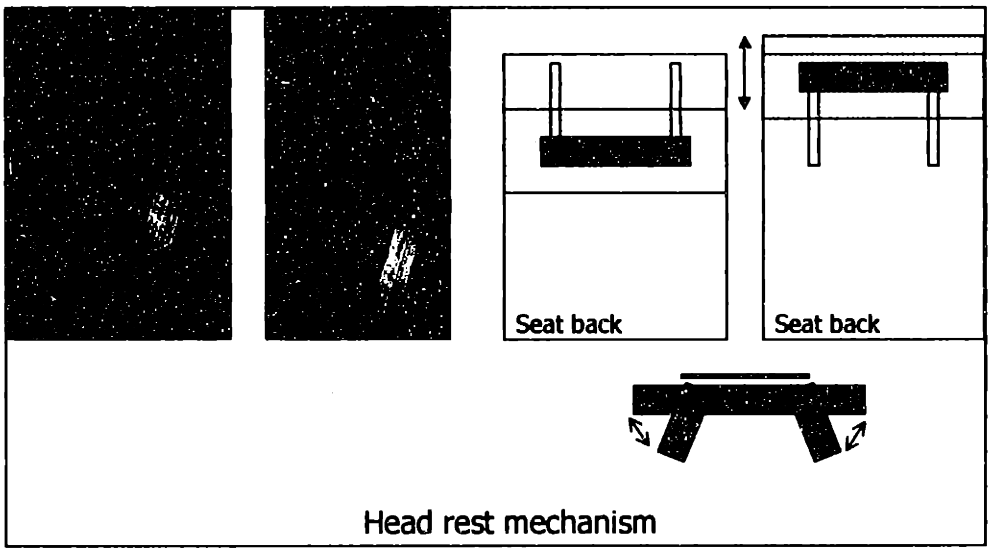


Figure 19: Wing headrest [14]

3.3 Final implementation

Photographs of the two concepts are provided in Figure 20 and Figure 21.

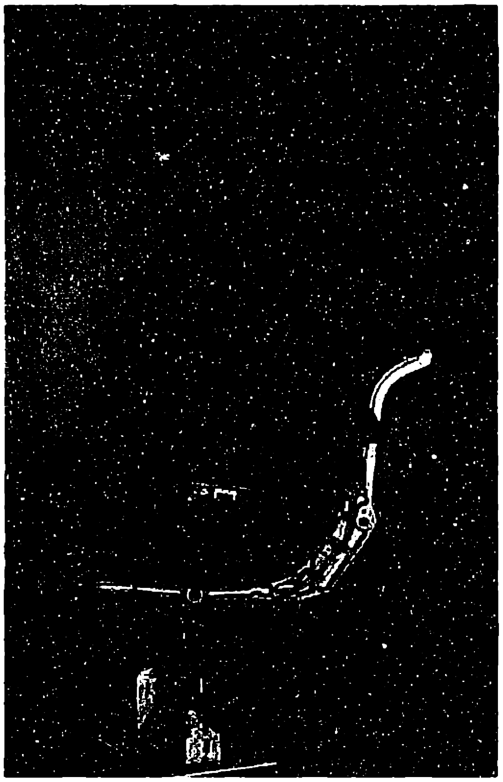


Figure 20: Forward-sliding seat

Figure 21: Webbed seat

4 SEAT EVALUATION

4.1 Overview of experiments

The purpose of the experiments was to test and compare the comfort of the team's two prototypes to a current airline passenger seat.

4.1.1 Subjects

First, pressure mappings of team members were taken before the final evaluation in order to modify the seats if necessary. Then, to test the seats objectively, the team needed subjects. Subjects were recruited at MIT, among students and faculty members, via e-mails. A special authorization from COUHES (Committee on Use of Humans as Experimental Subjects) was requested to recruit subjects. An experimental protocol was written and sent to COUHES for approval, a copy of which can be found in Appendix 6.

4.1.2 Evaluation plan

The plan was to make subjects sit on each seat for three hours, in a similar environment that they would be in if they were traveling by plane.

To represent the airplane environment, three rows of two seats each were used, and an artificial wall and ceiling were placed to limit space.

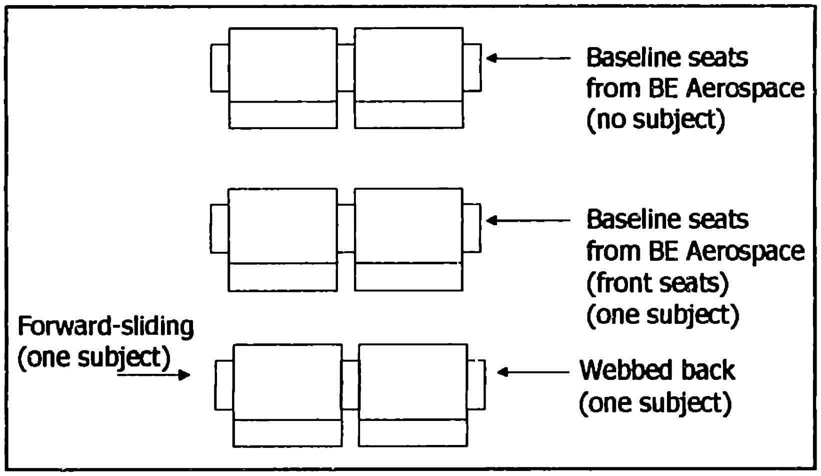
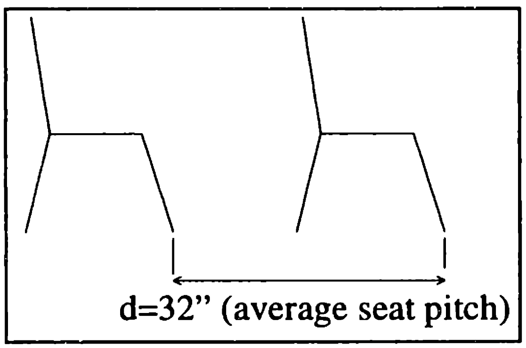


Figure 22: Top view



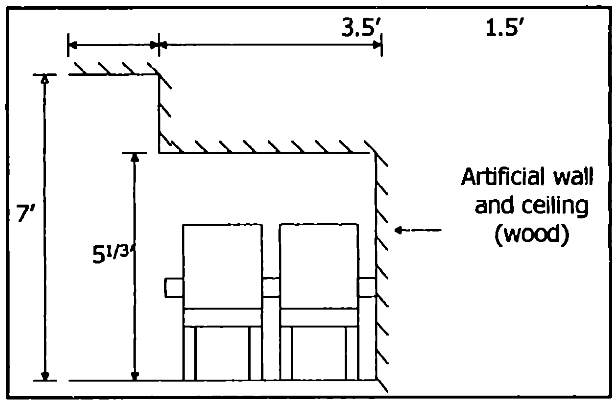


Figure 23: Seat pitch

Figure 24: Front view

Seat pitch varies between 28" and 36" depending on the airline. Since the industry average is 32," this value was chosen for the environment.

Because the tests require that each subject feels as if he/she were really in an airplane, each subject had to have a row in front of him/her. So three rows were placed in the environment. The last row, as shown in Figure 22, is the row with the prototypes. The first two rows used current passenger seats.

Ceiling height was determined by data provided by B/E Aerospace, describing major dimensions of several aircraft. The team chose 5.33 feet from the floor to the ceiling above the seats, and 7 feet for aisle-to-floor height.

In order to have significant data on the specific tasks that were highlighted by the second survey, every subject was asked to perform a series of tasks in a certain order. It was then possible to rate the ease with which those tasks were performed, and how comfortable it was to perform them.

Also, because comfort is related to each individual, each subject was asked to test three seats: two concept seats and one baseline seat given to the team by B/E Aerospace. Comparisons between those seats are then more accurate.

4.1.3 Parameters

There are several independent variables which influence test results. They are:

- ✓ Seat type (concept 1, concept 2 or baseline).
- ✓ Subject weight/size.
- ✓ Tasks to be performed
- ✓ Seat position (aisle or window)

To minimize human bias, there should ideally be as many subjects as possible in order to be able to test every combination of those parameters as follows.

There were three seats and each subject must test each of them. There were six different orders in which one can test the seats, so the number of subjects must be a multiple of six, as shown in Table 3. This is the counter-balancing method for seats.

Subject	Seats		
1	A	B	C
2	A	C	B
3	B	C	A
4	C	B	A
5	B	A	C
6	C	A	B

Table 3: Counter-balancing method

Other combinations can be obtained by changing seat location: for example, moving concept 1 from aisle to window. But due to time constraints, the team decided to implement only the counter-balancing described in Table 3.

The sample of subjects should be representative in height and weight of the human population, at least that which is accounted for by airlines (from the 5^{th} percentile to the 95^{th} percentile). So subjects were selected mainly according to their height.

Finally, there are a variety of tasks that must be performed. Ideally, one should have an exhaustive list of tasks performed in different ways. Unfortunately, considering the time available, this could not be done for the project.

4.1.4 Procedure

For testing one seat, subjects came for a three hour period. During that time, they performed the tasks identified in the second survey which are listed below.

1. **Pressure mapping**: The subject sat on a pad (pressure pad) and the experimenter took maps of the pressure distribution directly on a computer. Three maps were taken: one while the subject was sitting correctly, the second one in a slouched position and then in a working position.

2. **Sitting**: The subject was asked to do nothing but remain seated and try to find his/her most comfortable sitting position. Reclining the seat and using the tray were not allowed. This simulated the takeoff phase.

3. **Questionnaire 1**: The subject filled in questionnaire 1.

4. **Break**: The subject was allowed a short break to get up and take a walk if he/she liked.

5. **Working or Rest Period**: The subject was asked to perform any work task (reading, writing, using a computer) which required the use of the tray. The subject was also welcome to sleep.

6. **Questionnaire 2**: The subject filled in questionnaire 2.

7. **Break.**

8. **Eating**: Refreshments were served.

9. **Questionnaire 3**: The subject filled in questionnaire 3.

10. **Break.**

11. **Working or Rest Period**: The subject was asked to perform any work task (reading, writing, using a computer) which required the use of the tray. The subject was also welcome to sleep.

12. **Questionnaire 4**: The subject filled in questionnaire 4 and gave general comments on the seat.

These tasks were repeated for each seat.

Subjects were asked not to get up from the seats during the tasks if possible. Questionnaires are attached at the end of Appendix 6 which describes the experimental protocol as sent to COUHES.

The test procedure timeline is shown in Figure 25. This timeline was the baseline. It was sometimes changed slightly during the experiment, in order to accommodate every subject equally, but the total test time for each seat was always three hours. Boxes labeled Q1-Q4 represent the phases in which questionnaires were filled in.

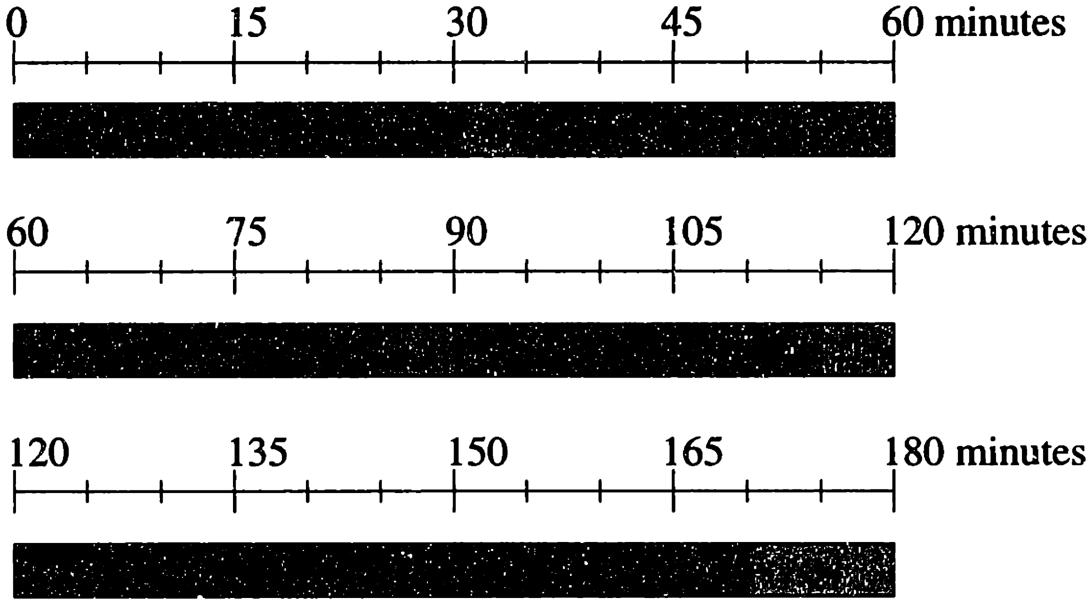


Figure 25: Timeline for the experiment

4.2 Evaluation method

4.2.1 Questionnaires

The first way of evaluating the comfort of a seat is to actually make people test it. Of course, just asking them how they feel would be too vague a question. So this question must be narrowed in some way and split into more specific questions. This way, there will be a set of compatible data from all the subjects who have tested the seats.

Automotive industries use common questionnaires: they ask the subjects testing the seats to rate the feelings they experience in specific areas of their body (e.g., arms, legs, neck or back). This reduces human biases in processing data.

4.2.2 Pressure mapping

A description of the pressure mapping system is given in Appendix 7.

Eight pressure maps were taken in total for each subject and each seat: four for the back, four for the bottom. Those four maps were:

- ✓ Seat in an upright position and subject sitting correctly.
- ✓ Seat in an upright position and subject slouched.
- ✓ Seat in a reclined position and subject sitting correctly.
- ✓ Seat in reclined position and subject slouched.

4.3 Experimental setup

The experiment was built as shown in Figure 22, Figure 23 and Figure 24. Lights were placed on the side on the wall but not above the seats. There were plugs near the seats for subjects with a laptop. The setup was isolated from the rest of the room with curtain. The computer with the Tekscan pressure pad system was placed near the setup. Seats were attached to the floor with rails, provided by B/E Aerospace.

4.4 Test results

4.4.1 Subjects

Twelve subjects (nine males, three females), were selected from the twenty responses to the e-mail sent.

Figure 26 and Figure 27 plot the distribution of height for men and women; vertical bars show where the subjects lie in these distributions.

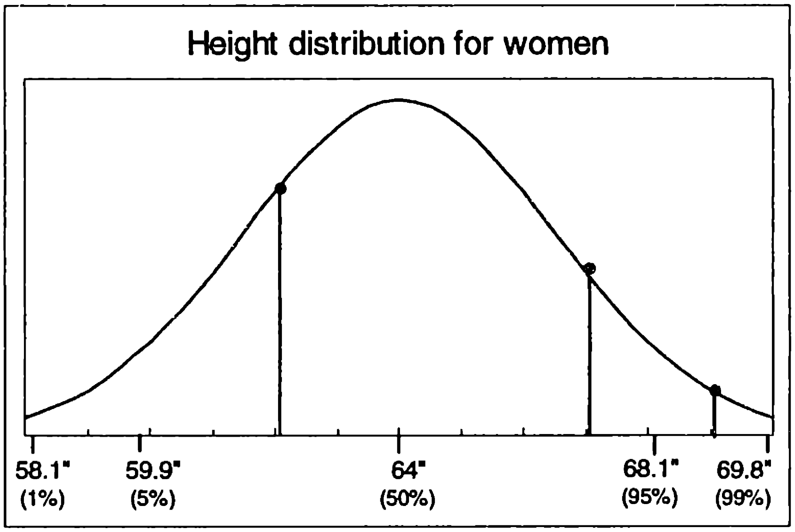


Figure 26: Height distribution for women

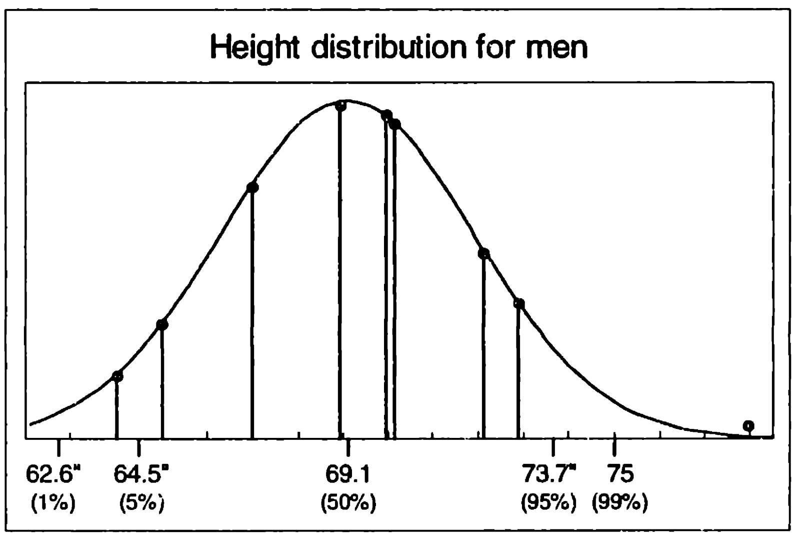


Figure 27: Height distribution for men

Table 4 presents the average of the personal data, as well as the standard deviation.

Data	Average	Standard deviation
Age	24 years	3.8 years
Height	172 cm / 5'8"	11 cm / 4.3"
Weight	75 kg / 167 lb.	20 kg / 43.5 lb.

Table 4: Test subject attribute

The selection of subjects spanned the desired height spectrum. But it was not possible to obtain equal numbers of male and female subjects. Only one subject did not complete all three tests: that subject only tested the baseline seat and the webbing seat. Subjects filled out the five questionnaires that are presented with the experimental protocol in Appendix 6 with descriptive comments.

4.4.2 Results of the questionnaires

Complete results of the questionnaires are presented in Appendix 8.

Figure 28, Figure 29, Figure 30 and Figure 31 plot the average comfort rating from the questionnaires.

It can be seen from Figure 28 that the webbing seat is more comfortable than the baseline and the forward-sliding seat, except for the lumbar area, neck, head and hip. For head and neck, this fact can be explained by the fact that the headrest that was added by the team to the back was not well adapted to the back shape, and thus did not support the head and the neck very well.

The question now is: are the differences in ratings between all the seats significant or not? In order to assess this significance, two statistical tests were performed: paired T-test and sign tests [15]. These tests were applied to the difference in rating between each pair of two seats for each part of the body mentioned in the questionnaires. If statistical tests show negative results, that means seats are comparable. Arrows in the figures indicate statistically significant differences between two seats at 95% confidence level. According to these tests, there is no significant difference between the two prototypes. But the back of the webbing seat is significantly more comfortable than the back of the baseline, and the lumbar support of the forward-sliding seat significantly induces more comfort than the baseline in the lumbar area.

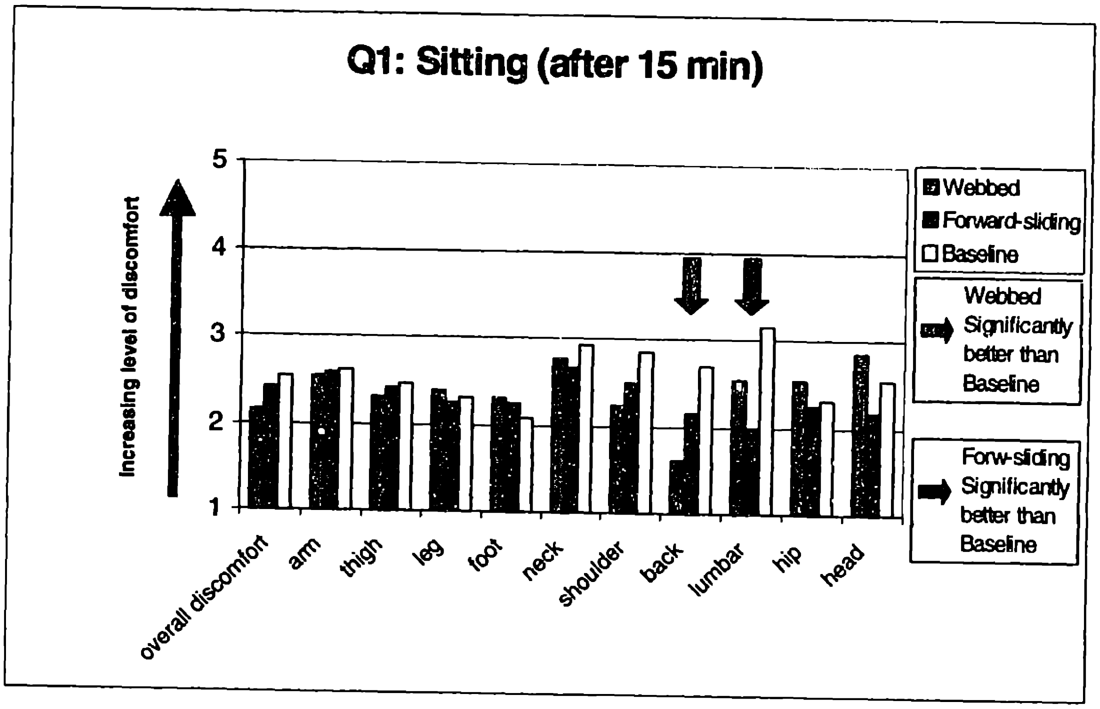


Figure 28: Results of tests after 15 minutes

In Figure 29, similar gradings as in Figure 28 can be found. Nevertheless there is a difference in the rating of the comfort in lumbar: the webbing seat is now also significantly more comfortable than the baseline seat. Once again there is no significant difference between both prototypes.

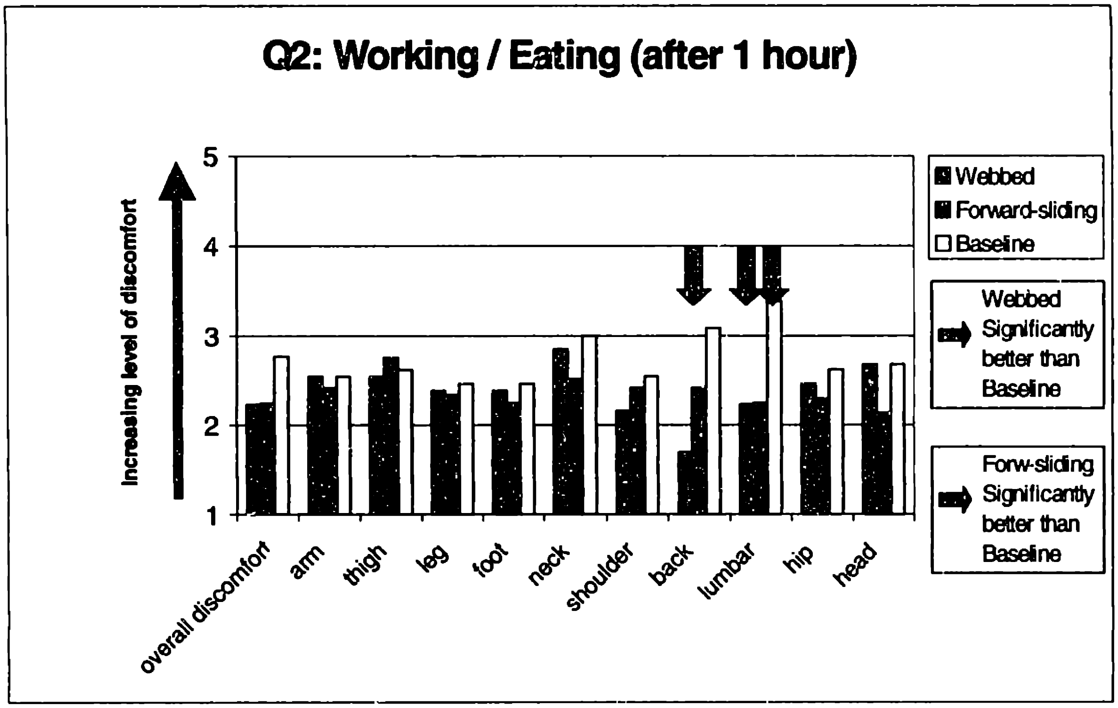


Figure 29: Results of tests after 1 hour

In Figure 30, there are more significant differences of comfort between the prototypes and the baseline, but not between both prototypes. These differences already existed in Figure 29, but have now become significant.

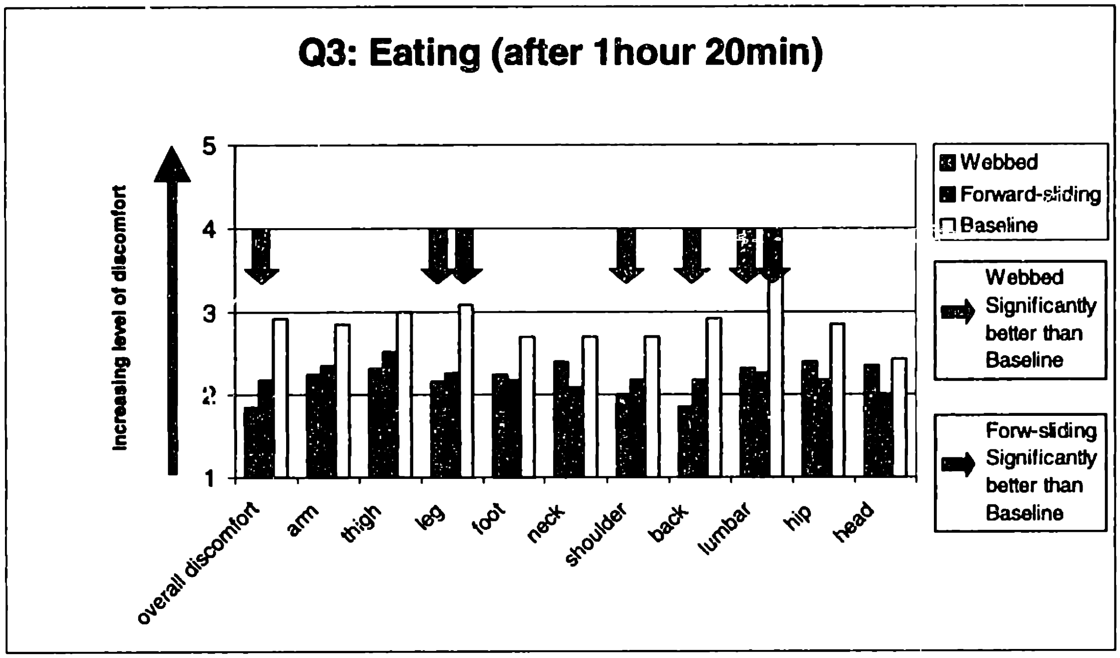


Figure 30: Results of tests after 1 hour and 20 min

In Figure 31, some significant differences disappeared compared to Figure 30, but the rating of comfort does show a better comfort in the prototypes.

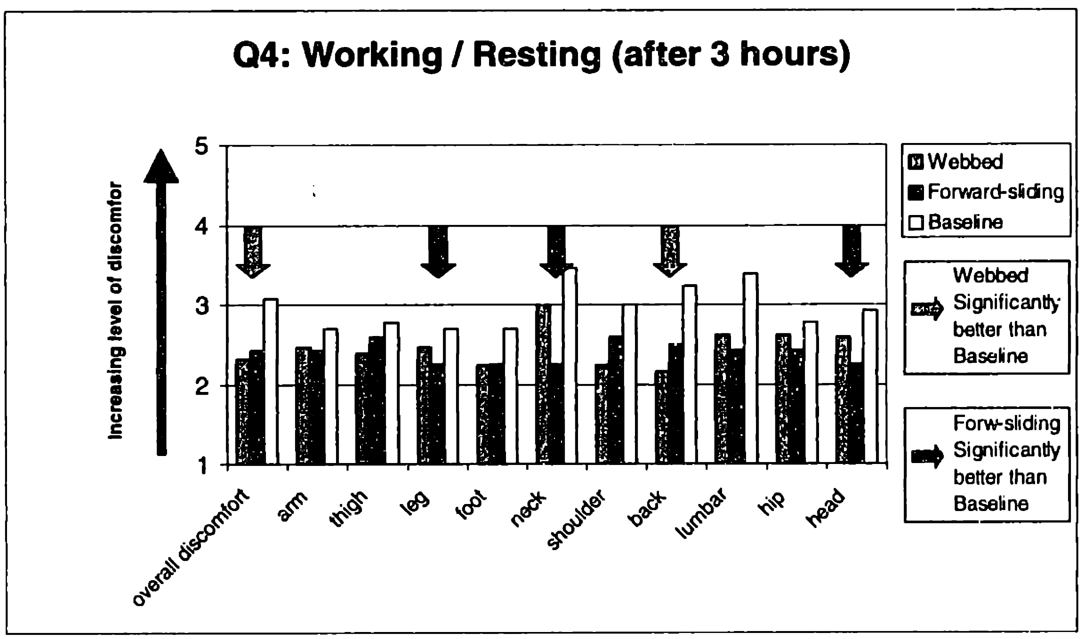


Figure 31: Results of tests after 3 hours

4.4.3 Evolution with time

Figure 32, Figure 33 and Figure 34 present the evolution of comfort throughout the questionnaires for all the seats. Statistical tests were again performed, this time to assess the difference of comfort with time, for each seat separately.

As shown in Figure 32, the webbing seat gets less comfortable with time, although this change is significant only for the back. But as indicated in Figure 31, the webbing seat was still significantly more comfortable at the end of the experiment than the baseline seat.

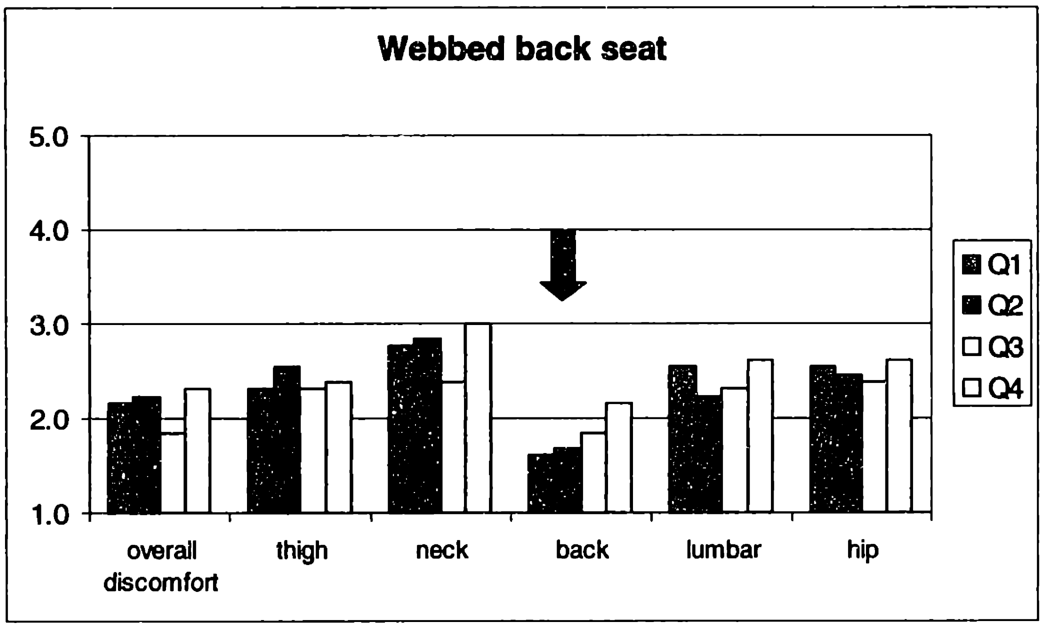


Figure 32: Evolution of comfort for the webbing seat

Although a relative degradation of comfort can be seen in Figure 33 for the forward-sliding seat, this degradation is not significant.

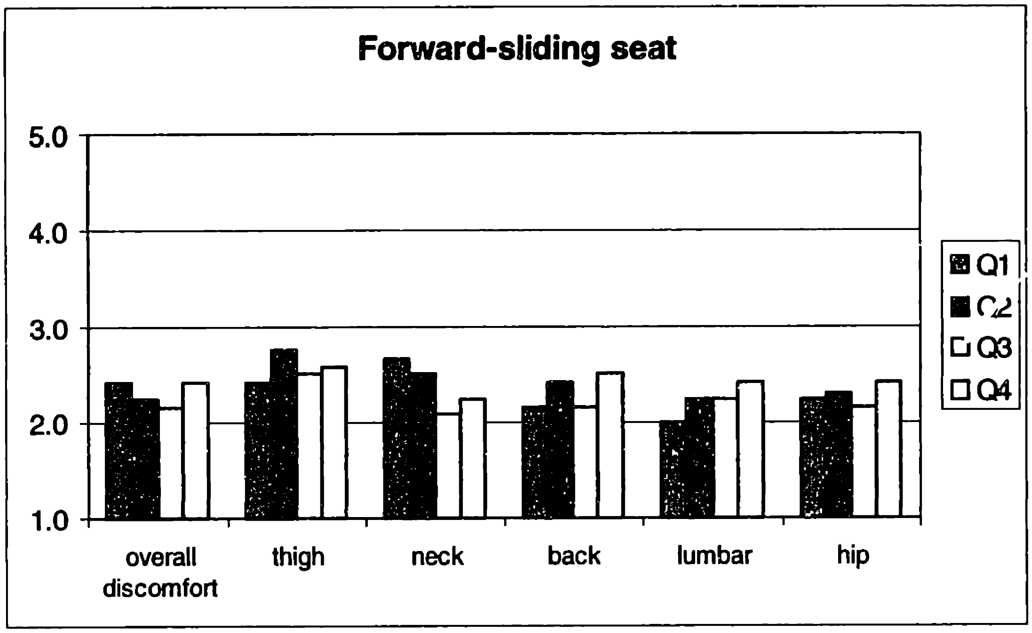


Figure 33: Evolution of comfort for the forward-sliding seat

Figure 34 shows that the baseline seat also get less comfortable with time, significantly for the overall comfort, which was not the case for the prototypes.

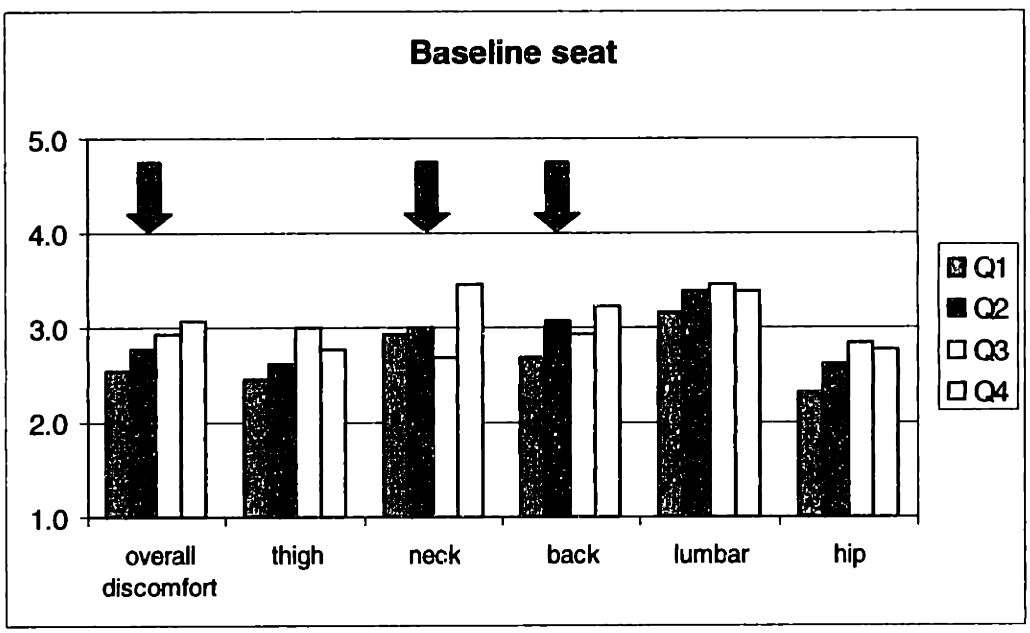


Figure 34: Evolution of comfort for the baseline seat

Degradation of comfort that was made obvious by the preceding figures is normal: subjects usually did not take any break during the tests and the human body cannot sit for extended periods of time without suffering some discomfort. But this degradation is not statistically significant for the prototypes.

Trends can be seen from the figures and from comments of subjects. On average, the webbing seat was judged to be more comfortable and preferred to the forward-sliding seat which comes next, just before the baseline seat. The last question of the questionnaires enhances this trend: ten subjects out of twelve preferred the webbing to the baseline; five preferred the forward-sliding seat to the baseline seat, and four found it comparable. It must be mentioned that several subjects indicated that the baseline was "surprisingly" comfortable at first. For specific areas such as head and neck, the webbed back does poorly because the headrest was rather crude. But the webbing seat started at an overall level of comfort comparable to the baseline and ended significantly more comfortable.

4.4.4 General comments on additional features

The height-adjustable tray was unanimously appraised. All subjects found it very comfortable because they did not have to lean over the tray and they did not have the tray on their thighs.

The height-adjustable headrest was also appreciated, but its position was not optimal for all subjects.

Most of the subjects were pleased with the aesthetics and comfort of the webbing seat. But the adjustability of the tray and the forward-sliding back could have been improved and subjects often pointed this out.

4.4.5 Pressure maps

Correlation with comfort

Computation of correlation coefficients between pressure in certain areas of the body and comfort in these areas shows no correlation between those variables. Indeed pressure is related to the weight, which has no direct influence on comfort. So hypotheses made to correlate pressure and comfort were based on Herman Miller's findings which were described in section 1.1.2.

Comparison between the webbing seat and the baseline

The comparison between webbing-seat and baseline was made on the basis of three subjects: the closest to the 5th 50th and 95th percentiles. Figure 35, Figure 36, Figure 37 show the pressure distribution of these subjects, for the baseline and the webbing seat in a reclined position (there was no significant difference between the pressure distribution in an upright and in a reclined positions). The upper pictures of each figure represent the back, the lower the bottom (sitting bones and thigh). Usually, from subject to subject, peak pressure points varied from 0.8 PSI to 1.5 PSI for the bottom and from 0.4 PSI to 0.8 PSI for the back. Pressure maps were compared to the rating of comfort given by these subjects: the scale went from 1 (very comfortable) to 5 (very uncomfortable).

One point to mention is that cushions for both seats were the same for these subjects, but the pressure distribution always showed different patterns between seats: this is presumably due to the effect of the back. So back and bottom need to be accounted for as a system in order to evaluate comfort.

In Figure 35 the subject rated the comfort of the webbing seat in the back at 4, worse than the comfort of the baseline seat, which was 2. Indeed, there is a hot spot in the spine area of the lumbar for the webbing seat which indicates discomfort, whereas the back of the baseline seat shows a low-value uniform pressure distribution. As for the bottom, the subject rated the comfort equally for both seats, but the webbing seat seems to have a better distribution.

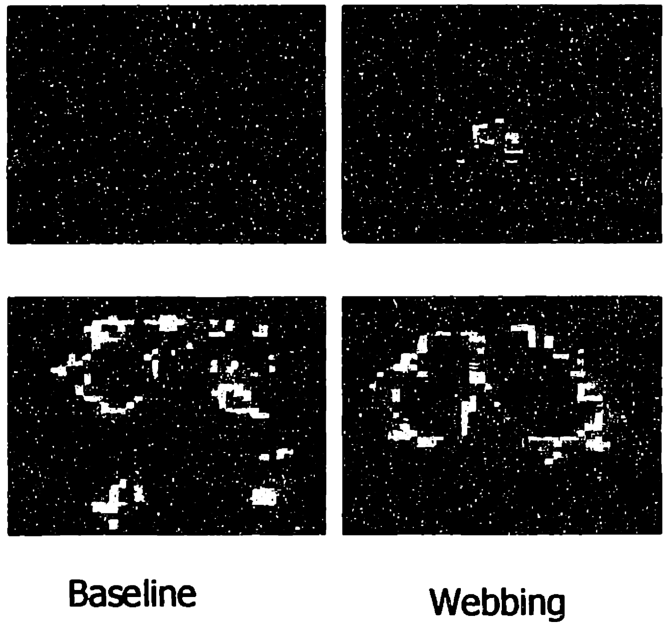


Figure 35: Pressure distribution for a 5th percentile subject

In Figure 36 the lumbar area had the same level of comfort in both seats (the scoring was 3) but the webbing seat was a little better for the back. And bottoms had the same level of comfort (3 also). Both seats are similar in comfort and the pressure maps are similar too.

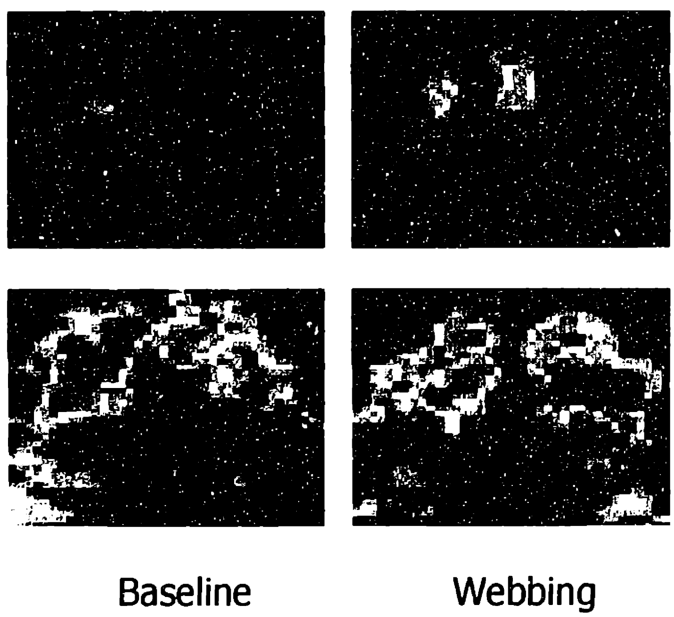


Figure 36: Pressure distribution for a 50th percentile subject

In Figure 37, the subject felt more comfortable in the webbing seat than in the baseline seat in all parts of his body (the overall comfort was 2 for the webbing seat and 3 for the baseline). Again, this can be seen in the distribution which shows high pressure points in the lumbar area away from the spine for the webbing seat, whereas the baseline induces a more diffuse distribution. As for the bottom, high pressure points are located under the sitting bones in the webbing seat, and the baseline induces high pressure points under the thighs. Pressure distribution is well correlated with comfort in this study.

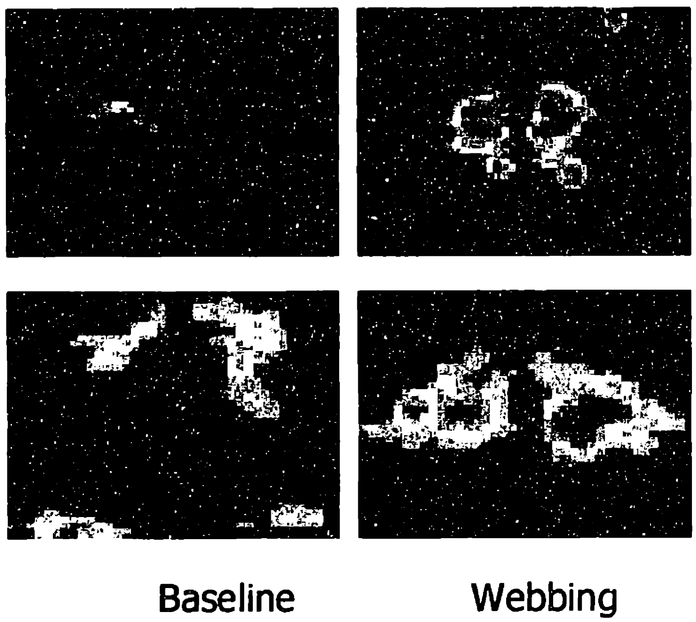


Figure 37: Pressure distribution for a 95th percentile subject

Comparison between the forward-sliding seat and the baseline

Figure 38 indicates that there is no difference in the comfort of the bottom for this subject (the subject rated thighs at 1: very comfortable). In this case the pressure is almost uniformly distributed over the bottom. But the back and especially the lumbar felt poor in the forward-sliding seat (level of comfort of 4 compared to 2 for the baseline seat, in both lumbar and back), and indeed there is a high pressure point right on the spine.

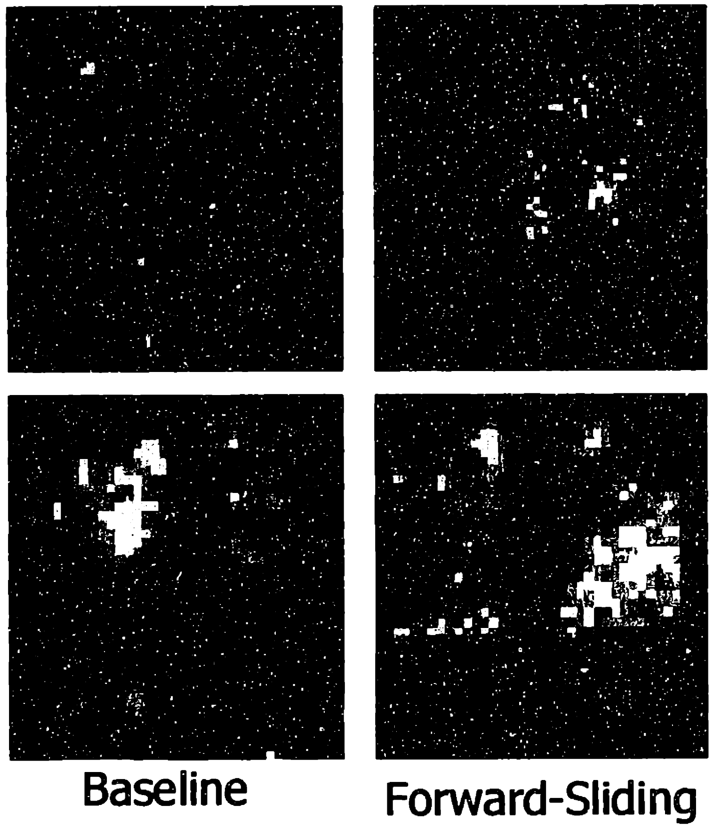


Figure 38: Pressure distribution for a 5th percentile subject

For the case presented in Figure 39, back and lumbar felt better in the baseline seat (both scored 3, whereas for the forward-sliding seat, it was 4 for the back and 3 for the lumbar), and the pressure maps enhance this observation. But thighs felt the same in both seats, with a medium level of comfort rated 3, whereas the distribution is completely different, and suggests that the forward-sliding seat should be more comfortable.

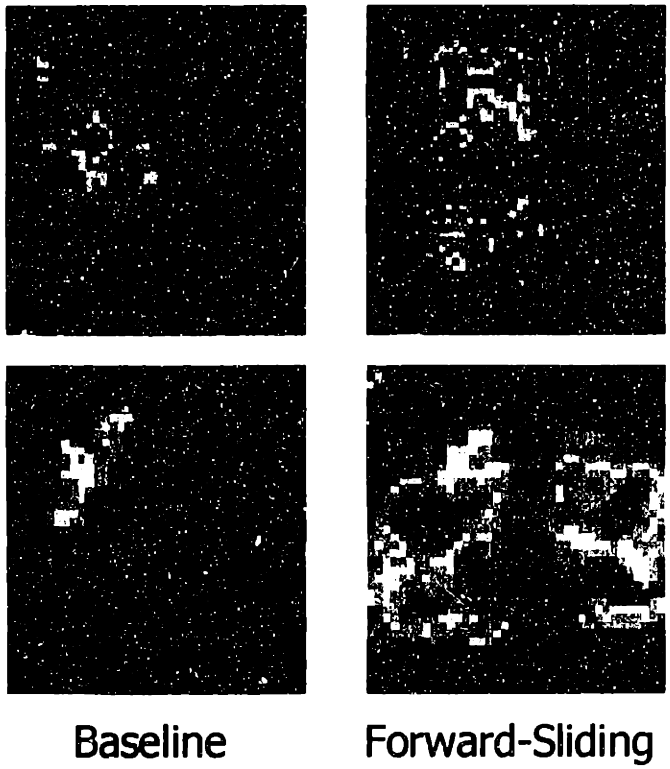


Figure 39: Pressure distribution for a 50th percentile subject

The subject presented in Figure 40 felt much more comfortable in the forward-sliding seat (level of comfort: 3) than in the baseline seat (level of comfort: 5), despite the high pressure point in the lumbar area, near the spine. But the distribution on the bottom does look like a distribution associated with comfort.

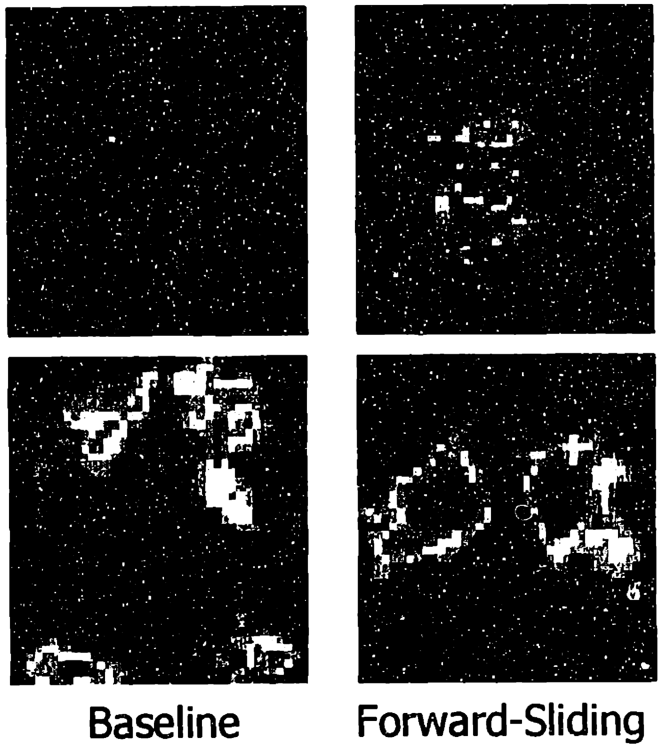


Figure 40: Pressure distribution for a 95th percentile subject

4.5 Dynamic tests

Dynamic pressure maps were also taken, in order to focus on dynamic comfort. Volunteers were asked to sit on the seats for a shorter period of time, namely 90 minutes.

Through these dynamic maps, movement was assessed. Subjects tended to move often and to a greater extent in an uncomfortable seat, which is likely due to the fact that they are always trying to find a comfortable position. But as has been mentioned in the research phase, movement is necessary in any sitting position [9, 13].

Another focus of these dynamic tests was to test a cushion manufactured by Oregon Aero. This cushion is supposed to distribute pressure evenly on it, which means more comfort and less movement. Some volunteers sat on this cushion and the results confirmed these hypotheses [12].

4.6 Conclusion of evaluation

4.6.1 Forward-sliding concept

The forward-sliding seat was judged comparable to the baseline seat as far as comfort is concerned. What makes this concept different, and better, is the absence of recline: benefits have already been discussed in section 2.4.1. Although no survey has been issued by the team to prove this, it is hypothesized that tall people would trade off more legroom against recline.

But this feature may be more efficient in business or first-class where legroom is already important. Besides, it is easier to use a laptop when the front seat is not reclined, because then it can be open completely. Moreover, the loss of cushion area when the seat is forward can be a real drawback which eventually induces discomfort and pain in the thigh area.

This concept may not be approved unanimously, and all its advantages may not compensate for all its drawbacks, if it were to be tested on a real airplane. But it is a very interesting concept, which plays on a combination of various features to improve comfort. It may be a good concept for medium range flights during the day (from three to five hours), when sleep is not necessary.

4.6.2 Webbing concept

The webbing concept was significantly better than the baseline. Besides, the weight reduction provided by a simple web rather than a whole frame and cushion is a great advantage for an aircraft, where weight is a one of the most important parameters (cf. section 2.4.1).

The web used by the team was not made to be used in an aircraft, and the design may not be classical enough to be approved by all passengers. But there are other ways of incorporating a webbed back in an aircraft seat: Milliken and Co presented some of these concepts to the team. The frame would have to be completely different, because there would not be any fiberglass frame. But then what would be the effect of the absence of a solid back for a passenger sitting behind in case of accident? How could the tray be closed? If a tall passenger is sitting behind, would his or her knees touch the front passenger in the back, thus causing discomfort?

Feasibility of such a seat raises many major questions that may be hard to resolve, but considering the success of the first prototype, it is certainly worth studying them.

CONCLUSION

The goal of this project was to bring new ideas and concepts to the aircraft seat industry, ideas which are implementable and which help improve passenger comfort.

In four months, and with the help of tools such as surveys and Quality Function Deployment analysis, the team came up with two new concepts, radically different from what can usually be found in an airplane today: a webbing seat (with a web on the back rather than a cushion) and a forward-sliding seat (the back reclines inward). These concepts included not only a different design of the seat itself, but also additional features: a height-adjustable tray, a height-adjustable headrest and a new type of cushion. Prototypes were built and tested with respect to comfort, although other parameters (e.g. FAA regulations) need to be taken into account. The tests resulted in a favorable comparison between each prototype and a baseline seat. Specifically, the webbed seat consistently provided back comfort ratings significantly higher than with a baseline seat.

There are many different paths that can be followed to study comfort. What has been presented in this thesis is first a qualitative study. It consisted of human evaluation, which means that subjects were asked to test the seat. In order to take as many neutral opinions as possible, they had to fill in questionnaires relating to comfort in specific areas of their bodies. Additional comments resulted in an almost complete delineation of negative and positive effects of the seat on the level of comfort. Then a ranking of the prototypes and the baseline seat was made. The conclusion was that the webbing seat and the forward-sliding seat were more comfortable than the baseline seat.

Another study investigated quantitative measures of a variable that is supposedly linked to comfort: pressure patterns. Since only limited theory exists on their relationship, the goal of the use of pressure measurement was to try to emphasize certain trends that have already been revealed by other studies. Results did show the same trends but it could not be generalized to all seats. So the use of pressure distribution in order to assess comfort is not finalized yet.

Evaluating comfort is a difficult, long and complex task. Tests have proven that comfort was not only related to feelings in the body. It is rather a combination of various parameters, which represent the entire environment. In the case of the seats, this environment included the tray (and thus the possibility of working and eating correctly), the appearance of the seats, legroom, and also the service and the food!

There is still much work to do on evaluating comfort in an aircraft seat: first more subjects should be recruited. Only twelve subjects participated in this experiment and any statistical analysis that has been performed is not fully accurate. The aircraft environment was not completely reproduced during the tests: a real model of aircraft, simulating also noise, air conditioning and personal lights would be useful to obtain more accurate data. Besides, the entertainment system is part of a flight but could not be taken into account in this experiment. In any case, rigor in taking data (especially in taking notes of every single action of the subject) is a very important factor that provides really representative data.

Even with all these constraints, promising conclusions were drawn and many interesting discoveries are still to be made from these results.

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Appendix 1. Questionnaire of survey I

Biographical Data:

Age ___ Height ____ Weight ___ Gender: Male / Female

Flying Habits

1. How many times do you fly in a year? 1 2-5 6-10 >10

2. On average, how many hours is each flight? 1-2 3-5 6-10 >10

3. What class do you normally fly? First Business Economy

Opinions

4. Do you think the current seats can be improved? Yes No

5. How much are you willing to pay for improvement (as a percentage of your fare)? <5% 5-10% 10-15% >15%

6. Which aspects of the seats do you think requires the most improvement? Head Rest Foot Rest Arm Rest Back Support Passenger Room

Problems in Flight

8. Any physical effects at the end of the flight?

____

Seat Aspects

9. Rate the following aspects of the seats according to Excellent (1), Good (2), Satisfactory (3), Fair (4) or Mediocre (5).

a. Height	1	2	3	4	5
b. Width	1	2	3	4	5
c. Seat Fabric	1	2	3	4	5
d. Cushioning Comfort	1	2	3	4	5
e. Head Rest	1	2	3	4	5
f. Foot Rest	1	2	3	4	5
g. Arm Rest	1	2	3	4	5
h. Lower Back Support	1	2	3	4	5
i. Functionality for Slumber	1	2	3	4	5
j. General Comfort Level	1	2	3	4	5

10. Which of these features would you most like to see in passenger seats on your next flight?

Adjustable Lower Back Support   Adjustable Head Rest   Foot Rest

Better Overall Cushioning   More Passenger Room

Other ______________________________

Appendix 2. Detailed results of survey I

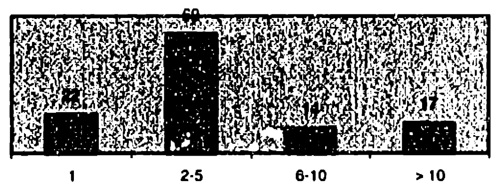
Biographical Data

Age (average) :	34 years	11.8
Height (average) :	172 cm	12.8
Weight (average) :	70 kg	18.0
Gender :	51 female / 71 male	

Flying habits

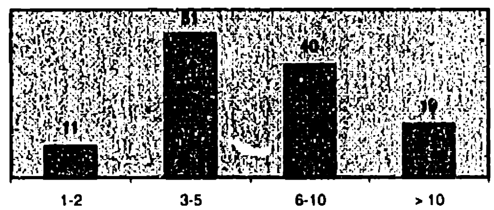
How many times do you fly in a year ?

1	22
2-5	69
6-10	14
> 10	17



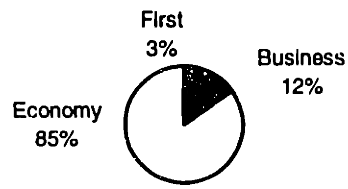
On average, how many hours is each flight ?

1-2	11
3-5	51
6-10	40
> 10	19



What class do you normally fly ?

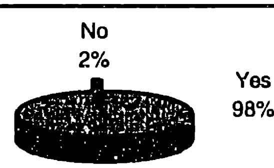
First	4
Business	15
Economy	104



Opinions

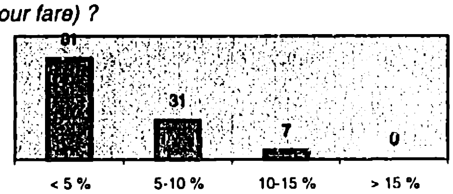
Do you think the current seats can be improved ?

Yes	120
No	2



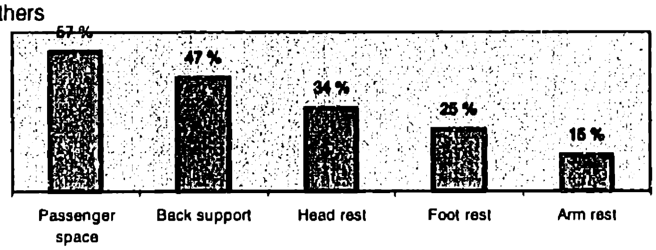
How much are you willing to pay for improvement (as a percentage of your fare) ?

< 5 %	81
5-10 %	31
10-15 %	7
> 15 %	0



Which aspects of the seats do you think requires the most improvement ?

Passenger space	70	(57 %)
Back support	57	(47 %)
Head rest	42	(34 %)
Foot rest	31	(25 %)
Arm rest	18	(15 %)
Others		



Problems in flight

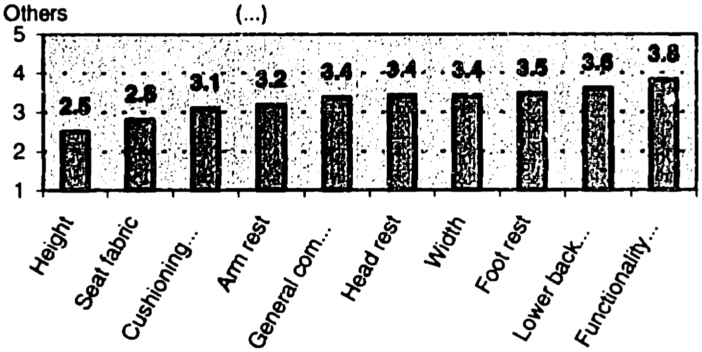
Any physical effects at the end of the flight ?

Pain in neck, back, legs, arms. Sore limbs. Tiredness, stiffness

Seat aspects

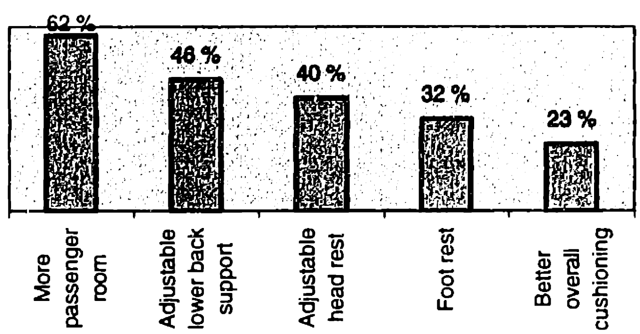
Rate the following aspects of the seats according to Excellent (1), Good (2), Satisfactory (3), Fair (4) or Mediocre (5).

Height	2.5
Seat fabric	2.8
Cushioning comfort	3.1
Arm rest	3.2
General comfort level	3.4
Head rest	3.4
Width	3.4
Foot rest	3.5
Lower back support	3.6
Functionality for slumber	3.8
Others	(...)



Which of these features would you most like to see in passenger seats on your next flight ?

More passenger room	76	(62 %)
Adjustable lower back support	57	(46 %)
Adjustable head rest	49	(40 %)
Foot rest	40	(32 %)
Better overall cushioning	29	(23 %)
Other	(...)	



Appendix 3. Questionnaire of survey II

AIRCRAFT PASSENGER SEAT QUESTIONNAIRE

Hi! We are graduate students in the Aeronautics and Astronautics Masters of Engineering program. We are designing an advanced aircraft seat that will provide passengers with better overall comfort. You may have received our first survey in January, where we asked you what aspects of the seat you thought needed the most improvement. The responses we got from that survey were extremely helpful. In fact, our industry supporter has indicated that such surveys are of great value to industry, and is increasing its level of support. This is an entirely different survey that will help us analyze how passenger comfort varies with different in-flight activities. We hope you will be able to spend some time filling out this questionaire. Your feedback will greatly aid us in our design.

Participation in this survey is voluntary and you may decline to answer any questions. All data will be collected in a confidential manner and will not be linked in any way to your identity. You will remain anonymous in any report that describes this work.

1. Biographical Data:

Age ___ Height ____ Weight ___ Gender: Male / Female

2. Flying Habits

i. How many times do you fly in a year? 1 2-5 6-10 >10

ii. What is the most common flight duration? 1-2 3-5 6-10 >10 hrs

iii. What class do you normally fly? First Business Economy

3. Flight Activities

Rate the level of comfort experienced during these activities:
(Excellent – 1, Good – 2, Neutral – 3, Poor – 4, Very Poor – 5)

a. Getting in/out of:

(i) aisle seat with front seat upright	1	2	3	4	5
(ii) aisle seat with front seat reclined	1	2	3	4	5
(iii) window seat w. front seat upright	1	2	3	4	5
(iv) window seat w. front seat reclined	1	2	3	4	5

(For the activities below, please also indicate the percentage of time spent on each activity.)

b. Reading	_____% of time	1	2	3	4	5
c. Working (writing, operating laptop, etc.)	_____% of time	1	2	3	4	5

a. Eating _____% of time 1 2 3 4 5

b. Sleeping _____% of time 1 2 3 4 5

f. Chatting _____% of time 1 2 3 4 5

4. Preferences:

a) How much would you desire a seat that provides privacy/isolation? (Very much) 1 2 3 4 5 (Not at all)

b) Do you usually recline your seat during flight? Yes____No____

a. How disturbed are you when the person in front reclines his/her seat? (Very much) 1 2 3 4 5 (Not at all)

b. How much would you be willing to trade off the recline feature of the seat for an adjustable back support? (Very much) 1 2 3 4 5 (Not at all)

e) Would you rather have the magazine/safety card storage pocket below your seat than in front of you? Yes____ No____

f) How much would you desire:

(i) a sliding in/out tray? (Very much) 1 2 3 4 5 (Not at all)

(ii) a tiltable tray (Very much) 1 2 3 4 5 (Not at all)

(iii) a height-adjustable tray (Very much) 1 2 3 4 5 (Not at all)

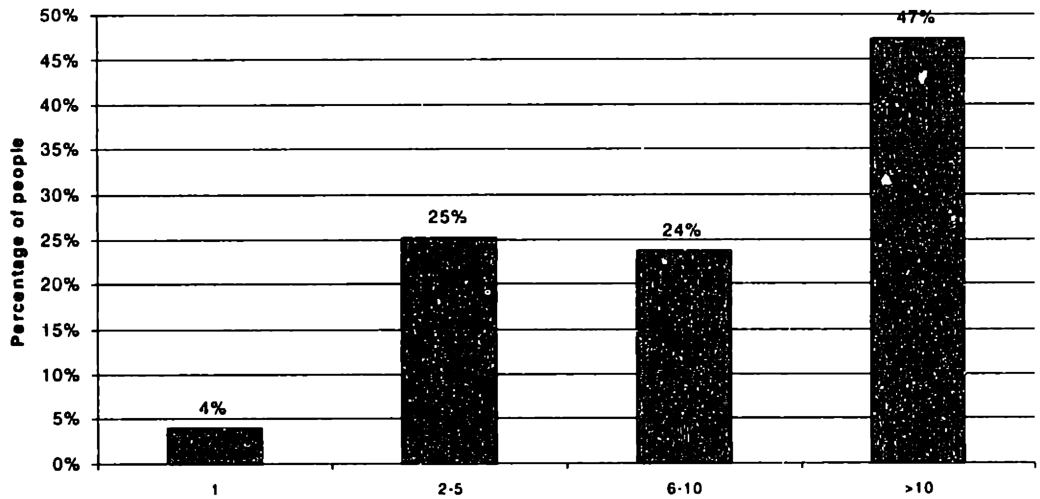
Rank the following seat fabric colors in order of preference:

Blue____ Green_____ Blue-green_____ Red_____

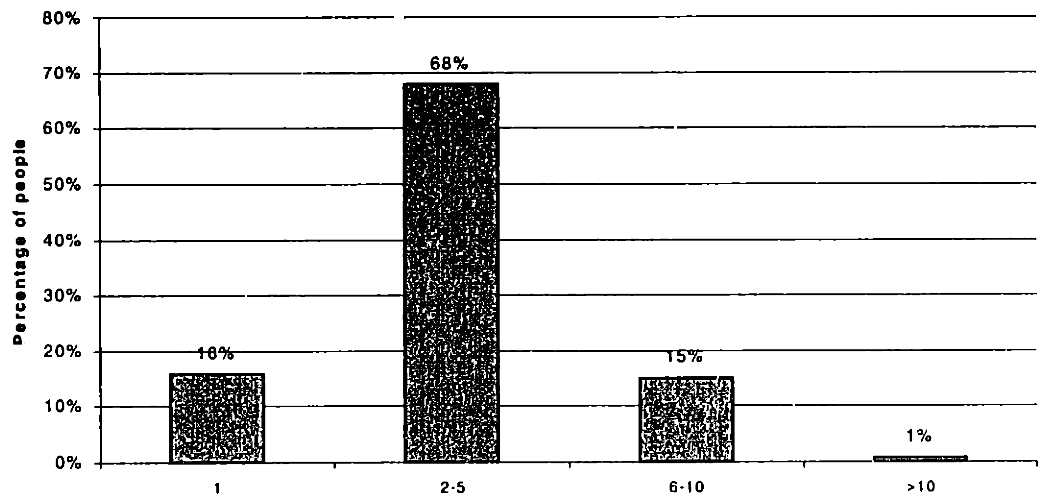
Done? You can now fold up this questionnaire and drop it in a campus interdepartmental mailbox for delivery to the address below. Thank you very much for your cooperation!

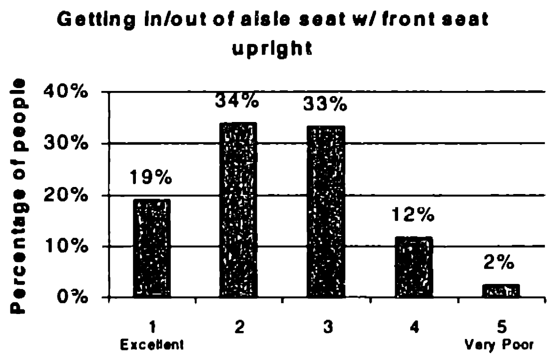
Appendix 4. Additional results of survey II

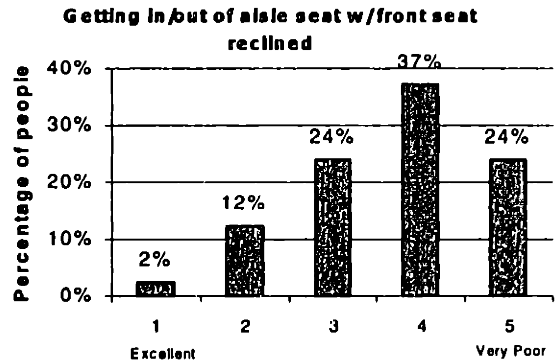
Flights per Year

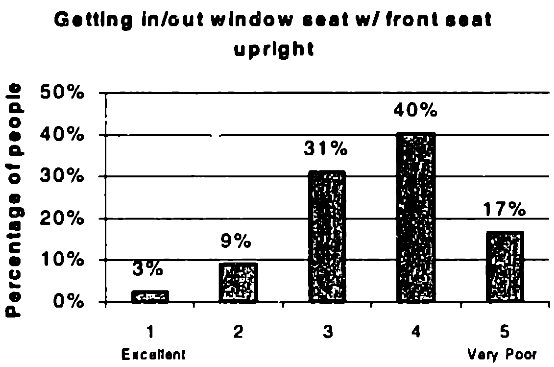


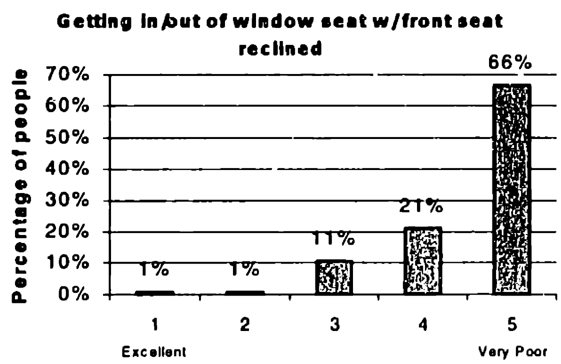
Hours per Flight

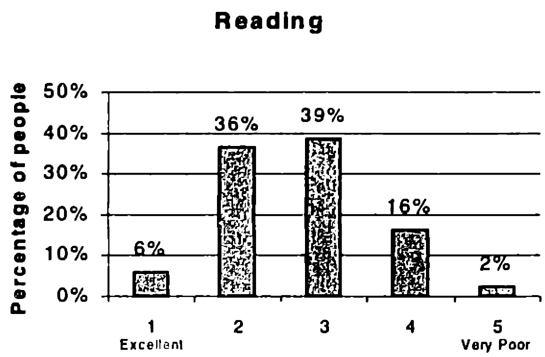


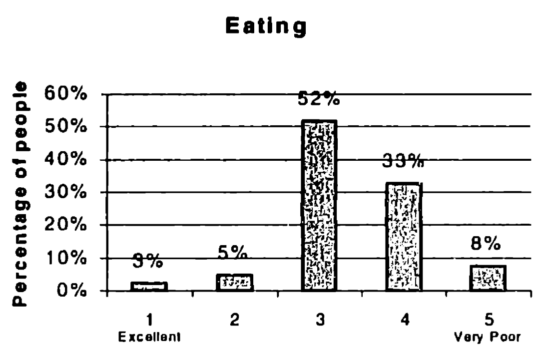

Getting in/out of aisle seat w/ front seat upright
Percentage of people
40%
30%
20%
10%
0%
19%
34%
33%
12%
2%
1
Excellent
2
3
4
5
Very Poor

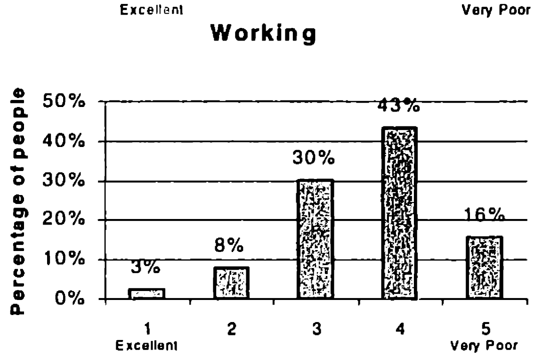

Getting in/out of aisle seat w/front seat reclined
Percentage of people
40%
30%
20%
10%
0%
2%
12%
24%
37%
24%
1
Excellent
2
3
4
5
Very Poor

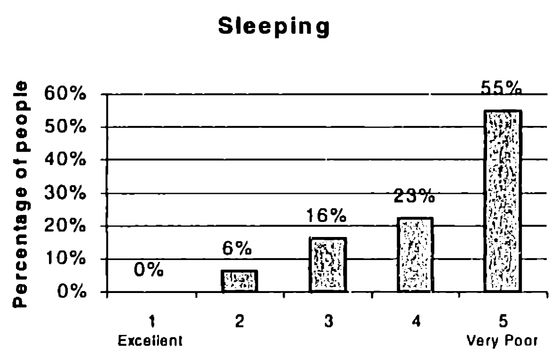

Getting in/out window seat w/ front seat upright
Percentage of people
50%
40%
30%
20%
10%
0%
3%
9%
31%
40%
17%
1
Excellent
2
3
4
5
Very Poor

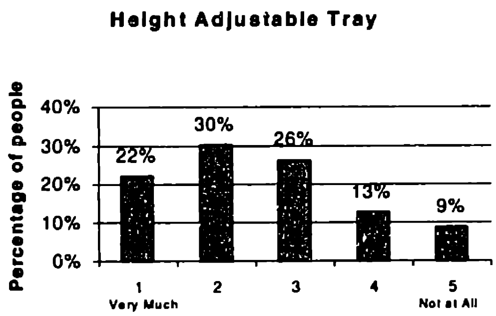

Getting in/out of window seat w/front seat reclined
Percentage of people
70%
60%
50%
40%
30%
20%
10%
0%
1%
1%
11%
21%
66%
1
Excellent
2
3
4
5
Very Poor

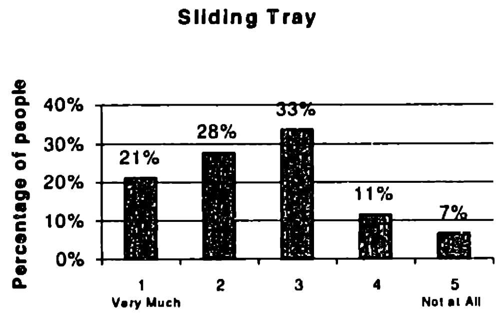

Reading
Percentage of people
50%
40%
30%
20%
10%
0%
6%
36%
39%
16%
2%
1
Excellent
2
3
4
5
Very Poor

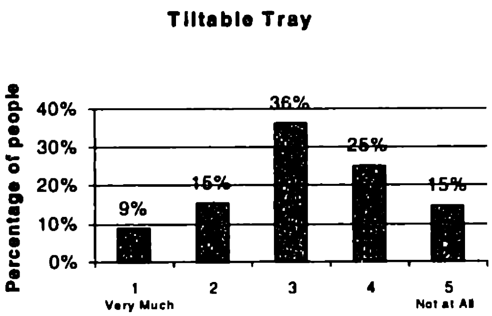

Eating
Percentage of people
60%
50%
40%
30%
20%
10%
0%
3%
5%
52%
33%
8%
1
Excellent
2
3
4
5
Very Poor

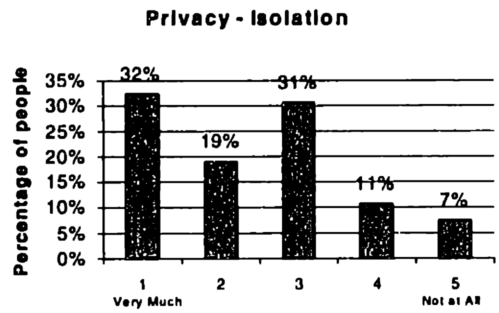

Working
Percentage of people
50%
40%
30%
20%
10%
0%
3%
8%
30%
43%
16%
1
Excellent
2
3
4
5
Very Poor

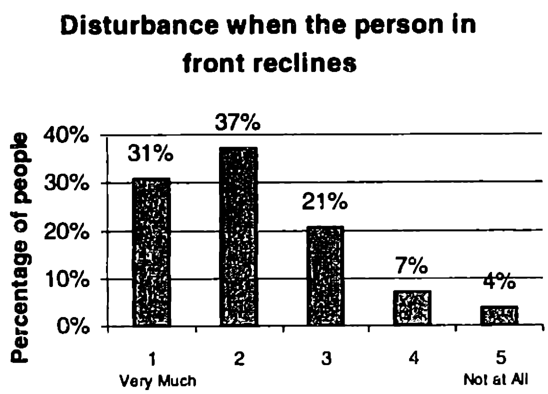

Sleeping
Percentage of people
60%
50%
40%
30%
20%
10%
0%
0%
6%
16%
23%
55%
1
Excellent
2
3
4
5
Very Poor

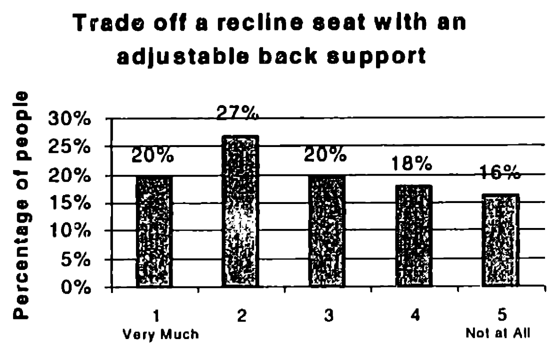

Height Adjustable Tray
Percentage of people
40%
30%
20%
10%
0%
22%
30%
26%
13%
9%
1
Very Much
2
3
4
5
Not at All


Sliding Tray
Percentage of people
40%
30%
20%
10%
0%
21%
28%
33%
11%
7%
1
Very Much
2
3
4
5
Not at All


Tiltable Tray
Percentage of people
40%
30%
20%
10%
0%
9%
15%
36%
25%
15%
1
Very Much
2
3
4
5
Not at All


Privacy - Isolation
Percentage of people
35%
30%
25%
20%
15%
10%
5%
0%
32%
19%
31%
11%
7%
1
Very Much
2
3
4
5
Not at All


Disturbance when the person in front reclines
Percentage of people
40%
30%
20%
10%
0%
31%
37%
21%
7%
4%
1
Very Much
2
3
4
5
Not at All


Trade off a recline seat with an adjustable back support
Percentage of people
30%
25%
20%
15%
10%
5%
0%
20%
27%
20%
18%
16%
1
Very Much
2
3
4
5
Not at All

Appendix 5. Tutorial on QFD (Quality Function Deployment) matrices

QFD means "**Quality Function Development.**" There are different kinds of QFD matrices. The first type of matrix is called the Technical Requirement matrix. The next matrix in the process of QFD is the Product Design matrix.

Technical Requirement matrix

Bases for this matrix are the customer needs for which technical requirements need to be found. Those requirements are not specific features yet, but just requirements towards which the needs lead.

The idea is to rank in order of importance the technical requirements found to fulfill customer needs. But human bias must be minimized: people who deal with QFD matrices must rank those requirements fairly, according to what is important for customers and not to what they think is important. This is the purpose of the QFD matrix.

A QFD matrix looks as follows:

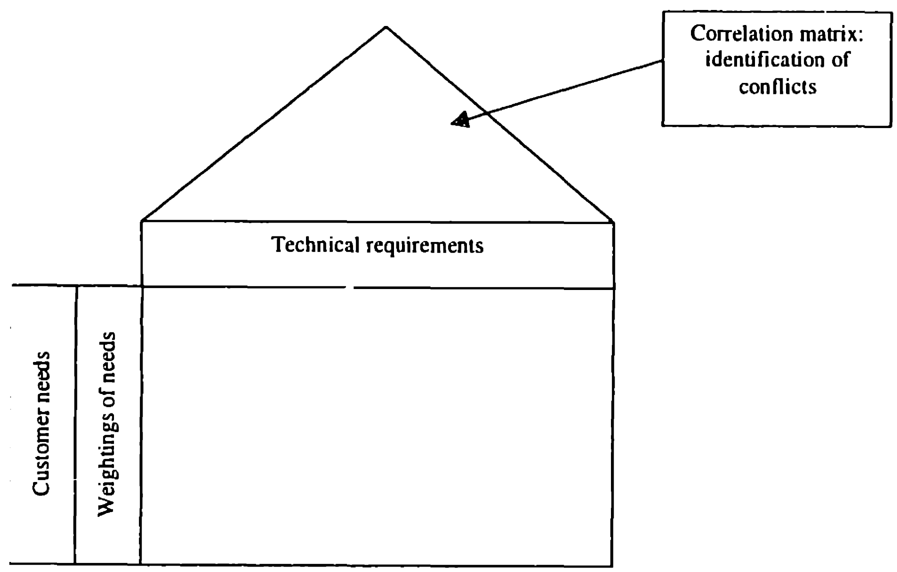


Figure 41: Aspect of QFD matrix

Customer needs are written in the rows of the matrix. Each need is allocated a weighting, according to its importance for the customer. These weightings are chosen arbitrarily, but must reflect the degree of importance of the needs.

In the columns technical requirements are written. They come from brainstorming sessions and are designed to fulfill one or several customer needs.

For each technical requirement, the way it fulfills the needs is ranked with four numbers: 0 (no influence on the need), 1 (small influence), 3 (influences the need) and 9 (completely fulfills the need). The reason for these huge differences between the numbers is to allow an easy differentiation between the technical requirements at the end. Indeed for each technical requirement, we sum the results of the product of the corresponding column times the weight of the needs. Those which score the most are considered to be the most important ones. Nevertheless, those numbers (0,1,3,9) are arbitrary and a more refined scale could be chosen.

The last element is the top of the matrix: the crosses on its hat represent the conflicts (when they occur) between technical requirements. Thus we can identify the requirements that can not be implemented simultaneously.

Product design matrix

The idea is the same. But instead of beginning with customer needs, we begin with the technical requirements resulting from the first matrix. Now we have to find physical features and concepts and rank them with the same idea: the same numbers 0, 1, 3, 9 are used but once again, these numbers are arbitrary and another scale could be used.

Principles of QFD are here simplified but more information can be found in Ref. [16].

Appendix 6. Experimental protocol

Experimental Study on

the comfort of a passenger aircraft seat

EXPERIMENTAL PROTOCOL

Objective

To evaluate the comfort of two seat concepts designed by the team of MEng students from the Aero/Astro Department and compare them to an actual aircraft seat.

The first concept is a non-reclinable seat, the second one uses webbing instead of cushioning.

Four seats in total will be used for the experiments: two seats designed by the team and two actual seats. Aircraft environment is to be represented as precisely as possible. See attached figures.

Setup

Recruiting of experimental subjects will begin in April 1999. 12 subjects will be solicited (18 years or older) by e-mails to faculty members and students from all engineering school at MIT and by posters around MIT.

Here is a draft of the e-mail and the poster that will be sent:

"Hi!

We are a group of MIT Master of Engineering students from the Department of Aeronautics and Astronautics. We are working on a project to design aircraft passenger seats more comfortably than the ones already existing in aircraft today.

We have designed and built two new seat concepts and we need to know if we really achieved our goal: a truly comfortable seat!

We are looking for people to test the seats.

You would have to spend 9 hours in total, 3 hours in each seat (our two seats and an actual aircraft seat) in three separate days. For each seat you will be asked to perform specific tasks : sitting, reading, eating, sleeping. And filling in questionnaires!

You will be paid $10/hour.

If you are interested, please send us an e-mail specifying your height, your age, your sex and the time you would be available to come and test the seats. The tests should go from April, 16 to April, 23.

All data will be collected in a confidential manner and you may decline to participate to this experiment.

Thank you!"

Subjects may be accepted or rejected according to their height, because we need to cover the same spectrum of sizes the airline companies do (i.e. from the 5^{th} percentile to the 95^{th} percentile of the human population)

They will be paid $10 an hour as a compensation.

Experiments will be conducted at MIT. Two to three subjects will participate to the test at the same time.

Procedures

For each experiment subjects will spend three hours per day for three days. There will be two to three subjects at a time. They will be asked to perform the tasks described below for each of the three seats. The questionnaires (which are attached) are aimed at determining how comfortable they felt during those tasks.

A final questionnaire will be distributed to rank the overall comfort of the seat.

1. **Pressure mapping**: the subject will sit on a pad (pressure pad) and the experimenter will take maps of the pressure distribution directly on a computer. Three maps will be taken: one while the subject is sitting correctly, the second one in a slouched position and then in a working position.
2. **Sitting**: the subject will be asked to do nothing but remain seated and try to find his/her most comfortable sitting position.
3. **Questionnaire 1**: the subject will fill in questionnaire 1.
4. **Break**: the subject will be allowed a short break to get up and take a walk if he/she likes.
5. **Working**: the subject will be asked to perform any work task (reading, writing, using a computer) which requires the use of the tray.
6. **Questionnaire 2**: the subject will fill in questionnaire 2.
7. **Break**.
8. **Eating**: refreshments will be served.

Questionnaire 3: the subject will fill in questionnaire 3.

9. **Break.**
10. **Rest period**: the subject will be asked to rest on the seat and test the comfort of the lumbar support.

11. **Questionnaire 4**: the subject will fill in questionnaire 4 and give general comments on the seat.

The timeline is attached.

All twelve tasks will then be repeated in each of the next two seat types.

Subjects will be free to leave and use the restroom at any point in the study.

Personal data

Sample personal data to be taken for each subject (on a voluntary basis) include age, height and gender. Under no circumstances will these be linked to the names of the subject (anonymity preserved).

Narmada
e-mail: narmada@mit.edu

Experimental Study
on the comfort of a passenger aircraft seat

INFORMATION ON EXPERIMENT

Participation in this study is voluntary. You are free to withdraw your consent and to discontinue participation in the project or activity at any time, without prejudice. Please feel free to refer to the above contact if you have any question concerning the purpose, procedures, or risks associated with this experiment.

All data will be collected in a confidential manner, and will not be linked in any way to your identity. You will remain anonymous in any report that describes this work.

This study is designed to evaluate the comfort of two economy class aircraft seats with new features, and to test these features. You will be asked to perform the following tasks:

1. **Pressure mapping**: you will sit on a pad (pressure pad) and the experimenter will take maps of the pressure distribution directly on a computer. Three maps will be taken: one while you are sitting correctly, the second one in a slouched position and then in a working position.
2. **Sitting**: you will be asked to do nothing but remain seated and try to find your most comfortable sitting position. The safety belt will be fastened.
3. **Questionnaire 1**: you will fill in questionnaire 1.
4. **Break**: you will be allowed a short break to get up and take a walk if you like.
5. **Working or Rest Period**: you will be asked to perform any work task (reading, writing, using a computer) which requires the use of the tray. You are also welcome to sleep if you like.
6. **Questionnaire 2**: you will fill in questionnaire 2.
7. **Break.**
8. **Eating**: refreshments will be served.
9. **Questionnaire 3**: you will fill in questionnaire 3.
10. **Break.**
11. **Working or Rest period**: you will be asked to rest on the seat and test the comfort of the lumbar support. You will also be able to work.

12. **Questionnaire 4**: you will fill in questionnaire 4 and give general comments on the seat.

You are welcome to get up and stretch your legs during break periods. You may go to the restroom at any point during the study.

But please, if possible, remain seated during the other periods.

Refreshments will be provided.

You will be paid $10 an hour.

Each sequence presented above is expected to take three hours and will be repeated for each of the three seats.

The experimenter will be in your presence during the entire experiment.

Spending several hours in an airplane is known to be uncomfortable so some discomfort is expected. But if this feeling of discomfort happens to be unbearable, feel free to interrupt the test right away and inform the experimenter. If you decide to terminate the experiment, you will receive $10 for each hour you participated.

INFORMED CONSENT

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid, emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the Investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights.*

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, MIT 253-6787, if I feel I have been treated unfairly as a subject.

I volunteer to participate in this experiment, with the understanding that I may discontinue my participation at any time. I have been informed as to the nature of this experiment and the risks involved, and agree to participate in the experiment.

Date____________Name_______________________Signature_________________

* Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.

Experimental Study on the comfort of a passenger aircraft seat

Personal data

Age:

Height:

Sex:

For the experimenter use

Seat type:

Subject number:

Seat type:

Subject number:

Questionnaire 1: sitting

Overall comfort	very comfortable	1	2	3	4	5	very uncomfortable
arm	very comfortable	1	2	3	4	5	very uncomfortable
thigh	very comfortable	1	2	3	4	5	very uncomfortable
leg	very comfortable	1	2	3	4	5	very uncomfortable
foot	very comfortable	1	2	3	4	5	very uncomfortable
neck	very comfortable	1	2	3	4	5	very uncomfortable
shoulder	very comfortable	1	2	3	4	5	very uncomfortable
back	very comfortable	1	2	3	4	5	very uncomfortable
lumbar	very comfortable	1	2	3	4	5	very uncomfortable
hip	very comfortable	1	2	3	4	5	very uncomfortable
head	very comfortable	1	2	3	4	5	very uncomfortable

How was the level of comfort hen the front seat aws reclined (if applicable)?:

Comments (if any):

Seat type:

Subject number:

Questionnaire 2: working/resting

What tasks have you performed and how long did these tasks take?

____

____

____

____

Overall comfort	very comfortable	1	2	3	4	5	very uncomfortable
arm	very comfortable	1	2	3	4	5	very uncomfortable
thigh	very comfortable	1	2	3	4	5	very uncomfortable
leg	very comfortable	1	2	3	4	5	very uncomfortable
foot	very comfortable	1	2	3	4	5	very uncomfortable
neck	very comfortable	1	2	3	4	5	very uncomfortable
shoulder	very comfortable	1	2	3	4	5	very uncomfortable
back	very comfortable	1	2	3	4	5	very uncomfortable
lumbar	very comfortable	1	2	3	4	5	very uncomfortable
hip	very comfortable	1	2	3	4	5	very uncomfortable
head	very comfortable	1	2	3	4	5	very uncomfortable
use of tray	very easy	1	2	3	4	5	very uneasy
comfort with tray	very comfortable	1	2	3	4	5	very uncomfortable

If those answers differ from task to task, please state it here:

Did the recline of the seat affect your abiliy to work?

Comments (if any):

Seat type:

Subject number:

Questionnaire 3: eating

Overall comfort	very comfortable	1	2	3	4	5	very uncomfortable
arm	very comfortable	1	2	3	4	5	very uncomfortable
thigh	very comfortable	1	2	3	4	5	very uncomfortable
leg	very comfortable	1	2	3	4	5	very uncomfortable
foot	very comfortable	1	2	3	4	5	very uncomfortable
neck	very comfortable	1	2	3	4	5	very uncomfortable
shoulder	very comfortable	1	2	3	4	5	very uncomfortable
back	very comfortable	1	2	3	4	5	very uncomfortable
lumbar	very comfortable	1	2	3	4	5	very uncomfortable
hip	very comfortable	1	2	3	4	5	very uncomfortable
head	very comfortable	1	2	3	4	5	very uncomfortable
use of tray	very easy	1	2	3	4	5	very uneasy
comfort with tray	very comfortable	1	2	3	4	5	very uncomfortable

Comments (if any):

Seat type:

Subject number:

Questionnaire 4: working/resting

What tasks have you performed and how long did these tasks take?

____

____

____

____

Overall comfort	very comfortable	1	2	3	4	5	very uncomfortable
arm	very comfortable	1	2	3	4	5	very uncomfortable
thigh	very comfortable	1	2	3	4	5	very uncomfortable
leg	very comfortable	1	2	3	4	5	very uncomfortable
foot	very comfortable	1	2	3	4	5	very uncomfortable
neck	very comfortable	1	2	3	4	5	very uncomfortable
shoulder	very comfortable	1	2	3	4	5	very uncomfortable
back	very comfortable	1	2	3	4	5	very uncomfortable
lumbar	very comfortable	1	2	3	4	5	very uncomfortable
hip	very comfortable	1	2	3	4	5	very uncomfortable
head	very comfortable	1	2	3	4	5	very uncomfortable

If applicable:

use lumbar support	very easy	1	2	3	4	5	very uneasy
lumbar support	very comfortable	1	2	3	4	5	very uncomfortable

If those answers differ from task to task, please state it here:

How was the level of comfort when the front seat was reclined (if applicable):

Comments (if any):

Seat type:

Subject number:

General comments about the seat

What was your general feeling about the seat you have just tried?

For the webbed seat and the forward-sliding seat: how does this seat compare to a tourist-class seat in use?

____	____	____	____	____
Much better	Better	Comparable	Worse	Much worse

Appendix 7. Description of the Tekscan pressure pads system

The team used the Tekscan pressure pad system. It is a pad made of sensors which is then connected to the computer. There are several types of sensors, with various shape and size. The team had two different kinds of pads: one for the bottom and one for the back. The bottom one was made of 38 rows and 41 columns. Row and column spacing is 0.4", so each single sensor cell had an area of contact of 0.16 in^2. The back pad was an array of 42 rows and 48 columns.

The picture that appears than on the monitor shows the color of each sensor according to the pressure it is subjected to. So we have a combination of little squares. To make the picture more attractive to the human eye, there are several ways to smooth it: squares can be averaged with their neighbors, or one can average only the edges of the squares.

Here are some functions the software allows us to implement for the maps:

- ✓ **2-D** or **3-D** maps.
- ✓ **Static mapping**: A picture of the distribution is taken at a time t.
- ✓ **Dynamic mapping**: A video of the pressure distribution is taken for a certain period of time. Dynamic changes can then be seen.
- ✓ **Cross sections**: Focus can be made on a particular line of the body and sketch the pressure distribution or the force along it.
- ✓ **Force vs. time** and **Pressure vs. time**: Along the same lines, from dynamic maps, force (or pressure) can be sketched as a function of time.

Before using a pad, one has to be sure that it is calibrated. Thus the sensor can have a scale of pressure it can refer to. The calibration is not the same for the bottom and the back sensors, because forces applied are less on the back.

The same calibrations were kept for all subjects throughout the experiments.

Appendix 8. Detailed results of experiments

Webbing seat: Questionnaire 1

		Biographical				Questions											Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*comfort w/ seat reclined*	*others*
XT					M	3	2	2	2	2	4	4	4	2	3	5		head rest too high
1*	3	23	6'6	285	M	2	3	3	3	3	2	2	1	2	3	2	-	reclined bad for legs and esp knees - back support really comfy
2	1	27	5'11 3/4	180	M	2	3	2	2	2	3	1	1	4	2	2		I have an easily aggrevatible lower back, and although I like the springiness of the tight mesh, the lumbar support is WAY TOO LUMPY
3	2	22	5'2	120	F	3	1	1	1	1	1	1	2	4	2	3		
4	1	32	5'4	145	M	3	4	3	4	3	2	2	2	2	2	2		arm rest low, face of arm rest should be softer and larger
5*	2	21	5'5	178	M	2	3	3	2	3	4	2	1	2	3	4		back support excellent. Feels really good for middle back
6	1	20	5'10	178	M	2	2	3	2	1	4	2	1	3	3	4	+	head rest too far from person (should be moved forward) - too much pressure on the lumbar area (nothing more than a slight discomfort) - hip/buttocks area too flat (more comfortable with deeper thigh/butt indentions ?)
7*	3	23	5'9	150	F	1	1	1	1	1	1	1	1	1	1	2		webbed back offers increased support to upper back and shoulders - head rest not as comfy as lumbar seat head rest, too low
8	2	24	6'1	190	M	3	4	3	3	3	4	4	2	4	3	2		webbed seat a little hard at beginning, but quite comfy; No lumbar support: hurts; Head rest comfy but too small; Should be a neck support; (if sitting straight, comfy, but if slouched, neck not supported anymore); Arm rests not wide enough and not comfy at all; hurts shoulders
9	1	21	5'10	165	M	2	3	2	3	3	2	1	1	3	3	2		webbed backing very comfortable
10*	2	21	5'7	145	M	2	2	2	2	2	3	3	1	1	2	3		lumbar supp is fine but head and neck have nothing to rest on unless slouched
11	2	30	5'6.5	120	F	2	3	3	4	4	3	3	2	3	3	3		
12*	2	24	5'9	150	M	1	2	2	2	2	3	3	2	2	3	3		

Webbing seat: Questionnaire 2

		Biographical				Questions														Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Tasks*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*use of tray*	*comfort with tray*	*comfort w/ seat reclined*	*others*
XT					M	sleeping, chat (15mn)	4	2	2	2	2	5	4	4	2	3		2	2		head rest too high
1*	3	23	6'6	285	M	reading (35mn), resting (10mn)	2	4	4	3	4	2	2	1	1	3	2	3		-	very little room to lean forward to work - hard to lean chair back to be comfy
2	1	27	5'11 3/4	180	M	reading (10mn), chat (20mn), rest (5mn)	2	3	2	2	1	4	2	1	5	1	3	2	1		lumbar "rock" should be removed or softened - height adjustment tray increased comfort and ease of filling out this form
3	2	22	5'2	120	F	slept (45mn)	1	1	1	1	1	1	2	2	2	1	4	4	1		a bit distracted to have knee up against front seat
4	1	32	5'4	145	M	reading (15mn)	2	2	3	2	2	2	2	1	2	3	2	1	2		tray okay fot thigh, but looks likely to break if heavy stuff on it
5*	2	21	5'5	178	M	talking, nap, pulled out tray table	3	2	3	3	3	4	1	1	1	2	4	3	4		neck support not adjust so hits head and not neck. Adjusting tray is very difficult
6	1	20	5'10	178	M	working (45mn)	3	3	4	4	3	2	1	1	1	4	2	2	2	-	not enough arm & leg space - interfernce of room with the second passenger
7*	3	23	5'9	150	F	reading, working	1	1	1	1	1	2	1	2	2	1	2	3	1		decrease in head/neck comfort due to leaning forward - tray table very comfy - back a little bit uncomfy
8	2	24	6'1	190	M	working (1hour)	2	4	3	3	3	3	4	2	3	3	3	3	1		can't use head rest when working b/c leaning forward, tray very useful and comfy (don't have too lean too much so back better and arms better b/c on the tray and not on arm rests)
9	1	21	5'10	165	M	homework (40mn)	2	4	3	3	3	3	2	2	3	3	2	2	1	=	
10*	2	21	5'7	145	M	reading (15mn), sleeping (10mn)	2	2	2	2	2	3	2	1	2	2	2	2	2		neck support would be great
11	2	30	5'6.5	120	F	reading	3	3	3	3	4	3	3	2	3	3	3	2	3	-	no foot rest. Did not know for the tray adjustability
12*	2	24	5'9	150	M	reading (1hr)	2	2	2	2	2	3	2	2	2	3	3	1	1		pillow would be a good idea

Webbing seat: Questionnaire 3

		Biographical				Questions													Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*use of tray*	*comfort with tray*	*comfort w/ seat reclined*	*others*
XT					M	2	1	2	2	2	3	3	3	2	3		2	2		
1*	3	23	6'6	285	M	2	3	4	3	3	3	2	2	2	3	3	3	3		
2	1	27	5'11 3/4	180	M	2	1	1	2	1	4	2	2	5	2	2	3	1		
3	2	22	5'2	120	F	1	1	1	1	1	1	1	1	1	1	1	4	1		very comfortable b/c tray adjustable. (difficult to adjust)
4	1	32	5'4	145	M	2	2	2	3	3	2	2	2	3	3	2	2	2		
5*	2	21	5'5	178	M	2	3	3	2	3	2	1	1	2	3	4	3	4		neck support not adjust so hits head and not neck. Adjusting tray is very difficult
6	1	20	5'10	178	M	2	4	3	2	2	2	2	3	2	3	1	1	1		seat & tray very well suited for eating process - does not require use of head rest (for eating) - space is less of a problem when eating except for arm/elbows which still interfere heavily
7*	3	23	5'9	150	F	2	1	1	1	1	2	1	2	2	1	2	3	1		
8	2	24	6'1	190	M	2	3	3	2	2	2	3	2	3	3	2	2	1		tray helps for good position. Head rest useless
9	1	21	5'10	165	M	2	3	3	3	3	3	2	2	3	3	2	1	1		
10*	2	21	5'7	145	M	2	2	2	2	2	2	2	1	1	2	2	2	2		
11	2	30	5'6.5	120	F	2	3	2	3	4	3	3	2	2	2	3	3	3		
12*	2	24	5'9	150	M	1	2	3	2	2	2	2	1	2	2	4	1	1		head rest too much backwards

Webbing seat: Questionnaire 4

		Biographical				Questions														Comments	
Subject number	Exp number	Age	Height	Weight	Gender	Tasks	Overall comfort	arm	thigh	leg	foot	neck	shoulder	back	lumbar	hip	head	use of lumbar support	lumbar support	comfort w/ seat reclined	others
XT					M	sleeping	5	2	2	2	2	5	3	3	2	4					
1*	3	23	6'6	285	M	reading (45mn)	2	3	4	4	3	3	2	2	2	4	2				
2	1	27	5'11 3/4	180	M	chat (20mn), reading (20mn)	2	2	1	1	1	4	2	1	5	2	2				really like the mesh back
3	2	22	5'2	120	F	slept, talked	2	2	1	1	1	3	3	4	4	4	4			-	knees against seat
4	1	32	5'4	145	M	talkgin(50mn), reading(30mn)	2	2	2	3	3	2	2	2	2	2	2				
5*	2	21	5'5	178	M	relaxed and talked	2	3	3	4	3	4	2	1	2	3	4			+	loved that tray did not move forward when front seat was reclined
6	1	20	5 10	178	M	studying, talking (30mn), resting	2	4	3	2	2	1	2	3	2	2	1				discomfort did not increase appreciably after several hours in the seat
7*	3	23	5'9	150	F	working, talking	2	1	1	1	1	2	1	3	3	1	2			=	lower back and back in gen became more and more uncomfy w/ time - when front seat rec, failry comfy but a small protion of table area reduced
8	2	24	6'1	190	M	working (1hour)	2	3	4	3	2	3	3	2	2	2	3				tray helps for good position. But too much pressure on thighs
9	1	21	5'10	165	M	homework (1h)	2	3	3	3	3	3	2	2	3	3	3				
10*	2	21	5'7	145	M	studying (1hour)	2	2	2	2	2	3	2	1	1	2	2				
11	2	30	5'6.5	120	F	reading, resting, thunb-doodling	3	3	2	3	4	3	3	2	2	2	3			-	less space, less comfy
12*	2	24	5'9	150	M	reading (2hr)	2	2	3	3	2	3	2	2	4	3	3			=	okay w/ front seat rec: enough space - using inflatable lumb supp and adj head rest would be perfect

Webbing seat: Final comments

		Biographical				Comments					
							Compare with...				
Subject number	Exp number	Age	Height	Weight	Gender	General feeling	Much better	Better	Comparable	Worse	Much worse
XT					M	real pain in neck so failed to notice other feelings				1	
1*	3	23	6'6	285	M	very comfy back. Much better than others. Adj tray is very good as well	1				
2	1	27	5'11 3/4	180	M	mesh pretty cool, probably great weight savings, supports upper back very well - lumbar support extremely awkward & uncomfortable, especially with my bad lower back		0.5	0.5		
3	2	22	5'2	120	F	really liked tray. No head support so neck and shoulders sore. Arm rests and cushion good. Mesh seat comfortable, although lacked lumbar and back support (lumbar supp uncomfy and hard)			1		
4	1	32	5'4	145	M	overall comfort good. Arm rest too hard, low, narrow				1	
5*	2	21	5'5	178	M	more comfortable for back, but lacks neack area. Hard to sleep because of that. Knees hurt after a while	1				
6	1	20	5'10	178	M	better than a standard tourist class seat - fewer "pressure points" of discomfort - very little variation in comfort level over time - head rest could have been moved closer to the head so it could be used more easily - lumbar area felt excess pressure on it at the beginning but then it passed		1			
7*	3	23	5'9	150	F	great shoulder support - adj head rest preferable - adj tray is a plus - lower back supp uncomfy w/ time: lumbar support would be a nice combo with webbed backing		1			
8	2	24	6'1	190	M	tray provides bettre position. Back support much bettre. Head rest too far for working. Arm rest bad and seat too narrow (but height of tray also helps for this). Fell less tired than with a regular seat. Lack of lumbar support not a pb when working		1			
9	1	21	5'10	165	M	more comfortable than other airline seats		1			
10*	2	21	5'7	145	M	great for back and lumabr, but really lacks neck/head rest - therefore great for working/eating but not for sleeping		1			
11	2	30	5'6.5	120	F	generally better than reg seats, except for foot b/c no foot rest		1			
12*	2	24	5'9	150	M	very comfy except for lumbar supp (hard) - head rest too much backwards - pillow would be welcome		1			

Forward-sliding seat: Questionnaire 1

		Biographical				Questions											Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*comfort w/ seat reclined*	*others*
N					M	3	3	4	3	3	2	3	3	2	3	1		
1	2	23	6'6	285	M	2	3	4	3	3	2	2	3	2	3	2		wish lumbar supp were taller - a little too narrow - head rest an inch too short - sliding back hard to use and eliminates leg room
2	2	27	5'11 3/4	180	M	2	2	1	1	1	3	1	2	2	2	2		much better lumbar support than webbed seat
3	1	22	5'2	120	F	2	1	1	1	1	2	2	2	2	1	2		large lumbar support --> body too straight --> can not use head rest
4	2	32	5'4	145	M	3	2	2	3	3	4	3	2	2	2	5		head support makes head very uncomfy b/c pushed too much forward
5																		
6	2	20	5'10	178	M	2	2	1	2	1	1	3	1	1	2	1		overall comfort 1.5 (not 1 b/c not perfect). Pump in neck would be wonderful, would make shoulders feel more comfy b/c wouldn't be floating as much. Arms felt crampy (cushion not good?)
7	1	23	5'9	150	F	1	2	2	2	3	1	1	1	1	1	1		left foot align with the seat bracket in front of me, does not allow me to put foot where it would go naturally
8	3	24	6'1	190	M	2	3	3	2	2	3	2	1	3	3			lumbar support very comfy - headrest a little far when seated properly - armrest too small - seat not wide enough
9	2	21	5'10	165	M	4	4	2	3	3	5	4	4	2	3	4		
10	1	21	5'7	145	M	2	3	3	2	2	2	3	1	2	2	1		like the inflatable back support most - head rest a little low, would be great if adjustable
11	3	30	5'6.5	120	F	4	4	3	3	3	3	3	4	4	3	4		webbed seat obviously ths most comfy
12	1	24	5'9	150	M	2	2	3	2	2	4	3	2	1	2	1		head too much backwards

Forward-sliding seat: Questionnaire 2

		Biographical				Questions														Comments
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Tasks*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*use of tray*	*comfort with tray*	*comfort w/ seat reclined*	*others*
N					M	reading brochure, taking notes	2	3	4	3	3	3	3	2	2	3			2		
1	2	23	6'6	285	M	reading (25mn), resting (20mn)	3	3	4	3	3	2	3	4	2	3	2	3	2		adj tray height good, mechanism could be improvred - good lumb support - okay for shoulders - bad in-between
2	2	27	5'11 3/4	180	M	chatting (15mn), reading w/ tray raised (40mn)	2	2	1	1	1	3	1	2	2	1	3	2	2		lumbar pillow nearly deflated when seat reclined. Reclining does not allow much leg room, and effective seat becomes very shallow. Bad design
3	1	22	5'2	120	F	studying, talking	2	1	1	1	1	2	2	3	3	1	1	4	1		tray difficult to adjust, once adjusted it was excellent (much more than a standard one)
4	2	32	5'4	145	M	reading (20mn), resting (10mn)	2	2	2	2	2	3	3	3	3	3	4	2	2		
5																					
6	2	20	5'10	178	M	reclined seat, talked, rested. Fiddled with tray	2	2	2	2	1	2	2	1	1	2	1	4	3		seat adjustments pretty awkward. Perhaps more convex head rest would feel bettre for neck. Tray diff to adjust, makes it bothersome to use. Rating actually about 2.4
7	1	23	5'9	150	F	talking (20mn), working (40mn)	1	2	2	2	3	1	2	1	1	1	1	2	2		working with tray down --> head/neck/shoulders had no contact with seat - excellent lumbar support, seem to place most of my weight on it
8	3	24	6'1	190	M	reading (30mn), restting(10mn)	3	3	4	3	3	3	3	2	2	3	2	1	2		fs position makes use of head rest easier but decreases leg room
9	2	21	5'10	165	M	working (30mn) sleeping (5mn)	3	3	3	3	3	3	3	3	2	3	3	2	2		seat would be a lot more comfortable if the headrest was pushed back some
10	1	21	5'7	145	M	studying (20mn)	2	3	4	3	2	3	2	1	2	2	2	3	2		seat too small (the part you sit on) - lot of pressure on the seat at the thigh
11	3	30	5'6.5	120	F	reading	3	3	3	3	3	3	3	4	4	3	2.5	3	3		
12	1	24	5'9	150	M	reading (1h10)	2	2	3	2	2	2	2	3	3	3	2	1	1		in slouched position: back hurts a bit, bottom part of seat too short. Good tray

Forward-sliding seat: Questionnaire 3

		Biographical				Questions													Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*use of tray*	*comfort with tray*	*comfort w/ seat reclined*	*others*
N					M	3	3	4	3	3	2	3	2	2	3			2		
1	2	23	6'6	285	M	2	3	3	3	2	2	3	4	2	2	2	2	2		much better than conventional tray
2	2	27	5'11 3/4	180	M	2	2	1	1	1	2	1	2	2	2	2	3	1		tray nice and high, though small. Nice to maneuver legs beneath tray while in use. Thanks for food! Excellent service
3	1	22	5'2	120	F	1	1	1	1	1	1	1	1	3	1	1	4	1		(not for eating) difficult to recline the seat - leg room greatly diminished with seat reclined - in reclined position, head rest works very well & is quite comfortable, lumbar support feels better
4	2	32	5'4	145	M	2	3	2	3	3	2	2	2	2	2	2	2	2		
5																				
6	2	20	5'10	178	M	2	1	2	1	1	2	2	1	1	2	1	3	2		
7	1	23	5'9	150	F	1	2	2	2	2	1	1	1	1	1	1	1	1		felt very comfortable with tray (have been using it entire flight) - lumbar support excellent - did not try to adjust tray
8	3	24	6'1	190	M	3	3	3	3	3	3	3	2	3	3	3	1	1		use of tray helps for a better eating position
9	2	21	5'10	165	M	3	3	3	3	3	3	3	4	4	3	3	2	2		
10	1	21	5'7	145	M	2	2	3	2	2	2	2	1	2	2	2	2	1		height of tray adjustable : great, would be better if even higher (always had problems eating in planes before, because food is so far away !!)
11	3	30	5'6.5	120	F	3	3	3	3	3	3	3	4	4	3	3	3	3		
12	1	24	5'9	150	M	2	2	3	2	2	2	2	2	1	2	2	1	1		

Forward-sliding seat: Questionnaire 4

		Biographical				Questions														Comments	
Subject number	Exp number	Age	Height	Weight	Gender	Tasks	Overall comfort	arm	thigh	leg	foot	neck	shoulder	back	lumbar	hip	head	use of lumbar support	lumbar support	comfort w/ seat reclined	others
N					M	reading, sleeping	2	3	3	3	3	2	3	1	2	3	1	2	2		ranks for sleeping
1	2	23	6'6	285	M	writing (30mn), reading (l0mn), resting (5mn)	3	3	4	3	3	2	3	4	3	3	2	3	2		thigh less comfy when trying to lean back and rest
2	2	27	5'11 3/4	180	M	read (5mn), sleep (40mn). Seat reclined to position 3 the whole time and tray raised	1	2	1	1	1	2	2	1	2	1	1	1	2		not much room leaft when reclined. Feels like sliding off the seat
3	1	22	5'2	120	F	reading, studying & sleeping (45mn)	3	1	1	1	1	3	3	4	4	2	3	3	4		see previous
4	2	32	5'4	145	M	sleeping (30mn)	2	3	2	2	2	2	2	3	3	2	4				
5																					
6	2	20	5'10	178	M	class work and reading	2	2	2	1	1	2	2	1	1	3	2	1	1		should have shoulder support, neck support further forward. Seat sliding too complex backwards
7	1	23	5'9	150	F	studying, talking	2	2	2	2	2	2	2	1	1	1	2	1	1		deflate the lumbar support bc lower back became sore, decreasing pressure absolved the discomfort - chair not comfortable at all in reclined position
8	3	24	6'1	190	M	resting (90mn)	3	3	3	3	3	2	3	3	3	3	2	2	2		side head rest very useful and comfy in this position
9	2	21	5'10	165	M	studying (40mn)	4	3	3	3	3	3	4	4	3	3	3	2	3		
10	1	21	5'7	145	M	working (2h)	2	2	3	2	2	2	2	1	1	2	2	2	1		
11	3	30	5'6.5	120	F	chatting	3	3	3	3	3	3	3	4	4	4	3	4	4		worst comfort level of the 3 types of seats
12	1	24	5'9	150	M	reading(1h30), talking(1h)	2	2	4	3	3	2	2	3	2	2	2	1	1		knees hurt but probably beacause didn't get up and walk. Will next time

Forward-sliding seat: Final comments

		Biographical				Comments					
Subject number	Exp number	Age	Height	Weight	Gender	General feeling	Compare with... Much better	Better	Comparable	Worse	Much worse
N					M	not good support for leg, thigh, foot, hips when seat slided-out. But slouched position comfortable, easier to sleep. Head rest very comfortable			1		
1	2	23	6'6	285	M	overall fairly comfy - middle back support doesn/t quite work - sliding aspect pretty bad - hard to use and eliminates leg room - puts extra pressure on thighs at edge of seat - best improvement is adj headrest		1			
2	2	27	5'11 3/4	180	M	head room welcomed addition when decided tosleep: gave nec support to keep head from bobbing side to side. Could relax more. Reclining mechanics detrimental to leg and butt room. Bansk better b/c of head rest		1			
3	1	22	5'2	120	F	lumbar support not too comfortable - tray table very difficult too open, but VERY comfortable & useful once deployed - prefer reclining seats to sliding seats - head rest made sleeping more comfortable (when reclined) because there was more suppot for turning your head			1		
4	2	32	5'4	145	M	arm rest too small and too hard. Head rest not comfy				1	
5											
6	2	20	5'10	178	M	fs feature too complicated and effects on position not simple enough to be useful. Reduced total seat area limbar support very nice, adjustability simple and specific enough to be effective			1		
7	1	23	5'9	150	F	seat extremely comfortable - lumbar support made this chair stand out as the most comfotable airline seat I have ever sat in - did not really use the head rest (leaning position) - chair uncomfortable in reclined position - would be nice if (middle) armrest wider to accomodate two arms - A normal reclining seat with lumbar support & adjustable head rest would be ideal					
8	3	24	6'1	190	M	seat semed comfy at beginning but less and less during flight (esp lumbar supp: maybe didn't find right position and lumping) - fs quite comfy but decreases too much leg room and cuts thighs - head rest comfy but can be used only in resting position, seat ranks a little better		0.5	0.5		
9	2	21	5'10	165	M	uncomfortable - head rest should be back more - sliding seat forward left me with lesss leg room - layout of seat did not support my back well				1	
10	1	21	5'7	145	M	pretty good - especially like the inflatable thing for the back - sliding part makes seat small		1			
11	3	30	5'6.5	120	F	cumbersome: pumping of back and having to adjust			1		
12	1	24	5'9	150	M	good points:tray, limbar support. Bad points: bottom too narrow		1			

Baseline seat: Questionnaire1

		Biographical				Questions											Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*comfort w/ seat reclined*	*others*
C					M	4	3	3	3	4	5	4	5	5	4	5		
1	1	23	6'6	285	M	3	2	4	3	2	4	5	4	3	4	3		head rest at shoulder level
2	3	27	5'11 3/4	180	M	2	2	1	1	1	3	2	2	3	1	2		very familiat feel. Diff to make first impressions. Seat back a little too firm
3	3	22	5'2	120	F	2	1	1	1	1	1	1	3	4	1	2		very comfy - head rest in a very nice position/location
4	3	32	5'4	145	M	2	2	2	3	2	2	2	1	1	1	2		front edge of seat a little bit too hard. Should be softer than center
5	1	21	5'5	178	M	3	4	4	2	1	3	4	3	3	3	2		
6	3	20	5'10	178	M	2	2	2	2	1	3	1	2	2	2	1		neck supp not adequate - shoulder supp much better in this chair than in fs - overall comfort close to 1.8 - no noticeable pressure point in discomfort
7	2	23	5'9	150	F	2	2	1	1	1	1	2	2	3	1	1		surprisingly, feel very comfy in this seat (attributing to early comfort familiarity w/ this type of seat). Immediately after sitting, felt as if was actually sitting in an aircraft. Nice lteg/foot room. Noticeable difference in back support dut to lack of ulmbar support
8	1	24	6'1	190	M	4	5	3	4	3	4	5	3	5	3	4		
9	3	21	5'10	165	M	2	3	3	3	3	3	2	2	3	3	2	=	
10	3	21	5'7	145	M	2	2	2	2	3	2	2	2	3	2	2		
11	1	30	5'6.5	120	F	3	3	3	3	2	4	4	3	3	2	5		
12	3	24	5'9	150	M	2	3	3	2	3	3	3	3	3	3	2		

Baseline: Questionnaire 2

		Biographical				Questions														Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Tasks*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*use of tray*	*comfort with tray*	*comfort w/ seat reclined*	*others*
C					**M**	**reading (40mn)**	**4**	**3**	**3**	**4**	**4**	**5**	**4**	**5**	**5**	**4**		**4**	**4**		
1	1	23	6'6	285	M	reading (20mn) resting (25mn)	3	2	3	4	3	5	4	4	3	3	4	5	4		tray table hard to use with any leg comfort
2	3	27	5'11 3/4	180	M	read (45mn). Seat up, tray down	2	2	1	1	1	4	2	2	3	2	2	1	4		tray table too low
3	3	22	5'2	120	F	slept and just sat (45mn)	2	1	1	1	1	1	1	2	3	1	1	5	5		tray too low, can't cross legs or maneuver at all when down
4	3	32	5'4	145	M	sleeping (30mn)	3	2	2	2	2	4	3	2	2	2	5	2	3		
5	1	21	5'5	178	M	talking / reading / relax	3	3	3	3	3	2	2	4	4	4	3	2	4	=	
6	3	20	5'10	178	M	rested/slept (45mn)	2	2	2	1	2	2	1	2	3	3	1	1	1		with time, lower back (lumbar) got sore
7	2	23	5'9	150	F	homework	3	2	3	2	2	1	1	2	3	1	1	1	4		overall comfort went down due to tray table along w/ thighs and legs. Tray uncomfy: sat low on and put pressure on thighs. Lower back support decreasing
8	1	24	6'1	190	M	working (55mn)	4	5	4	4	3	3	4	5	5	3	3	4	5	-	
9	3	21	5'10	165	M	reading (30mn)	3	3	3	3	3	3	3	3	3	3	3	3	4		
10	3	21	5'7	145	M	resting (30mn)	2	2	3	2	3	2	2	3	3	2	2	2	3		
11	1	30	5'6.5	120	F	sleepng(15mn), reading(45mn)	3	3	3	3	3	4	3	3	3	3	4	3	5		
12	3	24	5'9	150	M	rested	2	3	3	2	2	3	3	3	4	3	3	3	3		

Baseline: Questionnaire 3

		Biographical				Questions													Comments	
Subject number	*Exp number*	*Age*	*Height*	*Weight*	*Gender*	*Overall comfort*	*arm*	*thigh*	*leg*	*foot*	*neck*	*shoulder*	*back*	*lumbar*	*hip*	*head*	*use of tray*	*comfort with tray*	*comfort w/ seat reclined*	*others*
C					M	4	4	4	4	3	5	4	4	5	4		5	5		
1	1	23	6'6	285	M	3	3	3	4	4	3	4	3	4	3	3	2	4		legs cramped being under the tray table especially feet and ankles
2	3	27	5'11 3/4	180	M	3	3	1	1	1	3	2	3	4	2	2	1	3		tray ok but a but low. Tall person and have to slouch way over to reach food. Very little maneuverability ofr legs beneath tray. Very tight space to eat in. hard surface under arms and elbows cause discomfort
3	3	22	5'2	120	F	2	3	4	4	3	1	1	2	2	2	3	5	5		tray very low - eating diff b/c tray so low (like eating from your lap) - otherwise seat comfy for sitting upright
4	3	32	5'4	145	M	2	2	2	2	2	2	2	2	2	2	2	2	3		tray little bit too low
5	1	21	5'5	178	M	4	4	4	3	3	3	3	3	3	3	3	2	2		not too bad for a coach class
6	3	20	5'10	178	M	2	2	2	2	1	2	2	4	3	3	1	1	1		back hurts even more while eating and leaning over - front seat rec was in the way significantly for any activity, esp eating - overall comfort 2 b/c tray is 1 but chair irself closer to 3
7	2	23	5'9	150	F	3	2	3	3	3	2	2	2	4	2	2	1	4		miss lumbar support and moveable tray. Believe decrease in head/shoulder rating due to leaning fwd for homework. When front seat reclined, extremely cramped in this seat area
8	1	24	6'1	190	M	5	4	4	4	4	4	5	4	5	4	3	3	4		
9	3	21	5'10	165	M	2	3	3	3	3	2	2	2	3	3	2	4	4		
10	3	21	5'7	145	M	2	2	2	3	2	2	2	2	3	2	2	2	3		
11	1	30	5'6.5	120	F	3	2	4	4	3	3	3	3	3	4	3	4	5		
12	3	24	5'9	150	M	3	3	3	3	3	3	3	4	4	3	3	3	3		tray too low

Baseline: Questionnaire 4

		Biographical Data				Questions													Comments	
Subject number	Exp number	Age	Height	Weight	Gender	Tasks	Overall comfort	arm	thigh	leg	foot	neck	shoulder	back	lumbar	hip	head	use of lumbar support	lumbar support	comfort w/ seat reclined	others
C					M	sleeping(80mn) reading(30mn)	4	4	4	4	4	5	6	5	5	6					
1	1	23	78	285	M	reading (35mn) resting (10mn)	4	4	3	4	4	4	4	4	3	3	3				very hard to rest - uncomfortable esp. neck - no head support
2	3	27	72	180	M	read, seat slightly rec, tray down. Front seat fully rec	3	3	1	1	1	4	2	2	3	2	3			-	choice of tasks made it diff to be comfy w/ fron seat rec. very little room to read, trya too low. Arm tired having to hold paper at eye level
3	3	22	62	120	F	rested, sat, talked (45mn)	2	1	1	1	1	1	1	2	2	1	2				
4	3	32	64	145	M	sleeping (30mn), relaxing (20mn)	2	2	2	2	2	4	2	2	2	2	4			fine	
5	1	21	65	178	M	talking / relaxing	3	3	2	3	4	3	3	3	3	3	4				neck very sore because head rest not adjustable
6	3	20	70	178	M	wrote (20mn), read (30mn).	3	2	2	1	2	3	2	3	3	2	1			-	front seat annoying when writing
7	2	23	69	150	F	homework	3	2	4	3	3	2	2	4	4	2	2			-	space extremely resticted w/ front seat rec. diff to have drink on table. Back achy, tray uncmofy b/c pressure on thighs
8	1	24	73	190	M	working (1h30)	5	3	5	4	4	5	5	4	5	3	4			-	tray to low
9	3	21	70	165	M	sleeping (1hour)	3	3	3	3	3	4	4	3	3	3	3			fine	neck and shoulders felt good when not sleeping
10	3	21	67	145	M	chatting (1h)	2	2	2	3	2	3	2	3	3	2	2				
11	1	30	67	120	F	reading, resting (1h1/2)	3	3	3	3	2	4	3	4	4	4	4				resting: head and neck uncomfortable
12	3	24	69	150	M	rested	3	3	4	3	3	3	4	3	4	4	3				tray definitely too low

Baseline: Final comments

		Biographical				Comments	Compare with:				
Subject number	Exp number	Age	Height	Weight	Gender	General feeling	Much better	Better	Comparable	Worse	Much worse
C					M	lack back support					
1	1	23	6'6	285	M	alright - uncomfortable - head support too low					
2	3	27	5'11 3/4	180	M	very average. Overall vey firm, making any position other than upright slightly uncomfy. Head rest at very uncomfy height. Very little side-to-side restraint for head, keeping from sleeping comfy and deeply. Tray tavle should be higher					
3	3	22	5'2	120	F	fairly comfy - only complaint; tray table very diff to use and too low - headrest nice, standard but comfy					
4	3	32	5'4	145	M	head support makes head uncomfy when sitting reclined					
5	1	21	5'5	178	M	very average - neck support OK for short while but then quickly strains neck - arm rest : could use softer material - neck rest should be adjustable					
6	3	20	5'10	178	M	pain in back/butt region and strain in neck while writing - nice shoulder supp, easiest to sleep/rest in - while other seats ratings were consistent, this one gets more uncomfy with time, a large factor for longer flights					
7	2	23	5'9	150	F	started off fine. Lower back achy after eating. Tray too low, incomfy for thighs. Not enough room to operate tray table when front seat rec					
8	1	24	6'1	190	M	not comfortable for lumbar, shoulders & back - really bad tray - here leg room not too bad - really tired at the end like always					
9	3	21	5'10	165	M	seat comfy overall but not when sleeping					
10	3	21	5'7	145	M	pretty comfy sitting up right, but when sleeping or slouhing, lack support in back and head/neck					
11	1	30	5'6.5	120	F	leg space okay, considering time period. Bur for resting, head and neck uncomfortable					
12	3	24	5'9	150	M	at beginiing, seemed very comfy but no lumbar support, tray too low and was lying on thighs					