Long-Term Comfort Study of Seating Supports in Level 3 & 4 Automated Vehicles

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Table of Contents

1 Abstract

This report examines the long-term comfort of seating supports in Level 3 and Level 4 automated vehicles, addressing the challenges and opportunities of autonomous mobility. It evaluates how the transition from active driving to passive passenger roles necessitates a redefinition of comfort standards. The study assesses comfort and discomfort across four seating configurations at Levels 3 and 4 automations, combining subjective feedback with objective measures such as IMU sensors, skeleton tracking, thermal imaging, and physiological data. Subjective measurements capture participant feedback on comfort and discomfort during extended use of different seating configurations. Questionnaires and interviews examine factors such as fatigue, local postural discomfort, and thermal comfort. Objective findings identify key factors influencing comfort and discomfort, including passenger movement, seat pan angles, headrest adjustability, and backrest shape. Combining subjective and objective measurements, the report provides actionable recommendations to address the identified issues, emphasizing design improvements aimed at enhancing user experience in automated vehicle environments.

2 Introduction

Automated vehicles, commonly referred to as self-driving cars, represent a transformative leap in transportation technology. These vehicles are equipped with advanced systems that enable them to perform driving tasks with minimal or no human intervention. As automated driving technology continues to evolve, the shift from traditional vehicles to intelligent, self-operating cars is accelerating, paving the way for safer, more efficient, and more convenient mobility solutions.

The Society of Automotive Engineers (SAE) has established a framework that classifies vehicle automation into six levels, ranging from no automation (L0) to full automation (L5) (SAE International, 2021). Levels 3 (L3) and 4 (L4) represent significant milestones in this progression. In L3 vehicles, the system can perform specific driving tasks under defined conditions but requires the driver to take over when prompted. On the other hand, L4 vehicles are capable of handling all driving functions automatedly, but only within predefined operational domains, such as urban centers or highways.

With the rise of automated vehicles, there is growing interest in understanding and optimizing passenger comfort, particularly in L3 and L4 settings. Unlike traditional vehicles, where the primary focus is on driving, automated vehicles allow passengers to engage in various Non-Driving Related Activities (NDRAs), such as reading, using electronic devices, or relaxing (Cai et al., 2024). These activities, coupled with extended periods of passive travel, pose new challenges for designing seats that support comfort while minimizing discomfort, fatigue, and other negative experiences.

2.1 Objectives

This research aims to evaluate and compare the comfort provided by two distinct passenger seating support systems in L3 and L4 automated vehicles. Building on a prior short-term study that identified optimal seating positions and features enhancing comfort during various Non-Driving Related Activities (NDRAs), this long-term study expands the scope to a 2-hour driving scenario. The focus is on understanding the dynamic interplay between passenger comfort and activities over an extended period.

Integrating subjective feedback (comfort, discomfort, thermal comfort, fatigue, stress, and emotional responses) with objective metrics (e.g., skeletal movements, inertial measurement units (IMUs), and thermal imaging), this study aims to deliver actionable insights for seat design improvements. These findings will inform recommendations for future L3 and L4 automated vehicles, with the ultimate goal of enhancing passenger well-being and developing seating solutions tailored to the evolving demands of automated mobility.

2.2 Research Questions

This study is guided by the following key research questions:

- Comparative Comfort Analysis: What are the differences in passenger comfort and discomfort between the two seating support systems during a 2-hour drive in Level 3 (L3) and Level 4 (L4) automated vehicles?

- Insights from Subjective and Objective Measures: How do subjective evaluations (e.g., perceived comfort and discomfort) and objective measurements (e.g., thermal imaging, skeletal movement, and other physiological indicators) vary between the two seating systems and what do these findings reveal about human responses to different seat designs?

- Design Recommendations: Based on the findings, what specific design recommendations can be proposed to improve future seating systems in automated vehicles to better support passenger comfort and reduce discomfort?

2.3 Impact

The outcomes of this research are expected to contribute significantly to the development of passenger-centric designs for automated vehicles. By addressing both short-term comfort during NDRAs and long-term comfort over extended travel durations, this study aims to:

- Provide evidence-based guidelines for designing ergonomic, adaptable, and comfortable seating systems.
- Highlight the role of advanced monitoring technologies, such as thermal imaging and IMU sensors, in assessing and improving passenger comfort.
- Bridge the gap between human needs and technological advancements in automated vehicle design.

Ultimately, as L3 and L4 vehicles become more prevalent, creating a comfortable and engaging passenger experience will be a key factor in their acceptance and success. This study takes a step forward in ensuring that future automated vehicles not only transport passengers efficiently but also enhance their overall well-being during the journey.

3 Literature Review

This literature review examines the subjective and objective measurements relevant to evaluating comfort and discomfort in the context of the upcoming experiment. It draws on prior research to define key terms, highlight established methodologies, and outline tools and techniques used to gather relevant data.

3.1 Subjective Measurements

Subjective measurements are inherently tied to the personal perceptions and experiences of individuals. These assessments are crucial in evaluating comfort and discomfort as they capture psychological, emotional, and physical responses to external stimuli.

3.1.1 Comfort and Discomfort

Vink and Hallbeck (2012) define comfort as "a pleasant state or relaxed feeling of a human being in reaction to its environment," while discomfort is described as "an unpleasant state of the human body in reaction to its physical environment." This distinction underscores the dual nature of comfort: while discomfort primarily stems from poor ergonomics and physical interactions, comfort extends beyond physical sensations to include psychological and environmental influences.

To quantify these subjective experiences, researchers often rely on questionnaires employing a 0–10 scale, where 0 represents no comfort or discomfort and 10 denotes extreme comfort or discomfort (Anjani et al., 2021). These responses provide a baseline for understanding user perceptions, which can then be cross-referenced with objective data or qualitative insights derived from interviews to create a more comprehensive understanding of the factors influencing comfort and discomfort.

3.1.2 Local Postural Discomfort (LPD)

The Local Postural Discomfort (LPD) method, developed by Grinten and Smitt (1992), offers a region-specific assessment of discomfort. The tool uses a body map divided into 22 regions—such as the neck, shoulders, back, and limbs—where participants indicate discomfort levels on a 10-point scale (0 = no discomfort, 10 = extreme discomfort).

Anjani et al. (2021) highlight the application of this method over time, particularly in longitudinal studies, by evaluating discomfort at the beginning of product use and at periodic intervals thereafter. This temporal analysis provides valuable insights into how discomfort evolves, especially during prolonged usage scenarios such as extended drives in automated vehicles.

3.1.3 Thermal Comfort

Thermal comfort is a key factor in overall comfort, as thermal sensations significantly influence physical and psychological well-being. The ASHRAE 7-point Thermal Sensation Scale, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), measures thermal comfort on a scale ranging from -3 (cold) to +3 (hot), with 0 representing a neutral thermal sensation (ASHRAE, 2023).

Wang et al., (2022) emphasize that thermal comfort is not uniformly distributed across the body; different regions perceive temperature changes uniquely. This localized approach to thermal comfort is particularly relevant for automated vehicles, where precise climate control can improve passenger satisfaction during long journeys.

3.1.4 Emotional Response

Mehrabian (1980)'s VDA Model (Valence, Dominance, and Arousal) provides a framework for understanding emotional responses: 1) Valence: Measures how positive or negative an emotional experience is, 2) Arousal: Captures the intensity of emotional reactions, ranging from calm to excitement, and 3) Dominance: Reflects the sense of control or influence an individual feels. Building on this model, Bradley and Lang (1994) introduced the Self-Assessment Manikin (SAM), a non-verbal, pictorial tool for assessing emotional states. The SAM enables participants to visually represent their emotional responses, making it especially useful in diverse contexts where language may pose a barrier to traditional survey methods.

3.2 Objective Measurements

Objective measurements complement subjective data by offering quantifiable and unbiased insights into physiological, behavioral, and environmental interactions.

3.2.1 Inertial Measurement Units (IMUs)

IMUs are devices combining accelerometers, gyroscopes, and sometimes magnetometers to capture orientation, angular velocity, and specific forces in three-dimensional space. They are widely used for motion tracking, particularly in ergonomic and automotive studies.

In the context of this research, IMUs can be embedded into car seats to monitor movements of components like the backrest, armrest, and headrest. This integration allows for precise tracking of seat adjustments and user behavior, enabling researchers to correlate movement patterns with comfort and discomfort levels.

3.2.2 Skeleton Tracking

The Microsoft Kinect, initially developed as a gaming device, has found significant utility in ergonomic research due to its ability to track human skeletal movements. The Kinect v2 sensor, for instance, captures up to 25 joints in three-dimensional space, offering detailed insights into posture and movement (Diego-Mas & Alcaide-Marzal, 2014).

In automotive applications, the Kinect has been used to analyze passenger and driver postures in simulated environments. This capability is particularly valuable for assessing how different seat designs influence skeletal alignment and physical comfort during prolonged travel in automated vehicles.

3.2.3 Thermal Imaging

Thermal imaging provides a non-invasive method to assess both physiological and emotional states. Cruz-Albarran et al. (2017) demonstrated the link between emotional arousal and facial thermal patterns, showing how changes in skin temperature correspond to emotional states. For instance:
Anger: Decreases temperature in the nasal and upper lip regions while increasing it on the forehead.
Stress: May lead to elevated temperatures across the face due to heightened physiological activity. This method holds significant potential for evaluating both thermal comfort and emotional responses in automated vehicle studies, offering a dynamic view of how passengers react to various conditions over time.

The combination of subjective and objective measurements provides a holistic framework for evaluating comfort and discomfort. Together, these approaches enable researchers to comprehensively assess and enhance passenger experiences, paving the way for improved seating designs in automated vehicles. This integrated methodology is essential for understanding not only the physical but also the psychological and emotional dimensions of comfort, especially in the evolving landscape of L3 and L4 automated vehicles.

4 Methods

4.1 Participants

The study was approved by the Human Research Ethics Committee of Delft University of Technology and involved a total of 17 participants. The sample size was determined using G*Power calculations for the Wilcoxon signed-rank test, which indicated that 16 participants were sufficient to detect medium to large effects (effect size = 0.8) in a within-subject study design with a one-tailed setup and a statistical power of 0.90. This ensured the study was designed to yield reliable and meaningful results.

Before participation, all individuals provided informed consent, in compliance with ethical research standards. Each participant completed two experimental sessions, with each session lasting approximately 300 minutes (~ 5 hours), enabling a thorough evaluation of the research objectives. As a token of appreciation for their involvement, participants received a €100 voucher upon completing the study.

4.2 Setups

4.2.1 Configurations and equipment

The maximum age limit of 40 years for participants was set to align with the anticipated demographic of future users of Level 3 (L3) and Level 4 (L4) automated vehicles. This targeted recruitment strategy was intended to capture the preferences and comfort-related needs of the projected user base.

The experiment was conducted using two seats —the AAA seat (sometimes referred to as the blue seat) and the BBB seat (sometimes referred to as the black seat). Additionally, the study incorporated two levels of automated driving—Level 3 (L3) and Level 4 (L4) - resulting in a total of four distinct experimental scenarios: **AAA_L3**, **BBB_L3**, **AAA_L4**, and **BBB_L4** (Table 1). These scenarios were structured to examine the interplay between seat design and automated driving levels under controlled conditions.

The seat dimensions and configurations used in this study were consistent with those evaluated in the short-term tests. For detailed specifications of the seats, please refer to the WP 1&2 short-term report. This continuity ensured comparability across experiments while allowing for the exploration of long-term effects during extended driving sessions.

Table 1: Four different study scenarios

	Level 3 AV	**Level 4 AV**
AAA	AAA_L3 - AAA seat on the driver side	AAA_L4 - AAA seat on the front passenger side
BBB	BBB_L3 - BBB seat on the driver side	BBB_L4 - BBB seat on the front passenger side

In the Level 3 scenarios, the experimental setup simulated a driver's position equipped with a steering wheel and pedals, closely resembling real-world driving conditions. However, to prevent interference with the second participant, participants in the L3 scenarios were not required to perform takeover tasks, even though the steering wheel and pedals were present. This design choice allowed for an evaluation of passenger comfort without introducing additional cognitive or physical workload associated with manual control.

In the Level 4 scenarios, participants were seated in the passenger position, reflecting the full automation expected at this level. Unlike L3 scenarios, participants were not required to perform any driving-related tasks during the session. This setup provided an opportunity to assess comfort and engagement in a fully automated context, where the vehicle independently managed all driving functions.

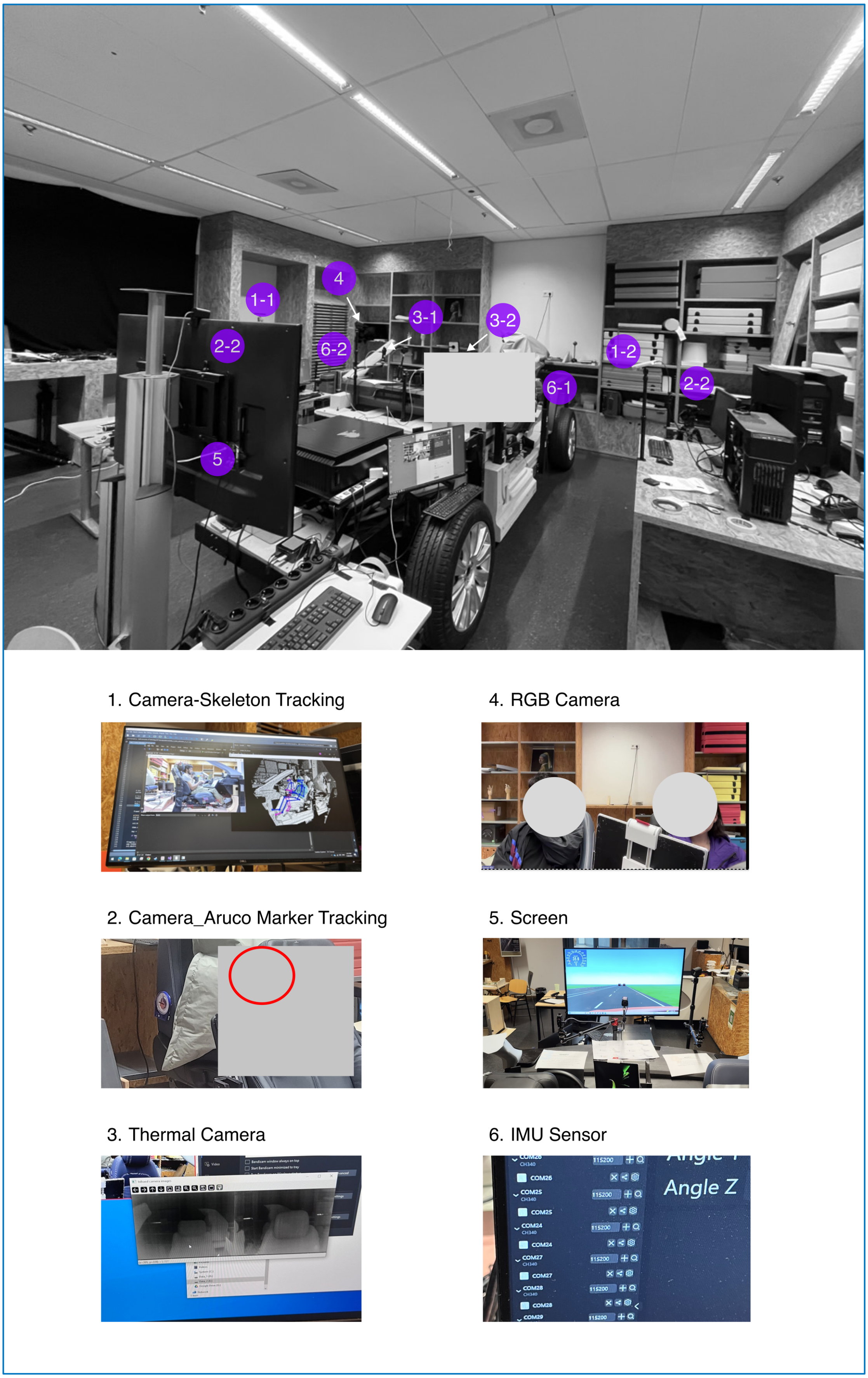

Figure 1: Experiment setup

Figure 1 provides a detailed illustration of the experimental setup. The experiment was conducted using a prototype vehicle centrally positioned within the lab. The vehicle faced a large display screen simulating a realistic driving environment to immerse participants in the automated driving experience. Surrounding the prototype vehicle, various cameras and sensors were strategically installed to capture objective data related to participant behavior and environmental conditions. They are:

Side Cameras: Each side of the prototype vehicle was equipped with two cameras:

- A skeleton-capturing camera recorded participants' joint postions, enabling analysis of postures and movements during the experiment.
- An ArUco Marker-tracking camera (4K resolution) monitored seat movement trajectories, providing data on seat adjustments and interactions throughout the session.

Front Cameras:

- Two thermal cameras were installed in the front to capture facial temperature data, offering insights into thermal comfort and emotional responses.
- A 4K camera was positioned to record the experimental process, ensuring all participant activities and interactions were documented.

Seat Sensors:

- IMU sensors were embedded in critical parts of the seat, including the seatbacks, armrests, and headrests. These sensors recorded:
  - Seat adjustments made by participants during the experiment.
  - Vibrations and movements experienced by the seat during different automated driving scenarios.

Empatica Wristband:

- Each participant wore an Empatica wristband, a wearable device capable of monitoring:
  - Heart rate: Providing insights into physiological stress and emotional states.
  - Electrodermal activity (EDA): Measuring changes in skin conductance to evaluate arousal levels.
  - Body temperature (at the wrist): Recording changes over time to assess overall thermal comfort and physiological responses.

4.2.2 Environments

The environmental conditions during the experiment were carefully controlled, maintaining temperatures between 23°C and 26°C and relative humidity within 30% to 60%. Table 2 and Figure 2 summarize the environmental parameters recorded during the study. The experiments for BBB_L3 and AAA_L4 were conducted in October, while those for BBB_L4 and AAA_L3 took place in September.

BBB_L3 and AAA_L4: The combined configurations of BBB_L3 and AAA_L4 were characterized by higher temperatures, with a mean of approximately 26°C. Variability in temperature was minimal, as indicated by standard deviations of 0.78°C (BBB_L3) and 0.72°C (AAA_L4), demonstrating tightly controlled conditions. For CO2 levels, the mean concentrations were 612 ppm for BBB_L3 and 613 ppm for AAA_L4. The overall variability was low, BBB_L3 25.16 ppm and AAA_L4 is 23.06 ppm. In terms of relative humidity, both configurations displayed lower humidity levels, with means of 38.71% for BBB_L3 and 38.74% for AAA_L4. The standard deviations of 5.47% (BBB_L3) and 5.55% (AAA_L4).

BBB_L4 and AAA_L3: The configurations of BBB_L4 and AAA_L3 were associated with lower temperatures, with mean values of 23.79°C (BBB_L4) and 23.82°C (AAA_L3). The standard deviations of 0.69°C (BBB_L4) and 0.67°C (AAA_L3). For CO2 levels, the mean concentrations were slightly higher than in BBB_L3 and AAA_L4, with 617 ppm for BBB_L4 and 619 ppm for AAA_L3. Variability was moderate, with standard deviations of 23.95 ppm (BBB_L4) and 23.16 ppm (AAA_L3). In terms of relative humidity, these configurations exhibited higher levels compared to BBB_L3 and AAA_L4. The mean values were 48.20% for BBB_L4 and 48.09% for AAA_L3, Variability was slightly higher than in BBB_L3 and AAA_L4, with standard deviations of 6.47% (BBB_L4) and 6.45% (AAA_L3).

Table 2 Descriptive statistics of the weather conditions: temperature (°C), relative humidity (%), and CO2 concentration (ppm).

Configuration	Temperature Mean	Temperature Std	CO2 Mean	CO2 Std	Humidity Mean	Humidity Std
BBB_L3	26.0	0.8	612.0	25.2	38.7	5.5
BBB_L4	23.8	0.7	617.5	23.9	48.2	6.5
AAA_L3	23.8	0.7	618.7	23.2	48.1	6.4
AAA_L4	26.0	0.7	613.3	23.1	38.7	5.5

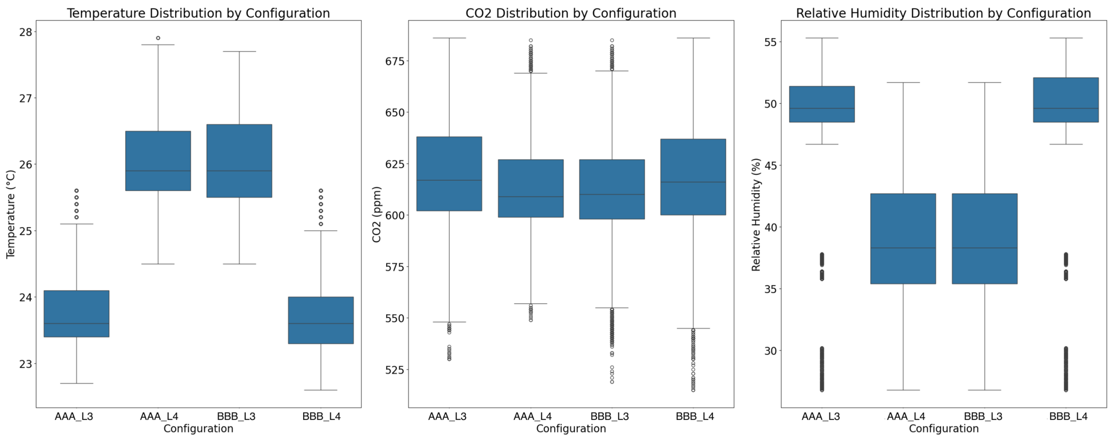

Figure 2: Local environment parameters

4.3 Protocols

The experiment consisted of two main parts. In each part, participants completed two 2-hour sessions covering two corresponding scenarios. Initially, the AAA seat was placed in the Level 3 position, while the BBB seat was positioned at Level 4. Two participants were required to sit in these seats and experience a simulated automated driving scenario for two hours. After the first session, the participants switched seats and repeated the two-hour experience.

Once all 17 participants completed the first part, the seat positions were swapped: the BBB seat was assigned to Level 3, and the AAA seat to Level 4. Participants repeated the same procedure, completing the second part of the experiment. To minimize the influence of seat order on the results, the sequence of the four scenarios was counterbalanced across participants (Table 3).

Table 3: Randomized orders in the experiment

First Part		**Second Part**		**Number**	**Percentage**
First 2 Hours	Second 2 Hours	First 2 Hours	Second 2 Hours		
AAA_L3	BBB_L4	BBB_L3	AAA_L4	4	23.53%
AAA_L3	BBB_L4	AAA_L4	BBB_L3	5	29.41%
BBB_L4	AAA_L3	BBB_L3	AAA_L4	5	29.41%
BBB_L4	AAA_L3	AAA_L4	BBB_L3	3	17.65%
Total				17	100%

Figure 3: Experiment Procedure provides an outline of the experimental procedure, which aimed to capture reliable data while minimizing variability. Participants engaged in two 2-hour experimental sessions in each part, following identical processes to facilitate comparison between sessions.

Before beginning the experiment, participants provided informed consent by signing a consent form and completed a detailed pre-questionnaire. This questionnaire collected demographic and personal information, including nationality, gender, age, driving habits, and opinions on Advanced Driver

Assistance Systems (ADAS) for L3 and L4 vehicles. Baseline questionnaires were also completed to establish reference points for comparison with responses collected during the experiment.

To ensure accurate data collection and reduce interference, any electronic devices participants brought into the experimental environment were weighed and measured to account for their potential impact on seat adjustments and movement tracking. Furthermore, participants were asked to remove any facial makeup to optimize the performance of thermal imaging equipment. Additionally, each participant was fitted with an Empatica wristband, a wearable device used to continuously monitor physiological data such as heart rate, EDA, and body temperature (measured at wrist) throughout the sessions.

After preparation, facilitator(s) guided participants to their assigned seats and provided detailed instructions about the seating mechanisms and the different levels of automated driving (L3 and L4). Participants were also familiarized with the seat adjustment controls to ensure they could make necessary adjustments for comfort during the session. These instructions aimed to simulate a realistic user experience in an automated vehicle setting.

Throughout the experiment, participants completed a series of paper-based questionnaires (Appendix B) at the following intervals:

- At the start of the session.
- Every 20 minutes during the session.
  At the end of the session.

At the end of the first 2-hour session, participants took part in a semi-structured interview (Table 4) to provide qualitative feedback. The interview focused on several key areas, including:

- Usability of seat adjustment mechanisms.
- Strengths and weaknesses of the seat design.
- How the levels of automated driving (L3 and L4) influenced their behavior.
- The impact of non-seat interior elements (e.g., lighting, materials) on their overall comfort.
- This feedback provided valuable insights into participants' experiences and allowed the research team to explore beyond quantitative data.

Between the two sessions, anthropometric measurements, such as body fat percentage and other body composition metrics, were taken. To ensure the accuracy of these measurements, participants were asked to refrain from eating before this stage. Following the anthropometric assessment, participants were given a short break to relax before beginning the second session.

The second 2-hour session followed the same procedure as the first, maintaining consistency in preparation, data collection, and feedback processes. This mirrored approach ensured that any differences observed in the data were due to the experimental variables rather than inconsistencies in the procedure.

Figure 3: Experiment Procedure

Table 4 Interview Questions

Interview Question
What do you think of the way the seats are adjusted?
What is good about the seat?
What needs to be improved on the seat?
Does the level of automation influence your activity?
What other non-seat interior elements effect your comfort e.g. steering wheel and the pedal?

5 Results

5.1 Participants Demographic

Participant demographics were collected through a questionnaire before the first session as shown in Table 5. In total there were 17 participants, with a mean age of 23 years, who completed both sessions of the experiment, 9 (53%) were male, and 8 (47%) were female.

In terms of ethnicity, most participants (71%) were West European, followed by 24% who were from East and Central Asia. Regarding dominant hand and driving license, 88% of participants were right-handed, and 71% had a driving license.

Additionally, participants showed significant trust and willingness to use the technology, with a mean trust rating of 6 on a scale of 0 (no trust at all) to 10 (absolute trust), and 76% of them would be willing to use ADAS.

Table 5: Participant Demographics

Participant	n=17	Percentage
Age	23±1.94	
Gender	Male	53%
	Female	47%
Ethnicity	Western Europe (e.g., Greece, Sweden, United Kingdom)	71%
	Eastern Europe (e.g., Hungary, Poland, Russia)	6%
	North Africa (e.g., Egypt, Morocco,Sudan)	0%
	Sub-Saharan Africa (e.g., Kenya,Nigeria,South Africa)	0%
	West Asia/Middle East (e.g. Iran, Israel, Saudi Arabia)	0%
	South and Southeast Asia (e.g. India, Indonesia, Singapore)	6%
	East and Central Asia (e.g. China, Japan, Uzbekistan)	24%
	Pacific/Oceania (e.g., Australia, Fiji, Papua New Guinea)	0%
	North America (Canada, United States)	0%
	Central America and Caribbean (e.g., Jamaica, Mexico, Panama)	0%
	South America (e.g., Brazil, Chile, Colombia)	6%
Dominant Hand	Left	12%
	Right	88%
Driving License	Yes	71%
	No	29%
Have experience with the driver-assistance system (ADAS)	Yes, I have tried and I frequently use ADAS	29%
	Yes, I have tried but I don't frequently use ADAS	18%
	No	53%
Trust towards the ADAS	6±1.73	
Willing to use ADAS	Yes	76%
	No	0%

Maybe	24%

During the initial session of the experiment, participants underwent anthropometric and body composition assessments. The collected data are summarized in Table 6, which categorizes the results into overall, male, and female populations. Figure 4 illustrates the distribution of participant height and weight, key variables that were used to calculate Body Mass Index (BMI). Figure 5 presents the calculated BMI values across the participant pool. Based on the BMI classification guidelines, the majority of participants fall within the "normal" range (18.5–24.9), indicating that the cohort generally represents a healthy population. However, to ensure that the findings remain inclusive and applicable to a wider demographic, a small proportion of participants were selected with BMI values in the "overweight" (25.0–29.9). The highest recorded BMI value in the study reached 29.2. Unfortunately, no participants with a BMI greater than 30 were recruited.

Table 6: Anthropometric Measurements of participants

Anthropometry	**Overall**		**Male**		**Female**	
	Mean	SD	Mean	SD	Mean	SD
Statue with shoes(mm)	1761	79	1812	57	1703	58
Stature(mm)	1735	82	1788	58	1675	63
Weight with shoes(kg)	67	9	73	8	61	6
Body weight(kg)	67	9	72	8	61	6
Sitting height(mm)	900	39	922	30	875	35
Eye height seated(mm)	791	32	808	29	772	24
Shoulder sitting height(mm)	591	34	608	36	573	22
Hip breadth(mm)	353	29	357	31	349	29
Shoulder breadth(mm)	405	25	420	23	388	12
Elbow to Elbow	430	43	455	34	402	35
Popliteal height with shoes(mm)	494	13	517	13	469	38
Popliteal to knee(mm)	106	12	112	9	99	11
Buttock to popliteal(mm)	489	31	495	36	483	23
Buttock to knee(mm)	595	35	607	39	581	25
Thigh Height(mm)	89	19	99	12	77	20
Body Fat Percentage (%)	23.4%	8.6%	17.5%	5.9%	30.1%	5.8%
Muscle Percentage (%)	36.4%	6.8%	41.1%	3.0%	31.0%	5.6%
Metabolism (Kcal)	1547	199	1679	113	1398	167
Visceral Fat	4	3	5	3	4	2

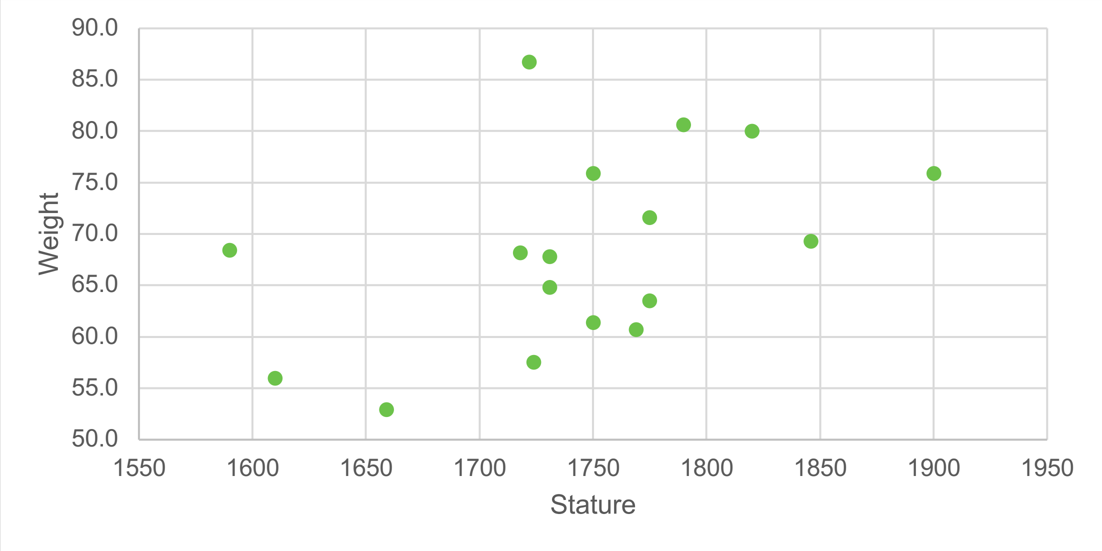

Figure 4: Participants' Weight and Stature Distribution

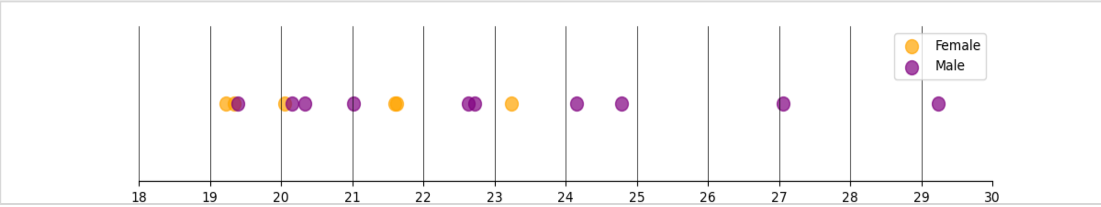

Figure 5: Participants' BMI Distribution, color indicated Sex

5.2 Questionnaires

Please refer to Appendix A for the results.

5.3 IMU

Please refer to Appendix A for the results.

5.4 Skeleton Motion

Please refer to Appendix A for the results.

5.5 Seat adjustment

Please refer to Appendix A for the results.

5.6 Thermal images

Please refer to Appendix A for the results.

5.7 Physiological data

Please refer to Appendix A for the results.

5.8 Interview

Please refer to Appendix A for the results.

6 Summary of findings

Please refer to the Appendix B for the summary of findings

7 Discussions

7.1 Comfort and Discomfort

7.1.1 Comfort Trends Across Scenarios

Participants' comfort ratings showed a consistent decline over time across all experimental scenarios, emphasizing the challenges associated with prolonged sitting in automated vehicles. Notably, the BBB seat consistently outperformed the AAA seat in terms of comfort under both Level 3 (L3) and Level 4 (L4) conditions. This trend was particularly pronounced in the L4 scenario, where the reduced need for driving-related tasks allowed participants to adopt more relaxed and flexible postures. The BBB seat's performance is attributed to its enhanced adjustability and softer materials, which were more effective in mitigating discomfort over extended periods.

However, while the BBB seat performed better overall, some participants reported that its overly soft cushions occasionally led to fatigue or insufficient support during longer sessions, and it was verified by IMU and skeleton tracking. This observation suggests that seat design must strike a careful balance between providing softness for immediate comfort and firmness for long-term support. In contrast, the AAA seat's firmer material and narrower design were consistently cited as significant contributors to discomfort. These shortcomings were especially evident in the L3 scenario, where participants' need to remain attentive and maintain a certain level of driving supervision limited their ability to adopt more relaxed postures, compounding their discomfort.

7.1.2 Factors Contributing to Discomfort

The experiment identified several key factors influencing participants' discomfort levels. The material and shape of the seats emerged as critical determinants, with the AAA seat’s firm construction frequently associated with increased pressure on the buttocks and thighs. Prolonged sitting duration further exacerbated discomfort in both seats, with significant differences in comfort ratings becoming apparent between 40 and 60 minutes into the sessions. This pattern highlights the importance of seat design in addressing the physical demands of extended periods of immobility.

Restricted physical activity also played a substantial role, particularly in the L3 scenarios. The requirement for participants to remain alert and supervise driving limited their ability to move and adjust their posture freely. Conversely, the more relaxed conditions of L4 scenarios alleviated some of these constraints but still revealed inadequacies in the seats' support systems, especially during reclined postures. Both seats lacked sufficient back support, which was frequently mentioned as a primary source of discomfort as sessions progressed.

7.1.3 Insights from Localized Postural Discomfort (LPD) Data

Data collected using the Local Postural Discomfort (LPD) method provided further insights into the specific body regions affected by discomfort. Over time, discomfort ratings increased significantly in the buttocks, lower back, mid-back, upper back, and thighs. These discomfort patterns were most pronounced in the later stages of the experiment, underscoring the cumulative effects of prolonged sitting.

The AAA seat exhibited higher discomfort ratings in these regions compared to the BBB seat, particularly during L4 scenarios. The combination of firm seat material and limited adjustability contributed to increased discomfort, particularly in the buttocks and thigh regions. Additionally, inadequate back support exacerbated issues in the lower, mid, and upper back, especially when participants adopted reclined postures.

The BBB seat, while demonstrating relatively lower discomfort ratings, was not without its shortcomings. Participants noted that its back support, while softer than the AAA seat, was insufficient for extended use. This issue was particularly apparent during reclined postures in the L4 scenario, indicating that both seat designs require further refinement to address back support challenges.

7.2 Thermal Comfort

Thermal comfort ratings varied significantly across scenarios and configurations, underscoring their critical impact on user experience during prolonged driving. Participants frequently reported heat buildup, especially in the buttocks and thigh regions, exacerbated by sustained seat contact during activities like laptop use. The lack of active thermal regulation systems in current seat designs further restricted heat dissipation, intensifying discomfort.

Softer cushioning materials tended to trap heat more effectively, providing inadequate ventilation, while firmer materials slightly improved dissipation but introduced pressure-related discomfort. Configurations such as BBB_L4, with reclining options and dynamic adjustments, enabled posture shifts that moderately alleviated heat buildup. In contrast, rigid designs like AAA_L3 were associated with higher thermal discomfort due to limited movement flexibility and constrained airflow.

Addressing these challenges in future seat designs is essential, particularly for long-duration or stationary activities. Integrating active thermal regulation systems—such as seat ventilation, cooling technologies, or thermoelectric systems—could significantly reduce localized heat buildup. Breathable materials or advanced fabrics promoting airflow would further enhance heat dissipation.

Dynamic seat mechanisms encouraging posture shifts and distributing pressure evenly can also improve comfort, as thermal imaging suggests that minimizing head-nose temperature differences correlates with reduced discomfort. Features like intuitive seat controls, automated prompts, or periodic vibration signals could encourage micro-adjustments, promoting circulation and mitigating thermal discomfort. These enhancements would not only address heat issues but also reduce fatigue, offering a more ergonomic and user-centered experience.

Future research should focus on testing active thermal management prototypes under various conditions to evaluate their effectiveness and user acceptability. Proactively addressing thermal comfort challenges can significantly enhance user satisfaction, particularly in highly automated driving scenarios where passengers remain seated for extended periods.

7.3 Relation between Body fat percentage and LPD

The relationship between body fat percentage and seating comfort is crucial in ergonomics and human factors. Research highlights the need for seat designs that accommodate diverse body types to enhance comfort and reduce discomfort.

Mastrigt et al. (Hiemstra-van Mastrigt et al., 2017) found that subcutaneous fat percentage influences seating contact areas, with cushion hardness and hip width affecting pressure distribution. This suggests individuals with varying body fat percentages experience different comfort levels. Sabri et al. (Sabri et al., 2022) emphasized the impact of anthropometric factors on discomfort in specific areas like the neck, shoulders, and hips, advocating for adaptable seat designs that cater to different body compositions. Khamis et al. (Khamis* et al., 2019) demonstrated that fat distribution around the buttocks significantly affects pressure distribution, highlighting its role in static comfort. Similarly, Takara et al. (2010) showed that seat design influences postural control and comfort, particularly for individuals with higher body fat percentages.

In summary, while body fat percentage is widely recognized as a significant factor influencing seating comfort, direct verification in the literature remains limited. This research provides new insights into this relationship by analyzing correlations between body fat percentage and Local Postural Discomfort (LPD) across different body regions in specific scenarios.

In the BBB_L3 and AAA_L4 scenarios, body fat percentage was found to be significantly negatively correlated with LPD in the buttocks, suggesting that individuals with higher body fat percentages experienced less discomfort in this region. Similar significant negative correlations were observed in the lower back region in BBB_L3 and in the left and right thighs in AAA_L3, further supporting the role of body composition in influencing perceived discomfort.

These findings highlight the importance of accounting for body fat percentage of the target group in seat design to enhance comfort and minimize localized discomfort, especially in critical contact areas like the buttocks, thighs, and lower back. By integrating these considerations, future ergonomic seating solutions can better accommodate the diverse needs of users, contributing to improved comfort and satisfaction in various scenarios.

7.4 Objective measures

The objective measures employed in this study were instrumental in providing a robust and multifaceted evaluation of comfort and discomfort across seating configurations. By integrating physiological monitoring, human motion analysis, thermal imaging, and IMU data, the methods allowed for a comprehensive assessment of seat performance beyond subjective feedback. Each methodology contributed unique insights, underscoring the value of an interdisciplinary approach to evaluating automotive seat design.

7.4.1 Contribution of Physiological Monitoring

The use of skin temperature, EDA, and HR metrics provided valuable insights into participants' physiological states, capturing subtle changes in thermal comfort, stress, and relaxation that subjective reports might miss. For instance, skin temperature highlighted thermal regulation challenges, while EDA and HR revealed shifts in stress and relaxation. However, no statistically significant correlations with comfort or discomfort were found, suggesting individual variability or environmental factors may obscure direct relationships. Future work should integrate these metrics with additional data or employ advanced analysis methods to better link physiological states to subjective perceptions.

7.4.2 Motion Analysis

Skeleton tracking and motion categorization effectively quantified postural adjustments, revealing how configurations supported or inhibited natural micro-movements. It highlighted that increased "small" amplitude motions correlated with better comfort, providing joint-specific insights into discomfort patterns.

Aruco marker tracking complemented this by precisely measuring seat pan and backrest angles, identifying mechanical constraints like limited height adjustment for taller participants, and assessing seat adjustability and alignment with high accuracy.

7.4.3 Thermal Imaging

Thermal imaging added a novel dimension to the study by visualizing temperature distribution on participants' faces, offering direct insights into thermal comfort dynamics, such as the temperature differences between the forehead and nose. This approach linked thermal patterns to seat configurations and participant feedback, underscoring how seat designs impact localized thermal comfort. While findings, such as smaller temperature differences in BBB configurations, provided valuable insights, no clear links between motion and comfort were established through thermal imaging. Further studies, integrating thermal imaging with other metrics, are needed to deepen understanding and expand its application.

7.4.4 IMU Data

IMU sensors on the headrest, backrest, and seat pan enabled a detailed evaluation of vibration characteristics, using metrics like Total Band Power, Peak Frequency, and Relative Power to quantify seat stability and movement dynamics. This approach provided objective validation of seat performance, complementing subjective comfort and discomfort reports.

The granularity of IMU data proved particularly valuable in assessing stability under dynamic conditions, such as during turns or abrupt accelerations. While IMU data offers significant potential for future innovation, road-induced vibrations present a challenge that warrants further investigation to ensure the accuracy and applicability of this method in diverse driving scenarios.

7.4.5 Integration

The integration of objective methods with subjective questionnaires established a holistic framework for evaluating comfort and discomfort in automotive seating. By combining physiological, biomechanical, thermal, and vibration data, the approach captured the multifaceted nature of seat performance. Each method complemented the others, ensuring a comprehensive assessment that addressed all dimensions of user experience.

The interdisciplinary nature of these measures also highlights their potential for future applications. For instance, combining thermal imaging with IMU data could facilitate advanced algorithms to predict discomfort by analyzing both temperature patterns and movement dynamics. Similarly, integrating physiological monitoring with skeleton tracking could refine our understanding of the interplay between stress, posture, and discomfort, paving the way for smarter, more adaptive seating solutions.

7.5 Limitation

7.5.1 Participants

The study's participant demographic was relatively homogenous, focusing primarily on young adults, which limits the generalizability of findings across a broader age spectrum. The BMI distribution of participants predominantly fell within the normal range, excluding individuals with extreme BMI values such as those who are obese or underweight. These factors reduce the comprehensiveness and applicability of the findings to the broader population, particularly the diverse user base of automated vehicles.

7.5.2 Experiment setups

The experiment was conducted in a stationary vehicle model, simulating Level 3 and Level 4 automated driving scenarios through visual cues and participant imagination. Dynamic driving factors, such as acceleration, deceleration, and road bumps, were not replicated, which could significantly influence comfort, discomfort, and thermal perception in real-world scenarios. The controlled environmental conditions, maintaining temperatures between 23°C and 26°C with 30% to 60% relative humidity, may also differ from variable real-world climates, potentially influencing thermal comfort ratings. Additionally, the two-hour experiment duration, while sufficient for some prolonged driving scenarios, may not fully capture the comfort and health issues associated with extended use over longer periods.

7.5.3 Objective measures

The use of objective measures presented certain challenges. Thermal imaging, for instance, relied on facial detection but achieved only a 40% success rate due to occlusion and camera positioning. IMU sensors required precise calibration to ensure consistent accuracy across configurations, but the setup did not account for real-world road vibrations that could influence measurements.

Skeleton tracking was affected by occlusions, such as the left side of the body in the BBB_L4 configuration, limiting the completeness of movement data. Similarly, physiological data collection encountered missing values, particularly in electrodermal activity (EDA) data, due to participant motion during the experiments. These challenges highlight constraints in capturing fully representative and reliable objective data.

8 Conclusions

This study comprehensively evaluates comfort and discomfort in AAA and BBB seating configurations at Level 3 and Level 4 automation, combining subjective feedback with objective measures such as IMU sensors, skeleton tracking, thermal imaging, and physiological data. It provides key insights into how seat design and automation levels influence user comfort.

Dynamic configurations like BBB_L4 enhanced comfort by supporting micro-movements and improving thermal regulation. In contrast, rigid designs such as AAA_L3 were associated with greater discomfort due to limited adjustability and airflow. Objective measures identified critical contributors to comfort and discomfort, including seat pan angles, headrest adjustability, and vibration dynamics, with recommendations provided to address these issues.

The study highlights limitations, such as a homogenous participant sample, static experimental setups, and challenges in methodologies like thermal imaging reliability and EDA data collection, pointing to areas for future refinement.

In conclusion, this research underscores the multifaceted nature of automotive seating comfort and the importance of integrating advanced technologies with user-centered designs. Addressing the identified challenges will enable the development of seating systems that enhance user satisfaction, health, and well-being in automated driving environments.

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