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Findings from an expert group workshop

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Conceptualising user comfort in automated driving: Findings from an expert group workshop

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A R T I C L E I N F O

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A B S T R A C T

The driving style of an automated vehicle (AV) needs to be comfortable to encourage the broad acceptance and use of this newly emerging transport mode. However, current research provides limited knowledge about what influences comfort, how this concept is described, and how it is measured. This knowledge is especially lacking when comfort is linked to the AV's driving styles. This paper presents results from an online workshop with nine experts, all with hands-on experience of AVs and a long track record of research in this context. Using online tools, experts were invited to introduce concepts they considered relevant to comfort/discomfort in currently available modes of transport which offer a ride (taxi/bus/train) to users and compare these to the concepts used to define comfort and discomfort in AVs. Results showed that a wide range of terms were used to describe user comfort and discomfort for both modes. Although all terms used for existing vehicles were found to apply to AVs, additional terms were proposed for determining comfort/discomfort of AVs. For example, to enhance comfort in AVs, designers should consider good communication channels, as well as ensuring that the AV's capabilities match users' expectations. Results also revealed that more terms were used, overall, to define discomfort, and that a comfortable ride in AVs is not just about mitigating discomfort. New concepts specific to AVs were also revealed when considering what increases their discomfort, such as whether riders' safety and privacy are affected, or if they feel in control. Experts' input from the workshop was used to enhance and expand a simple conceptual framework, explaining how AV driving styles, as well as other, non-driving-related factors, affect user comfort. It is hoped that this framework provides a more comprehensive list of the concepts affecting user comfort, also allowing more accurate measurement of the concept. As well as allowing for a more accurate comparison between empirical studies measuring comfort in AVs, this study will facilitate the design of more comfortable and acceptable automated driving for future vehicles.

Introduction

Comfort, as a positive user experience of automated driving, is essential for the broad acceptance of Automated Vehicles (AVs), (Dichabeng et al., 2021; Nordhoff et al., 2021a; Paddeu et al., 2020; Siebert et al., 2013). When being driven by a higher-level AV (SAE Level 4 and Level 5, SAE International, 2021), automated driving styles, such as the vehicle's kinematic behaviour, the distance it keeps with other road-based objects, and how it negotiates different road geometries, play an important role in user comfort (Beggiato et al., 2020; Bellem

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et al., 2016; Diels & Bos, 2015; Peng et al., 2022). It is argued that a wide range of factors influence user comfort when being driven by AVs. For example, *perceived safety* and *trust* are thought to affect comfort (Diels et al., 2017; Hartwich et al., 2021; Nordhoff et al., 2021b), with research showing that when users do not trust AVs, they will refrain from using automation, and not use the driving time for other (non-driving related) activities. Another concern is the prevalence of *motion sickness*. While manual driving does not necessarily result in motion sickness (Rolnick & Lubow, 1991), recent research suggests that as many as two-thirds of adults have suffered from car sickness (Diels & Bos, 2015) with around 10 % of passengers of AVs predicted to suffer from this condition in the future (Sivak & Schoettle, 2015). It is assumed that such discomfort may also be associated with unexpected and abrupt manoeuvres of automated driving. Therefore, understanding what factors affect user comfort, especially regarding the AV's driving style, is critical. Without sufficient knowledge of user comfort in automated driving, such as how it is defined and measured, it is challenging for automated system designers to develop comfortable, enjoyable, and acceptable AVs. Thus, the main aim of the present explorative study, based on an expert workshop, was to enhance our understanding of factors that contribute to an individual's comfort, when being driven by an AV.

Comfort and discomfort in automated driving

Comfort is a highly complex concept, affected by physical factors such as the vehicle's motion, the visual context of the environment, the "driver's" posture, as well as the sound, climate and interior design of the vehicle cab (e.g., da Silva, 2002; Oborne, 1978). It is also influenced by psychological factors such as feelings of safety, pleasure, and peace of mind (Ahmadpour et al., 2016; Carsten & Martens, 2018; Summala, 2007). Research in the automotive, air, rail, and marine sector, and those related to general ergonomics of systems, have resulted in ample definitions of comfort. For example, Slater (1986) defines comfort as "*a pleasant state of physiological, psychological and physical harmony between a human being and its environment*". De Looze et al. (2003) propose three main features, suggesting that comfort: a) is a subjective and personal construct; b) influenced by physical, physiological, and psychological factors; and c) comes from the interaction of the human with the environment. Comfort is derived from positive experiences, such as pleasure and trust, and the lack of negative experiences (discomfort), such as fatigue, anxiety, and fear. However, an overall comfortable experience is easily marred by a minor change in discomfort (Cohen-Lazry et al., 2022; Helander & Zhang, 1997).

Control in a highly or fully automated vehicle is shifted from the human driver to the automated system. In such situations, users will no longer have to monitor the road and can use the driving time for work or leisure activities. This means that users' experiences will be affected by how the automated system drives, i.e., its driving style. As the importance of comfort in AVs is gaining more interest, researchers have started to use a wide range of definitions for defining user comfort in this particular type of vehicle. For example, some studies emphasise the absence of discomfort (Bellem et al., 2016), where comfort is defined as "*a state which is achieved by the removal or absence of uneasiness and distress*" (p. 45). Other studies address both positive and negative aspects of comfort. For example, Carsten and Martens (2018) describe rider comfort as "*the subjective feeling of pleasantness of driving/riding in a vehicle in the absence of both physiological and psychological stress*". Others highlight the role of AV operations, such as "*a subjective, pleasant state of relaxation given by confidence and an apparently safe vehicle operation, which is achieved by the removal or absence of uneasiness and distress*" (Hartwich et al., 2018, p.1019). Similarly, Hartwich et al. (2018) describe discomfort as "*a subjective, unpleasant state of driving-related psychological tension or stress in moments of a restricted harmony between driver and environment, originating from unexpected, unpredictable or unclear actions of the automated system*" (p.1021).

Thus, there are currently various descriptions for user comfort in AVs, emphasising either the lack of discomfort, and/or the use of positive and pleasant concepts, while descriptions for discomfort are few, and are not exactly the opposite of that for comfort. When it comes to measurement of these states in automated driving, some studies have measured comfort directly (Hajiseyedjavadi et al., 2022), while others have solely measured discomfort (Radhakrishnan et al., 2020), by assuming that, for example, the physiological changes associated with this state are easier to detect and quantify (Siebert et al., 2013). These inconsistencies in the definition and measurement of comfort/discomfort for automated driving make cross-study comparisons, for example, about whether a particular AV driving style is comfortable, challenging.

A conceptual framework for comfort in automated driving

As outlined above, comfort in automated driving is an emerging research field which lacks definitions, methods, and models. Previously, conceptual models for comfort have been proposed based on cabin-based ergonomics. For example, in the aircraft cabin, factors such as peace of mind, physical well-being, and aesthetics (such as seat comfort) play a role in passenger comfort (Ahmadpour et al., 2014). Gaining similar knowledge for AVs will support the design of comfortable vehicle interiors, such as information about seat position. However, new insights and models will also be needed to design comfortable driving styles, managed by the AV's motion control strategies. Therefore, to assist with a better understanding of how AV driving styles, in particular, affect user comfort, we first created a simple conceptual framework to help facilitate the discussions of our expert group workshop (Fig. 1). This conceptual framework was then further developed by incorporating the experts' feedback, which forms the bulk of the manuscript. The next section provides more detail about each of the concepts chosen for the original framework.

The link between driving styles and comfort

The original framework focused especially on how automated driving styles affect user comfort. Adapted from a description of manual driving styles (Elander et al., 1993), automated driving styles are related to vehicle kinematics (e.g., acceleration and braking behaviour), and vehicle proxemics (e.g., distance kept to other on-road or roadside objects). Driving style is also about how the vehicle manoeuvre is influenced by road surface and geometry, such as how it negotiates different road curvatures, or whether the ride is smooth or jerky. A number of studies have investigated the link between changes in these aspects of driving style, and user comfort in AVs (Dettmann et al., 2021; Elbanhawi et al., 2015; Hajiseyedjavadi et al., 2022; Hartwich et al., 2018; Peng et al., 2022; Summala, 2007). For example, Bellem et al. (2018) propose a range of kinematics to assist with user comfort during different manoeuvres of highly automated vehicles, such as minimising acceleration and jerk – i.e. the rate at which the acceleration changes with respect to time. Peng et al. (2022) measured user comfort for two human-like and one machine-like driving style, and found that the replay of real human participants' driving (categorised as a "defensive" driving style - driving at lower speeds), was evaluated as more comfortable than the other two.

High levels of automation increase the importance of driving style for user comfort. SAE level 4 and 5 AVs (SAE International, 2021) can operate autonomously, without any input or action by users. This can detach the on-board users from the surrounding environment, taking them "out of the loop" (Merat et al., 2019). This reduces their overall situation awareness, especially if they are engaged in other, non-driving related, activities (NDRAs). In these situations, any unexpected or unpredictable manoeuvres of the AV (e.g., a sudden brake) may not only interrupt the user's engagement in the NDRA, but also cause concern, discomfort, or even motion sickness (Beggiato et al., 2020; Carsten & Martens, 2018; Hartwich et al., 2018; Kuiper et al., 2020). Elbanhawi et al. (2015) argue that a comfortable AV ride demands natural and familiar manoeuvres (see also Peng et al., 2022), smooth control, safe operations, and the mitigation of motion sickness, in addition to the

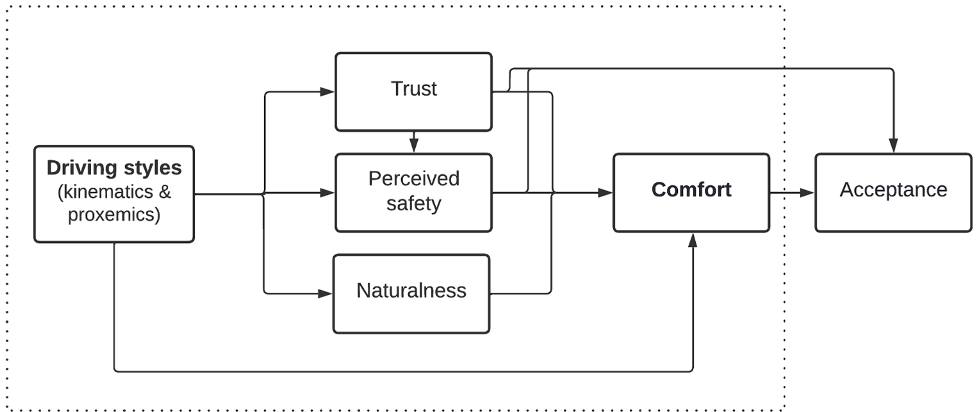

Fig. 1. The original conceptual framework for comfort in automated driving. This literature-based framework focused on incorporating psychological concepts to understand influences on comfort. The concepts and terms included in the dashed box are discussed in the present study.

traditional (physical) factors that enhance comfort (e.g., temperature, noise, and seat design; De Looze et al., 2003; Silva, 2002). Therefore, for our original framework, we focused particularly on understanding what *psychological aspects* affect comfort in AVs, to help enhance users' psychological experience (i.e., how they feel about different driving styles).

Perceived safety, trust, and naturalness

Perceived safety, trust, and naturalness (sometimes referred to as familiarity), have also been linked to comfort in automated driving (Elbanhawi et al., 2015; Paddeu et al., 2020), and each concept is also considered to be influenced by a vehicle's driving style (Hajiseyedjavadi et al., 2022; He et al., 2022; Lee et al., 2019; Oliveira et al., 2019; Summala, 2007). Some of these concepts, together with comfort, are frequently used interchangeably. For example, He et al. (2022) describe perceived safety as "*feeling relaxed, safe and comfortable*" (p.179). Although a number of studies have described trust in automation, perhaps the most cited is one provided by Lee and See (2004) as: "*the attitude that an agent will help achieve an individual's goal in a situation characterised by uncertainty and vulnerability*" (p.51). Finally, Peng et al. (2022) describe natural driving as "*a driving style that is closest to your own*" (p.6), while Hajiseyedjavadi et al. (2022) use a combined description of feeling "*safe/natural/comfortable*" to evaluate an overall pleasant experience with automated driving. Overall, similar (positive) affects are used to describe these concepts and also comfort, when discussing the effect of automated driving style on user experience. Hartwich et al. (2018) suggest that feeling safe, relaxed and certain can all lead to a positive experience of automated driving, which will ultimately enhance acceptance of these new forms of mobility (see also acceptance models reported by Madigan et al., 2016; Motamedi et al., 2020; Nordhoff et al., 2021b). Therefore, the original conceptual framework included these mostly investigated concepts (i.e., perceived safety, trust, and naturalness), in order to clarify the relationship between these, and establish if and how each contributes to comfort, based on different automated driving styles.

The current study

Based on the above literature review, and the resulting conceptual framework, the aim of the current study was to address the gaps in knowledge about the definitions and measurements used for comfort. To help address this gap, we conducted an online expert workshop with individuals who had a long tracking record of working with different types of AVs. Our objective was to improve the current understanding of what contributes to user comfort/discomfort in automated driving, with a particular focus on the role of driving styles. We believe this knowledge can ease cross-study comparisons for future empirical studies in this area. It can also help AV designers have a better understanding of user comfort, creating more comfortable, pleasant, and acceptable vehicles for a wide-ranging user group.

In particular, the main objectives of the present study were to:

1) Conceptualise comfort/discomfort in automated driving, by identifying the descriptions and terms used for both comfort and discomfort, as well as highlighting any differences and similarities between the terms used for these two states.
2) Elaborate our original conceptual framework of AV driving comfort, clarifying the relationship between a number of commonly used concepts, and comfort, especially for AV driving styles.

We expected a partial overlap between comfort when being driven by currently available human-driven vehicles (e.g., taxis, buses, and trains), and being driven by AV-controlled computer systems, because for both modes, the human is a passenger not controlling the vehicle. To assess this partial overlap, we discussed comfort in, and between, these transport modes.

Method

In this section, we provide a brief introduction of the method used in the workshop. More details can be found in Appendix A, including the rationale for the method used, how the discussion was facilitated, and the method used for data analysis.

Experts and the group workshop

Due to the Covid-19 pandemic, we conducted an online workshop with nine internationally-recognised experts in this field, which took place on the 27th July 2021. These nine attendees (RM, CM, JL, JK, MB, RR, CW, EW, and NM), and two more experts (MH and RH), were invited to comment on the manuscript, and are all co-authors of the manuscript, due to their verbal and written contributions. We were keen to include experts with some hands-on experience with higher-level AVs, because these vehicles are currently unavailable on the market (Madigan et al., 2017), and research shows that actual experience with new technologies is essential for understanding their limitations and capabilities (e.g., Hancock et al., 2020; Kyriakidis et al., 2019; Tabone et al., 2021). The group workshop loosely followed a focus group format, where experts discussed a range of proposed topics via the online meeting platform Microsoft Teams (https://www.microsoft.com/en-gb/microsoft-teams/online-meetings). In order to stimulate discussions, experts were encouraged to brainstorm a range of proposed topics, as well as write notes, grouping similar items, using the online collaborative whiteboard tool: Miro (https://miro.com). These notes were visible on the whiteboard, allowing the facilitators and experts to further discuss the evolving themes. The whole workshop was recorded via Microsoft

Teams, and lasted two hours.

Procedure

Fig. 2 shows the procedure used in the workshop. The workshop discussions were divided into four separate sessions, in which different, but connected, topics were covered:

Session 1: This session focused on a discussion of the terms used to describe comfortable and uncomfortable experiences when driven by currently available vehicles as a passenger, such as a taxi, bus, or train. This was done for two reasons: first, it helped experts familiarise themselves with the topic by talking about currently available transport modes. Second, we wished to understand if there were any similarities and differences in the perceived comfort/discomfort of "being driven" by a taxi/bus/train, compared to that of a Level 4 AV, because, in both cases, the user does not control the vehicle, and is also able to engage in NDRAs (Hecht et al., 2019).

Session 2: This session involved a discussion of any differences between being driven by a taxi/bus/train versus an AV, in terms of the experienced comfort/discomfort. This session was expected to connect with, and facilitate, the discussions in Session 3.

Session 3: This session involved a discussion of terms used to describe comfortable and uncomfortable experiences of being driven by AVs. Discussions in this session were based on the previous two sessions. After reflecting on the unique characteristics of AVs in Session 2, it was expected that experts would add or remove terms about comfortable/uncomfortable experiences of being driven by AVs, based on existing terms for a taxi/bus/train from session 1.

Session 4: This session focused on discussing the original conceptual framework for user comfort in automated driving (Fig. 1), with an emphasis on how comfort is affected by different driving styles. After discussions in the preceding sessions, experts were expected to give constructive feedback on the original framework, in terms of complementing and revising relevant aspects and concepts, rather than clarifying concrete terms. Here, we explicitly instructed experts to take driving styles into consideration, compared to the preceding sessions, in which the term "being driven" was used to implicitly remind experts of the driving scenario. However, we still encouraged discussions of broad but relevant concepts, in addition to driving styles.

Data analysis

Fig. 4 shows the approaches that we used to analyse the data, following the online workshop. Written notes from the experts were categorised, and verbal discussions were summarised. Experts were given an opportunity to suggest amendments to the categorisation of notes, the summarisation of their discussions, and the refined framework.

Results and discussion

Results are presented in order, based on the timeline of the four workshop sessions, outlined above. We first present the terms used by experts to describe comfort and discomfort when being driven by currently available transport modes (e.g., taxi/bus/train), in Session 1. Then, differences between these transport modes and AVs in terms of comfort/discomfort are summarised (Session 2), followed by additional notes associated with the comfortable and uncomfortable aspects of being driven by AVs (Session 3). Finally, a refined conceptual framework is outlined, by incorporating the input of this expert workshop into the original model. In each section, we discuss and summarise the key findings, to interpret their theoretical and practical implications.

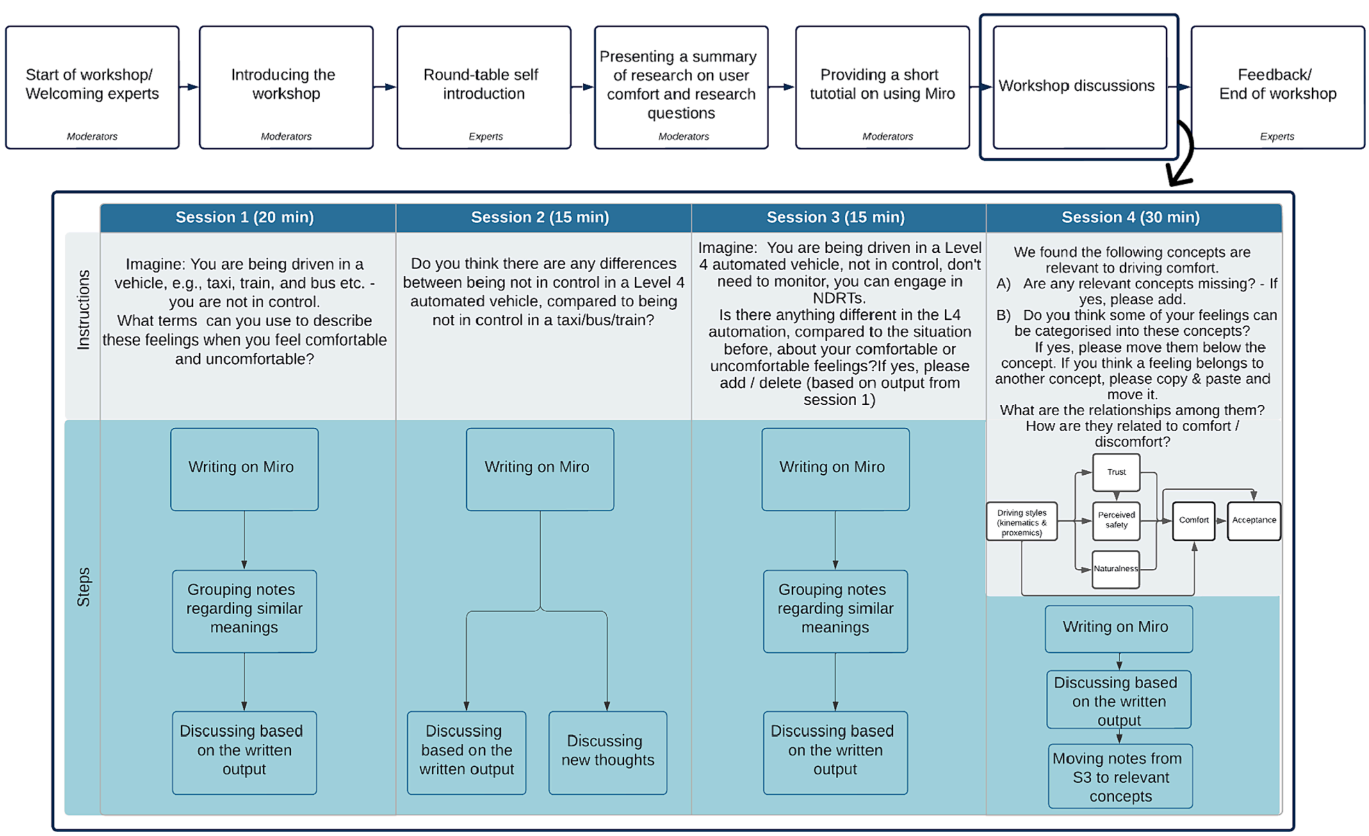

Fig. 2. Full procedure (top) and the four main sessions in the workshop. All introductions and the tutorial before the four sessions took around 15 mins, followed by around 5 mins for feedback and reflection. A 10-min break was included between Session 3 and 4.

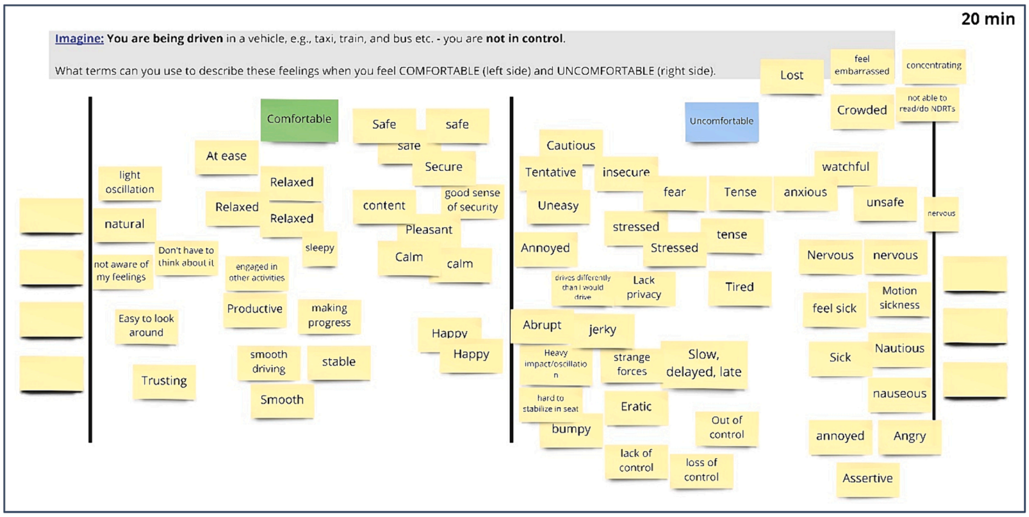

Fig. 3. The Miro whiteboard used for Session 1, in which experts posted notes to describe comfortable (left) and uncomfortable (right) experiences of being driven by a taxi/bus/train in the designated areas. The text in the shaded area on the top is the written instructions about the discussed topic, and the empty yellow sticky notes were "a pile of notes" for easy use, prepared by the moderators in advance of the workshop. The yellow sticky notes with texts were posted by experts during the writing session. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

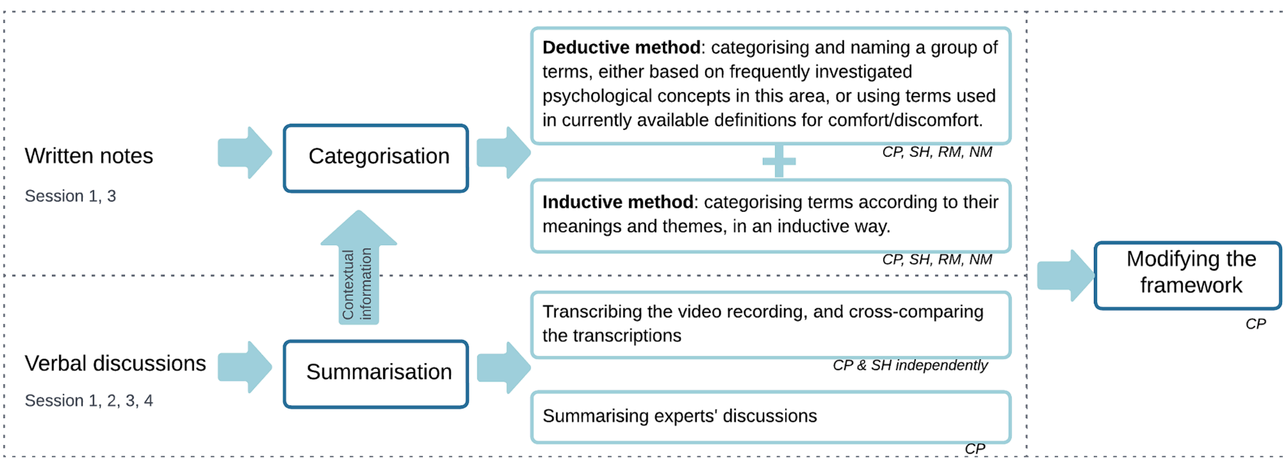

Fig. 4. Procedures used for the data analysis. Initials represent people who were responsible for different steps of the analysis.

Session 1: Comfort and discomfort of being driven by a taxi/bus/train

In this section, we present a categorisation of the terms used by the experts to describe comfort/discomfort when driven by currently available transport modes (Fig. 5). The terms were first provided and roughly grouped by experts during the workshop, after which a categorisation of these terms into new groups was done independently, and then as a team, by CP, SH, RM, and NM, after the workshop. We also provide a summary of experts' comments on emerging patterns for these terms.

Categorisations of terms provided by experts in session 1

Regarding comfort, we categorised the terms used to describe a comfortable experience when being driven by a taxi/bus/train into five groups (Fig. 5). A single term was then used to define each category of terms with similar definitions. These five categories were 1) *ease*, 2) *perceived safety*, 3) *physical comfort*, 4) *engagement in NDRAs, and* 5) *pleasantness.* As mentioned in the Method section (section 2.3, and Appendix A), when the content shared similarities with keywords from previously used definitions, we chose these same terms or concepts, with new terms used for new, previously absent, groups of terms. Further details are provided in Table 1.

Experts' discussions on emerging patterns from the written notes in session 1

After writing and roughly grouping the notes, experts selected and discussed the pattern of results that were of interest to them, rather than going through all of the possible terms and categories. In particular, the experts highlighted the differences between comfort and discomfort, with regards to affective and physical aspects, as summarised and presented below.

Two experts highlighted that affective feelings of comfort (e.g., calm, relaxed, pleasant) are less intense than that of discomfort (e.g., anxious, stressed, tense). When feeling comfortable, people may be unaware of the feeling, or unconscious of what is going on in the vehicle, whereas being uncomfortable is very "tangible and extreme". Another expert added that if expectations about a comfortable experience cannot be fulfilled, all aspects that cause discomfort become conscious, which may also cause them to feel insecure and uncomfortable. On the other hand, this expert also added that: "*If we expect uncomfortable situations of a taxi journey, but we are lucky that things turn out nicely and the taxi driver is skilled at everything, we are very much aware of the comfortable aspects*".

With respect to the physical aspects of comfort/discomfort, four experts pointed out that terms related to the vehicle's movement were used more often when describing discomfort than comfort, and one of them emphasised the role of vibrations. This expert explained that in the

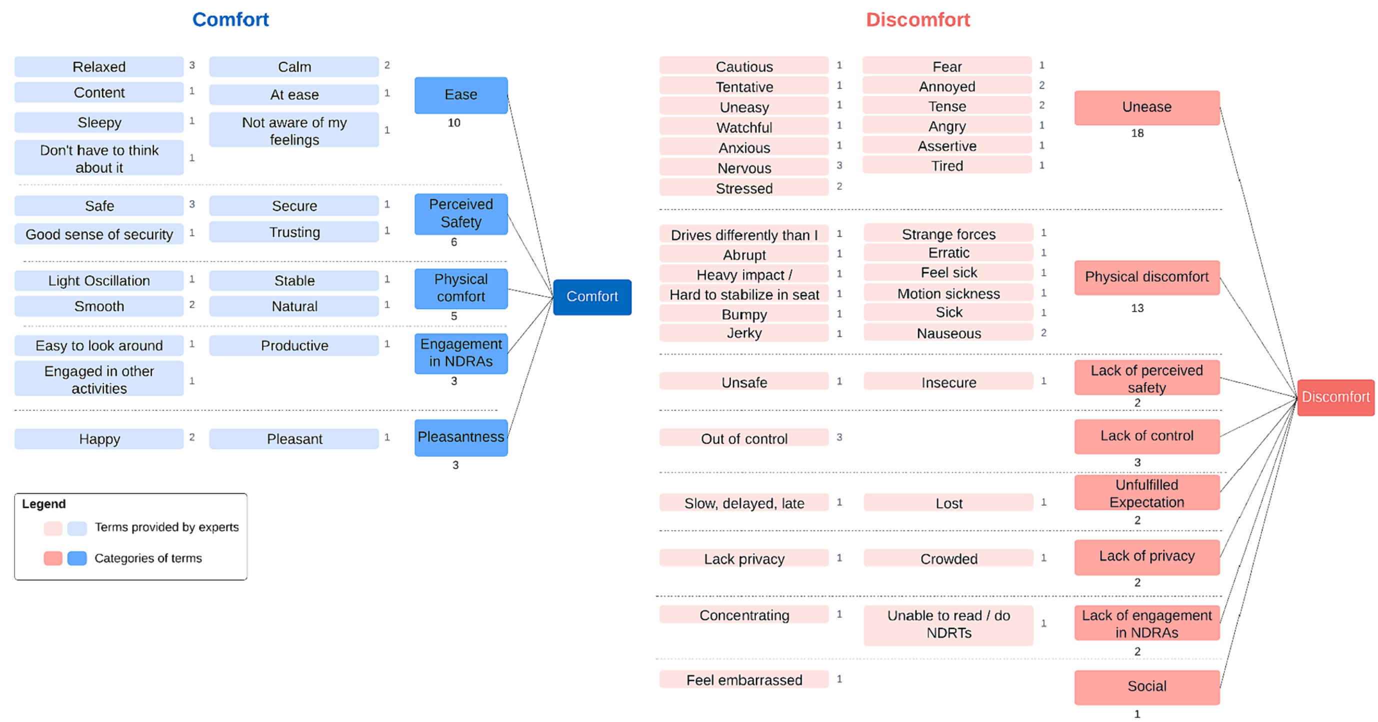

Fig. 5. Categorisation of the terms describing comfort and discomfort when driven by a taxi/bus/train. Numbers next to each box represent the number of times each term was mentioned by experts, and numbers below each category represent the number of terms in the category. Experts were instructed to write as many notes as they could and avoid repetitions, but they sometimes could not avoid repetition when writing in parallel, so a larger number of a term was not interpreted as more important.

vehicle and control domain, the concept of ride comfort is not about comfort itself, but refers to the lack of oscillations or vibrations in the vertical direction of the vehicle. For example, both high- and low-frequency vibrations, as well as noise are uncomfortable for vehicle users. This expert argued that this is because "*vibrations that are far away from the natural frequency of the humans make the user sick*", while another expert added that low-frequency vibrations are typically associated with carsickness. Therefore, it seems that the physical vehicle movement manifests more uncomfortable than comfortable feelings.

To summarise, both categorisation of the terms and experts' discussions about the patterns arising from these terms indicate that when being driven by currently available transport modes, the feelings and terms associated with comfort are different from the lack of discomfort. For example, more (and more concrete) terms were used to describe discomfort than comfort, whereas comfort demands more (and more positive) psychological and emotions than discomfort. This difference in the number of descriptions for comfort/discomfort might also be explained by the fact that humans have a wider vocabulary for expressing negative, than positive, emotions (Schrauf & Sanchez, 2004). This is also because negative experiences are associated with more elaborate and detailed cognitive interpretations compared with positive experiences (the psychological theory of *affect-as-information*; Schwarz, 1990). In terms of the intensity of these two states, the *Circumplex Model of Affect* (Russell, 1980) is used to represent affective concepts in two dimensions: *valence* (ranging from displeasure to pleasure) and *arousal* (ranging from sleep to arousal). Our results suggest that the affect-related terms for comfort are lower in arousal, but higher in valence, compared to discomfort. This implies that solely eliminating discomfort (e.g., lowering the arousal) does not necessarily lead to comfort, because comfort is also associated with pleasantness and enjoyment. This finding also has implications for measuring these two states, because physiological responses (e.g., heart rate, electrodermal activity) are more suitable for identifying the high arousal associated with discomfort (Beggiato et al., 2019; Radhakrishnan et al., 2020), and less likely to detect the lower levels of arousal linked to comfort.

Sessions 2 and 3: Differences between being driven by a taxi/bus/train versus an AV

In Session 2, when considering the differences in comfort/discomfort of being driven by currently available transport modes compared to an AV, experts focused on brainstorming and discussing the different terms, rather than writing notes. Four main topics were highlighted as being relevant to AVs, compared to current transport modes. These were: i) the duration of using AVs, ii) user expectations about AV driving styles, iii) privacy concerns, and iv) the presence of a human operator.

In terms of the duration of using AVs, an expert suggested that, at the early stages of AV deployment, there will either be no boundaries within what users believe the AV should and should not do, or no understanding of how the AV should behave, compared to that of a human taxi driver. Two experts also pointed out that, in the initial stages, the experience of comfort with AVs will be influenced by its novelty. Also, who will take responsibility of controlling the AVs is unclear for users, compared with a taxi, where the driver is responsible. However, it was also argued that these experiences and beliefs will likely change with the passage of time, and repeated use of AVs.

Regarding driving styles, four individuals agreed that AV driving styles should meet *users' expectations*, in order to ensure user comfort, which is thought to be different for expectations about how taxis/buses/trains should be driven. Although how users' expectations will develop over time remains unclear, experts suggested a number of factors, with regards to the AV's driving style, which might help with meeting expectations. First, an expert advised that at the very least, the automated drive should be smooth. Furthermore, the use of "human-like" and personalised driving styles (i.e., similar to the users' own driving behaviours) was also suggested, to meet users' anticipated trajectories and behaviour for automated driving. However, what should be personalised, and how, remained unclear. One expert mentioned a study on Level

Table 1
The categories used for comfort.

Category	Inclusion of terms	Rationale for category name
Ease	This category included terms such as calm, content, and relaxed, mostly describing a feeling of being at ease.	This term has been frequently used in previous definitions of comfort (e.g., Carsten & Martens, 2018).
Perceived safety	This category consisted of a group of terms describing feeling safe, secure, and trust. This term is considered to contribute to comfort (Elbanhawi et al., 2015), and also used previously (e.g., Hartwich et al., 2018).	
Physical comfort	This category included terms describing physical vehicle movements (e.g., smooth and stable), and natural driving styles.	This theme was derived from "physical harmony" between the user and the vehicle, used in previous studies (e.g., Slater, 1985).
Engagement in NDRAs	This category comprised terms about people's willingness to do non-driving-related activities. The theme has been considered as a key attractive feature of highly automated driving (Merat et al., 2012) and broadly investigated in this area.	
Pleasantness	This category consisted of terms describing feelings around happiness and positive affect.	This term was chosen because of its presence in previous studies (e.g., Summala, 2007)

Regarding discomfort, the terms used to describe an uncomfortable experience of being driven by a taxi/bus/train were grouped into eight categories: 1) *unease*, 2) *physical discomfort*, 3) *lack of perceived safety*, 4) *lack of control*, 5) *unfulfilled expectation*, 6) *lack of privacy*, 7) *lack of engagement in NDRAs*, and 8) *social* (Fig. 5). Some terms are antonyms of the terms used for comfort, such as *unease*, *physical discomfort*, *lack of perceived safety*, and *lack of engagement in NDRAs*, while explanations for other (new) terms are provided below (Table 2).

Table 2
The categories used for discomfort.

Category	Inclusion of terms	Rationale for category name
Unease	This category contained the most terms used for discomfort, which were all about people's negative affective feelings (e.g., anxious, nervous, and annoyed).	Thematic summary of terms. The opposite of ease.
Physical discomfort	This category included terms describing uncomfortable vehicle movements (e.g., jerky, abrupt, and erratic) as well as motion sickness.	Thematic summary of terms. The opposite of physical comfort.
Lack of perceived safety	This category included two terms describing unsafe and insecure feelings.	Thematic summary of terms. The opposite of perceived safety.
Lack of control	The category comprised of terms about the user's loss of active control over the vehicle.	This name was chosen because being a passenger without control over the vehicle is seen as one factor resulting in discomfort and motion sickness (Rolnick & Lubow, 1991).
Unfulfilled expectation	This category included terms which describe unexpected operations (e.g., slow) or consequences of an uncomfortable ride (e.g., was lost).	Thematic summary of included terms.
Lack of privacy	This category included two terms describing users' privacy concerns, for example, because of the presence of unknown co-passengers. The term crowded was grouped into this category as we interpreted that being in a crowded vehicle reduces personal space and increases privacy concerns.	Thematic summary of included terms.
Lack of engagement in NDRAs	This category contained terms describing the user's inability to concentrate on NDRAs.	The opposite of engagement in NDRAs.
Social	This category only included one term describing how the social context and other people's judgements affect user comfort.	Thematic summary of the included term.

2 vehicles which found that participants preferred not to change lanes all the time. However, there was a debate on whether or not users of personalised Level 4 AVs would like the AV to drive like a "good citizen" (e.g., staying in one lane or not speeding). For example, an individual commented that: "*I would be unhappy with a car that is too cautious. I do not want to totally waste time on my trip. But maybe it would change if I feel less stress about getting to the destination*". There is a question here, therefore, regarding safety versus efficiency offered by these new forms of transport. Further work is required to understand what driving styles users want from a Level 4 AV.

An expert highlighted a couple of examples regarding the privacy issues that influence user comfort in AVs, compared to taxis/buses/trains. This included issues around invasion of privacy, for example because their conversation may be heard by a remote operator, or unfamiliar co-passengers, which may or may not be different to being heard by a taxi driver. There was also concern about the use of user information by data owners, which can infringe user privacy, for example regarding route choice and location, and causing discomfort.

Three experts discussed how the presence of a driver in AVs might also affect user comfort. One expert suggested that sharing a taxi with an unfamiliar man might be uncomfortable for a woman; but that the presence of a driver might mitigate such discomfort. In comparison, when driven by an AV, where no driver is present, users might be uncomfortable with other unknown passengers, rather than being uncomfortable with the AV. On the other hand, it was noted that humans tend to trust other human beings more, even though algorithms may be much better for controlling the vehicle. This expert speculated that the sense of "self-preservation" of humans might play a role in this human-algorithm preference; in that human drivers do not typically intend to cause a crash, while this is perhaps more of a worry for the algorithms that control AVs. This led to the conclusion that such concerns cannot be solely mitigated by vehicle behaviour, its control or motion, and is more related to features such as the role of AVs as social agents.

To summarise, experts used knowledge about currently available transport modes to suggest how different aspects of driving style for future AVs can be used to improve user comfort. This information can be used by system designers and manufacturers of future AVs to create more comfortable driving, increasing the acceptance and uptake of these vehicles. However, there is currently little understanding of whether/how AV driving style should be personalised (e.g., Butakov & Ioannou, 2015), or human-like (e.g., Basu et al., 2017; Wei et al., 2019). An understanding of the value of these changes for different user groups is also limited (e.g., Feierle et al., 2020). Current technological and infrastructure-based limitations mean that AV capabilities are not matching user expectations, which can, in turn, lead to a more uncomfortable/unsatisfactory ride. This corresponds with work conducted by Nordhoff et al. (2019), who found that users' impressions of automated shuttles were idealised and unrealistic, resulting in disappointment, after experiencing a ride in a very slowly-operated automated shuttle prototype. Therefore, until the technology that enables these vehicles is improved, educating users on AV capabilities will play a key role in calibrating user expectations about AV driving styles.

Finally, experts' concerns about privacy are in agreement with other studies which found that users were worried and uncomfortable about access to their privacy, such as tracking their location and destination, or image capturing, and issues around how this data is protected from abuse by others (Bloom et al., 2017; Nordhoff et al., 2019). The importance of considering other factors not related to driving style in this context can be supported by the theory of constructed emotion, which suggests that the way that feelings and emotions are constructed is highly context-bound (Barrett, 2017). In our case, whether or not a particular driving style is experienced as comfortable may depend on, for example, whether or not the user is concerned about their privacy. However, this issue is unlikely to be solved via driving styles. Future studies should investigate ways to cope with these concerns, via, for example, personalised data-sharing settings.

As highlighted above, some additional terms were identified in Session 3, that were specific to feeling comfortable/uncomfortable when driven by AVs. Similar to the results of Session 1, we present the categorisations of these terms, combining the previously suggested terms with those which were newly added (Fig. 6). We also provide a summary of the experts' discussions about the observed patterns and the commonalities between these additional terms.

Categorisations of additional terms provided by experts in session 3

In addition to the five categories of user comfort already defined above (i.e., *ease*, *perceived safety*, *physical comfort*, *engagement in NDRAs*, and *pleasantness*; see also section 3.1.1), we identified two more categories for the terms describing a comfortable experience of being driven by an AV: *Design expectation*, and *communication* (Fig. 6 and Table 3).

With regards to terms describing an uncomfortable AV ride, several new terms were used that could be added to the existing categories, namely, *physical discomfort*, *lack of perceived safety*, *lack of control*, *unfulfilled expectation*, and *lack of privacy* (see also Fig. 6). For example, we added the term "*threat from passengers*" to the category "*lack of perceived safety*", because the user may feel unsafe when sharing an AV with

Table 3
The additional categories used for comfort in automated driving.

Category	Inclusion of terms	Rationale for category names
Design expectation	This category included terms describing users' high expectations about AVs, and these expectations relate to design aspects of AVs, such as personalisation, being intuitive, and being "pleasantly surprised".	Thematic summary of terms.
Communication	This category included terms describing effective communication between the user and the AV, such as sufficient communication of AV capabilities with users	Thematic summary of terms.

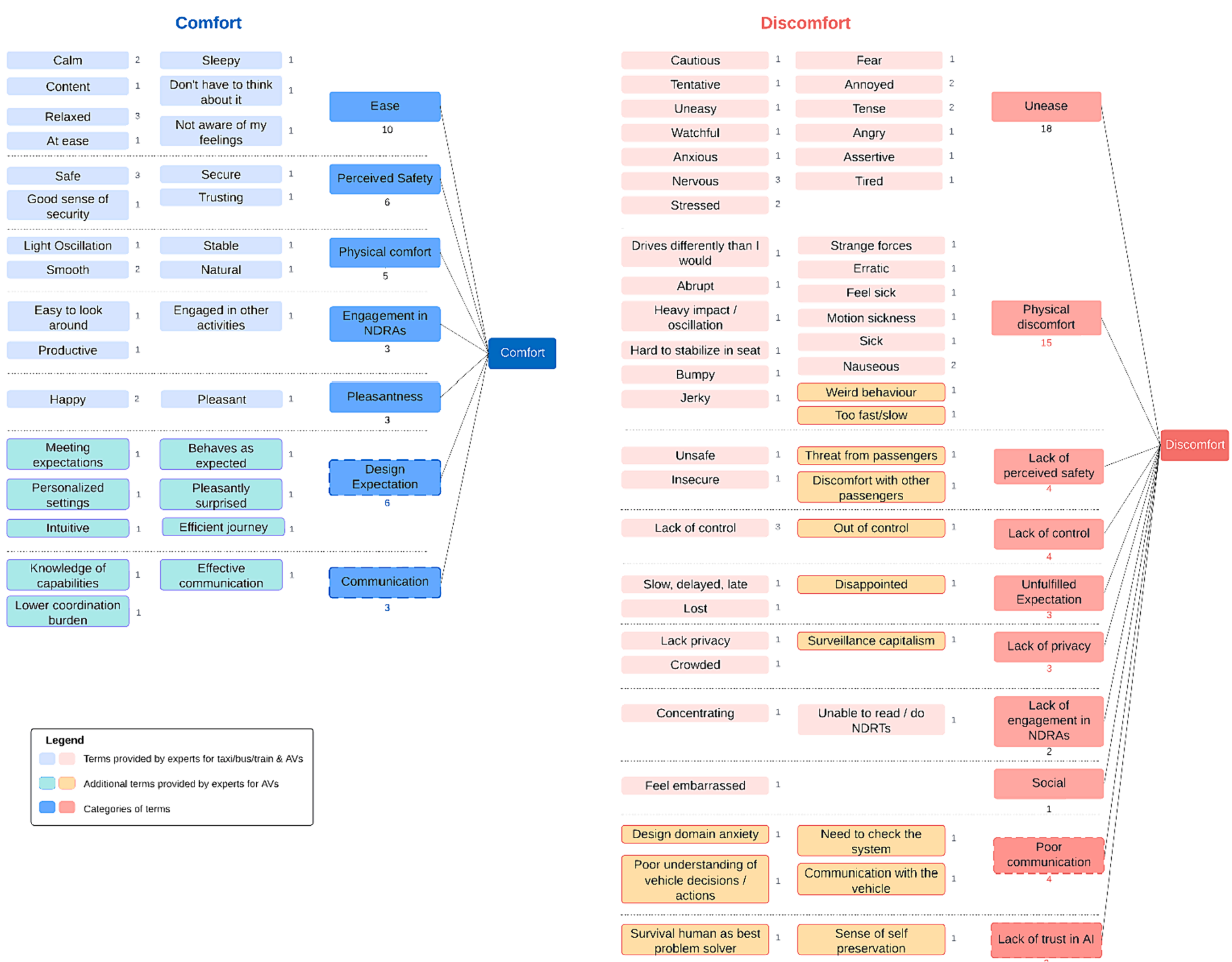

Fig. 6. Categorisations of terms describing comfort and discomfort of being driven by AVs. Numbers next to each box represent the number of times each term was mentioned by experts, and numbers below each category represent the number of terms in the category.

strangers, in the absence of a driver (see also section 3.1.1). In addition to these categories, we grouped a number of newly added terms into two more categories: *Poor communication*, and *lack of trust in AI* (Table 4).

Experts' discussions on emerging patterns from terms for comfort/discomfort of being driven by AVs in session 3

In Session 3, two experts commented that the *communication* with the AV is an important factor for user comfort, with the lack of communication leading to discomfort. One expert suggested that communication will become more important for users, especially when something unexpected happens. This is because it makes the user uncomfortable, especially if there is no explanation from the AV. However, explicit communication might be unnecessary if the vehicle acts as expected. Another expert added that *interaction* will be needed to improve human-AV communication, such as providing information about what the system is doing, its planned manoeuvres, or a message at the end of the Operational Design Domain (ODD). Moreover, the information provided by the AV system should not be disturbing, and, as an expert suggested, "*I would like to have a choice to select how much information I want to get*". Another type of interaction mentioned was the user's ability to change the settings of the system in certain circumstances. For example: "*for lane changing, if I am not in a hurry, it is totally ok that the AV drives defensively and stays in the same lane, but if I have to reach the destination in a certain time, I may change it to drive more aggressively*".

To summarise, when automated driving was considered (in both Session 2 and 3), further new terms and categories were added, but the number of terms and themes for discomfort was again higher than those provided for comfort. This pattern is in line with findings for currently available vehicles (section 3.1), and those of other studies, on ergonomics and product design (Helander & Zhang, 1997; Vink & Hallbeck, 2012). Thus, we suggest that the relationship between comfort and discomfort is not limited within a particular transport mode or a specific product, but applies to a broader area. Moreover, the discussions from Session 2 and 3 suggest that the factors which affect user comfort in currently available transport modes are clearly different to what is expected from automated driving. This suggests that actual experience with future transport modes is needed to further enhance our understanding of how their comfort can be improved, especially with respect to driving style.

Session 4: The refined conceptual framework of user comfort in automated driving

In this section, we present the refined conceptual framework (Fig. 7), by integrating the outputs from this expert workshop, also following feedback from our experts (Session 4). Experts re-emphasised some concepts that were discussed, but also suggested changes to the original framework. Using this conceptual framework, we explain how driving styles, as well as non-driving-related factors, influence user comfort of AVs. As suggested by the experts, we divided user comfort in automated driving into two layers: The physical layer and the psychological layer, both of which can influence each other in an iterative manner.

Physical factors

Regarding the physical layer, apart from driving styles, one expert emphasised that traditional aspects of the physical environment, such as stabilising the head and body, avoiding high G-force, reducing high levels of vibration/temperature/noise, and considerations about seating comfort, should be thought out for AVs, just as they are for traditional vehicles (see also section 3.1). This expert also suggested that although some of these aspects may not actually hurt the user, they will cause strong physical discomfort, and may also affect users' trust and perceived safety. Therefore, we highlighted *physical comfort* as a component of the model, which is directly influenced by AV driving styles.

Psychological factors

Regarding the psychological layer, *psychological comfort* was highlighted in the model, because becoming psychologically comfortable is linked to several positive affective feelings (e.g., happy, content, at ease) (see also section 3.1).

A number of factors were considered to contribute to this state of feeling comfortable. In addition to *trust, perceived safety,* and *naturalness,* proposed in the original model, the concepts *privacy, engagement in NDRAs, situation awareness,* and *expectation,* were added to the psychological layer. Here, we provide explanations for why and how these concepts fit the framework.

- Regarding *privacy,* although it may be considered somewhat irrelevant to driving styles, it is still an important factor that will ensure user comfort of AVs (as outlined in section 3.2).
- In terms of *engagement in NDRAs,* this can also be influenced by driving styles, when, for example, hard braking patterns impede users' ability to engage in reading. A more comfortable ride encourages engagement in NDRAs, which can, in turn, lead to a content passenger, reducing boredom and increasing enjoyment/productivity. Conversely, experts commented that looking away from the road and engaging in NDRAs may make some users feel sick.
- *Situation awareness* was added to the framework and linked to comfort, as suggested by experts in Session 4. This can be influenced by the AV's driving style (e.g., by providing the user with particular driving kinematic cues to keep them aware of the surrounding environment). Conversely, by allowing users to engage in other tasks, and not paying attention to the driving task, the AV can actually reduce situation awareness.
- With regards to the addition of *expectation* to the model, users are thought to hold a large number of high expectations about AV capabilities and driving styles (e.g., linked to personalisation), and whether or not these expectations can be realised and fulfilled leads to either pleasantness, or disappointment (see also section 3.2). Moreover, we added links between *expectation* and *trust*, *perceived safety*, as well as *naturalness*. For example, by having sufficient communication and interactions with AVs to calibrate users' expectations, their trust and perceived safety of the system might be enhanced. In terms of its link to naturalness, if the AV could drive as expected, users may feel the driving styles are intuitive and natural. One expert also pointed out that *expectation* is heavily featured in the Unified Theory of Acceptance and Use of Technology Model (UTAUT) and the Technology Acceptance Model (TAM), which also supports the importance of taking this concept into consideration.

Factors across the two layers

Experts suggested that the influence of *environmental and traffic* conditions on comfort of AVs is broad and applies to both physical and psychological layers in the framework. This is because the behaviour of the automated vehicle is not independent of the surrounding

Table 4
The additional categories used for discomfort in automated driving.

Categories	Inclusion of terms	Rationales for category names
Poor communication	This category included terms characterising users' poor understanding of the AV capabilities and manoeuvres, and linked to discomfort.	Thematic summary of terms. The opposite to *communication* for comfort.
Lack of trust in AI	This category included two terms describing the reduced trust of users in the automated system, compared to a human driver	Thematic summary of terms.

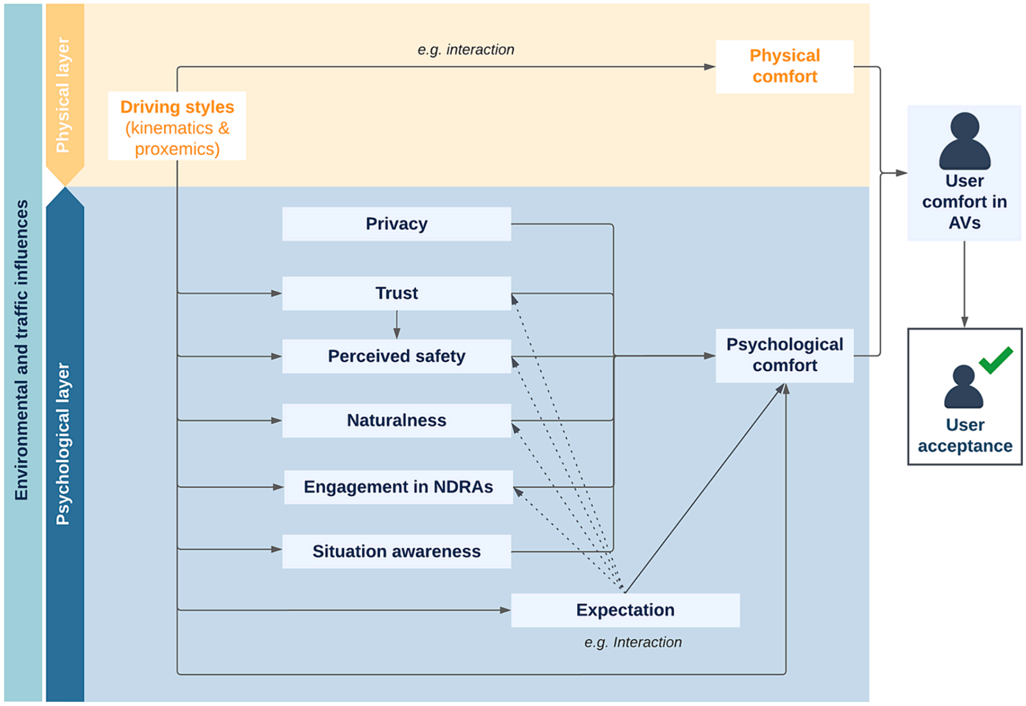

Fig. 7. The refined conceptual framework of user comfort in automated driving. Arrows represent the direction of the factors, either based on current literature (Section 1.2) or experts' considerations (Section 3.3). Dashed lines are used to ensure relationships are visible when lines intersect with each other.

infrastructural and road geometry, and is likely to be influenced by the behaviour of other road users sharing the same space.

Across the two layers, physical *driving styles* can influence *psychological comfort* directly, not solely because of an enjoyable driving style, but also because being driven by an AV is in a social context, as suggested by experts (see also section 3.1). Other road users will look at the AV, and the way they think about the user can influence the user's wellbeing. For example, an expert explained that the AV user would be embarrassed to be stuck waiting for road obstacles due to the AV's limitations, if all other manually driven cars can pass the obstacle. Another example included the use of ACC: "*I do not use my ACC very often because I have to override it – speed up or change lane. When it strictly follows the speed limit, everyone around me is like going faster than me.*".

Interaction is embedded in the framework on both layers, rather than being an independent concept. As re-emphasised by an expert, users will demand different types of interaction to communicate with the AVs. For example, on the physical level, users may be willing to set up a slower AV driving style for better physical comfort (e.g., avoiding motion sickness). From a psychological perspective, users might expect to have various information about the system to feel secure.

General discussion

In the present study, we used an online workshop to gather experts' insights on user comfort/discomfort when driven by automated vehicles (AVs). Based on the output from the workshop, we refined a conceptual framework of user comfort in automated driving, focusing on the effect of driving styles, but also taking into account the effect of factors not immediately related to driving style. To help discussions, we compared the concepts used for defining comfort and discomfort in current modes of transport where the user is "driven", with that used for AVs.

Our results identified seven aspects of user comfort (Defined as: *ease*, *perceived safety*, *physical comfort*, *engagement in NDRAs*, *pleasantness*, *design expectation*, and *communication*) and ten related to discomfort in automated driving (Defined as: *unease*, *physical discomfort*, *lack of perceived safety*, *lack of control*, *unfulfilled expectation*, *lack of privacy*, *lack of engagement in NDRAs*, *social*, *poor communication*, and *lack of trust in AI*). For both of these states, more terms were used for AVs, when compared to current modes of transport. When it comes to definitions and measurements of comfort, we recommend that future studies consider a wider range of concepts when assessing comfort and discomfort to help support the research, design and evaluation of these states in AVs. This also calls for new measures, including suitable questionnaires that can be validated in terms of their ability to discriminate a wide range of aspects of comfort and discomfort.

Apart from the content of the workshop, we found that the format of the online setup worked well in this study. By guiding experts to brainstorm, write, and discuss a series of devised topics, we gained clear and novel insights on user comfort/discomfort, such as how these can be described, and the relationship between these two states, to support future studies in this context.

In terms of follow-on work, we suggest a number of possibilities. First, the conceptual framework was developed based on the current literature, and discussions between a group of selected experts, but this needs further examination and validation, based on empirical studies. Second, our results illustrate that comfort is not the opposite of discomfort; since many more terms were used to define the latter. Therefore, further investigations will help identify the best methods for measuring user comfort in automated driving, focusing on how to quantify the relationship between the two states and the underlying aspects. Moreover, it will be valuable to consider the opinions of other, non-experts, for example, members of the general population, and users with mobility challenges (e.g., the elderly and physically impaired people) who are expected to benefit most from such AVs (Milakis et al., 2017; Reimer, 2014). Comparing these findings with our results from experts can provide a more comprehensive understanding of user comfort. Finally, understanding how interactions between the concepts proposed in the model affect comfort/discomfort would be valuable. For example, it would be useful to understand how changes in comfort/discomfort affect users' attention to the ride, and how this then influences their subsequent comfort/discomfort. For example, it can be argued that a higher level of jerk may cause users to disengage from NDRAs and observe the AV's behaviour. This may then lead to a higher level of attention to the ride, enhancing discomfort, which may not be the case if riders continue to be distracted by the NDRA.

While automated driving technologies have advanced rapidly since our workshop in 2021, our findings and conclusions remain relevant and applicable in this context. For example, as real passengers and riders start to experience these vehicles, in real world conditions (such as during trials in the streets of San Francisco), some of the issues highlighted in our workshop, such as the weird behaviour of the vehicle, lack of trust in AI, or issues with privacy are being reported by local and international press outlets. In some cases, this has led to severe responses from local residents, unhappy with the deployment of AVs in their streets (Templeton, 2024). These reports highlight the relevance of our findings from the expert workshop, which we hope will be of value to companies considering user acceptance as a factor for deploying their AVs.

In terms of study limitations, the conceptual framework is currently limited by how different factors influence comfort at different timeframes. For example, the impact of driving styles on the ability to engage in NDRAs can be immediate, whereas understanding the influence of trust on comfort may need a longer timeframe, following a period of user interaction and experience with the AV (Hoff & Bashir, 2015). Therefore, further work is required on how these factors influence user comfort over time, with repeated use of AVs. Moreover, to encourage discussions in this workshop, we did not limit debate on how the *type* of automated vehicle might affect comfort. We therefore found that experts mentioned both privately-owned, and shared automated vehicles during the workshop. However, it can be argued that due to some fundamental differences between these two categories of AV, such as the presence of co-passengers or an on-board safety driver, and the pre-planned route of AVs (Wang et al., 2020). Future work should consider how comfort might differ between these two AV categories. Finally, in terms of the variety of experts, while we included individuals from a wide range of areas working on automated vehicles, not all relevant domains were represented. Therefore, future research may benefit by including a wider range of experts, such as policy makers and individuals from standardisation bodies working on implementing AVs.

To conclude, using an expert group workshop, this study discovered a range of aspects of user comfort and discomfort in automated driving. We hope our findings improve the understanding, definitions, and measurements of user comfort in automated driving, and help system designers and manufacturers to design and develop more comfortable, pleasant, and acceptable automated vehicles.

CRediT authorship contribution statement

Chen Peng: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Stefanie Horn:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Ruth Madigan:** Formal analysis, Writing – review & editing. **Claus Marberger:** Writing – review & editing. **John D. Lee:** Writing – review & editing. **Josef Krems:** Writing – review & editing. **Matthias Beggiato:** Writing – review & editing. **Richard Romano:** Writing – review & editing. **Chongfeng Wei:** Supervision, Writing – review & editing. **Ellie Wooldridge:** Writing – review & editing. **Riender Happee:** Writing – review & editing. **Marjan Hagenzieker:** Supervision, Writing – review & editing. **Natasha Merat:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A

Method

Experts

Due to the COVID-19 pandemic, and related travel restrictions, we conducted an online workshop with nine internationally recognised experts in this field, chosen due to their long-term research experience with AVs, and balanced between industry and academia, as well as background expertise (engineering, psychology, human factors, and industrial design). These attendees, and two more experts (Prof Marjan Hagenzieker and Prof Riender Happee), who were invited to comment on the manuscript, are all co-authors of the manuscript, due to their verbal and written contributions to the work. We were keen to include experts with some hands-on experience with higher-level AVs, because these vehicles are currently unavailable on the market (Madigan et al., 2017), yet research shows that actual experience with new technology is effective for highlighting their limitations and capabilities (e.g., Hancock et al., 2020; Kyriakidis et al., 2019; Tabone et al., 2021). Moreover, because comfort/discomfort is the actual experience that results from interaction with AVs, we considered experts' direct experience with AVs as crucial and valuable. Experts were invited via emails, in which the date, estimated duration, the main topic of the workshop, and the expected output (i.e., an academic paper with attendees as co-authors) was briefly stated. Eleven out of thirteen experts accepted the invitation, and nine of them attended the workshop.

Techniques used for the workshop

A group workshop, loosely following a focus group format was considered more useful than individual interviews for this research. Focus groups are considered useful for investigating complex topics, allowing in-depth discussions between the participants, and gathering diverse information from a small group of people (Caretta & Vacchelli, 2015; Morgan, 1998; Ørngreen & Levinsen, 2017; Stewart & Shamdasani, 2014). By fostering discussions and interactions between the experts, a wide range of aspects related to this topic could be explored and uncovered, and it was favoured over individual interviews which only collect opinions from individuals, without interactions between interviewees, and thus produce less comprehensive information than group work (Coenen et al., 2012).

Apart from the group discussion via the online meeting platform Microsoft Teams (https://www.microsoft.com/en-gb/microsoft-teams/online-meetings), in order to stimulate discussions, experts were encouraged to brainstorm a range of proposed topics, as well as write notes and group similar notes, by using the online collaborative whiteboard tool; Miro (https://miro.com) (see examples of approaches of facilitating group discussion: Hagger et al., 2016; Iliffe et al., 2005). This combination of brainstorming and writing is sometimes called "brain-writing" (VanGundy, 1984). Writing notes in a shared workspace helps both the individual and the group to brainstorm ideas, while also providing an overview of all notes, with existing notes providing inspiration for new ideas (Aiken et al., 1996; Lockton et al., 2016; Michinov & Jeanson, 2021; Wilson, 2006). Grouping notes with similar themes together can highlight similarities and differences between individual notes, similar to a card-sorting task (Bussolon et al., 2006). These notes would then be visible on the whiteboard, allowing the facilitator and experts to further discuss the evolving themes.

Procedure

Before the main workshop, we conducted an online pilot session with six participants, who were all PhD candidates from the Human Factors and Safety research group at the Institute for Transport Studies, University of Leeds. The backgrounds of these pilot participants included psychology (N = 1), design (N = 2), control engineering (N = 2), and modelling (N = 1). The aim of the pilot session was to test the length and format of the main workshop and gather participants' views about the format and nature of our questions (see Appendix B). Ambiguous questions and instructions were modified following this pilot session, and we also simplified the procedure, and adjusted the time estimation for each session.

For the main workshop (which took place on 27th July 2021), after welcoming all experts, the moderators provided a short introduction of the workshop, including its main aim, the topic to be discussed, an estimation of the likely duration of the event, and re-emphasised the anticipated academic paper as the output of the workshop. This was followed by a round-table session in which all experts introduced themselves, their backgrounds, and their expertise. The moderators then presented a brief summary of the state-of-the-art research on user comfort in automated driving, including an overview of the diverse descriptions and measurements used for comfort, and provided the list of research questions that were to be considered for the workshop discussions. A short tutorial on the use of the Miro whiteboard was provided. The workshop was divided into four separate sessions, in which different, but connected, topics were covered:

Session 1: This session focused on a discussion of the terms used to describe comfortable and uncomfortable experiences when driven by currently available vehicles as a passenger, such as a taxi, bus or train. This was done for two reasons: first, it helped experts familiarise themselves with the topic by talking about currently available transport modes. Second, we wished to understand if there were any differences in the perceived comfort/discomfort of "being driven" by a taxi/bus/train, compared to that of a Level 4 AV, because, in both cases, the user does not control the vehicle, and is also able to engage in NDRAs (Hecht et al., 2019).

Session 2: This session involved a discussion of any differences between being driven by a taxi/bus/train versus an AV, in terms of the experienced comfort/discomfort. This session was expected to connect with, and facilitate the discussions, in session 3.

Session 3: This session involved a discussion of terms used to describe comfortable and uncomfortable experiences of being driven by AVs. Discussions in this session were based on the previous two sessions. After reflecting on the unique characteristics of AVs in session 2, it was expected that experts would add or remove terms about comfortable/uncomfortable experiences of being driven by AVs, based on existing terms for a taxi/bus/train from session 1.

Session 4: This session focused on discussing the original conceptual framework for user comfort in automated driving (Fig. 1), with an emphasis on how these are affected by different driving styles. After discussions in the preceding sessions, experts were expected to give constructive feedback on the original framework, in terms of complementing and revising relevant aspects and concepts, rather than clarifying concrete terms. Here, we explicitly instructed experts to take driving styles into consideration, compared to the preceding sessions, in which the term of "being driven" was used to implicitly remind experts of the driving scenario. However, we still encouraged discussions of broad but relevant concepts, in addition to driving styles.

Each session began with a verbal instruction provided by the moderator, including the topic of the session, the place to write notes, and the duration of the writing session. The workshop then began with writing and grouping notes on the Miro whiteboard, followed by a group discussion of the written notes and the patterns of the categorisations. For the note-writing, experts were advised to use one to two terms for each note, to keep descriptions succinct and easy to follow, so that other experts could read these through, within the limited time of a session. In order to get a comprehensive output, experts were encouraged to write as many notes as they could, and to avoid repetitions (i.e., to avoid writing a description that was already posted, allowing a maximisation of the number of concepts used). Instructions about the topic covered in each session was also shown on the Miro whiteboard, to remind experts of the focus of the current session. Along with writing, experts were instructed to move their notes closer to existing notes with similar meaning/themes. Fig. 2 shows instructions of topics for discussions on the Miro whiteboard, the order of events and rough length of each session. Fig. 3 shows the Miro whiteboard of session 1, as an example, which includes the written instructions, separated whiteboard areas for comfort and discomfort, the empty notes provided to experts, and an overview of the final notes provided by the experts. After the writing task, experts saw an overview of the whiteboard, and discussed the emerging patterns which were of interest to them. The Miro whiteboard screen was shared via Teams throughout the workshop, to ensure participants worked on and looked at the same area. All experts were thanked for their contribution after the workshop.

Both the pilot and the main workshop were moderated by the first two authors (CP and SH). These individuals also devised the questions and workshop format. For the main workshop, one moderator (CP) instructed and guided the discussion, while the other moderator (SH) monitored the online tools (e.g., timer setting and reminder in Miro).

Data analysis

For the two types of data (written notes and verbal discussions) collected from the workshop, we adopted different approaches to analysing data. For written terms describing comfort/discomfort of currently available transport modes and AVs (mostly from session 1 and 3), although experts have grouped most terms and discussed some patterns at a group level in the workshop, further categorisations were needed for two reasons. First, not all terms were moved into groups, while some groupings were roughly done with flaws, likely because, for example, experts overlooked some terms due to too much information on the whiteboard, and had insufficient time to refine these groups. Second, no explicit names were given to each group of terms to summarise the theme; however, it is important to identify the theme of a group of terms with similarities, because a theme summarises commonalities of these terms, and indicates one aspect of comfort/discomfort. Sorting text into meaningful categories is usually done by participants in group brainstorming (Clayphan et al., 2014), while it is also an approach of qualitative content analysis used after data collection (Ahmadpour et al., 2016; Hsieh & Shannon, 2005). Therefore, to complete the categorisation and highlight patterns of these terms, the categorisation was conducted as part of data analyses. The categorisation combined the theory-driven deductive approach and the data-driven inductive method (Berg & Lune, 2017; Duboz et al., 2022). To be specific, we tended to deductively categorise and name a group of terms, either based on frequently investigated psychological concepts (e.g., “perceived safety”, “trust”, and “engagement in NDRAs”) in this area, or using terms used in currently available definitions for comfort/discomfort (e.g., “ease/unease”, and “pleasantness”). We referred to these frequently used terminologies in academic literature rather than preparing a predetermined codebook based on existing research theories, because an elaborate theoretical framework of user comfort in automated driving is currently lacking. In the meantime, we categorised terms according to their similar meanings and themes, in an inductive way. Three individuals (CP, SH, RM) completed the categorisation (incl. grouping similar terms and naming the group) independently, and then discussed it in a team of four (the three raters, and NM). This team included moderators and experts from the workshop and thus had enough background knowledge for the categorisation. Other experts were given the opportunity to provide feedback at the time of writing. It is worth noting that the number of repeated notes was counted; however, we do not interpret the importance of a term according to the times it was repeated, because the purpose of the workshop was to have a comprehensive overview, and experts were instructed about this. Some terms were repeated because experts wrote in parallel, whereas monitoring the whole whiteboard in the meantime to avoid repetition was challenging.

For verbal discussions (from all sessions), the video recording was gone through and transcribed by the first two authors independently, and cross-compared to ensure no misunderstandings of the transcription. Then experts’ discussions were summarised by the lead author. Summarising statements and discussions of experts is an approach used by some studies based on expert work, for example, expert interviews (Kyriakidis et al., 2019; Tabone et al., 2021) and expert round-table discussions (Elliott et al., 2019). All other co-authors also had a chance to comment on the statements and suggest amendments. Moreover, as the discussions added contextual information to the simpler notes, some categorisations of the written notes were then further revised.

The original conceptual framework was refined based on the workshop (see examples of using group discussions to refine conceptual frameworks: Agbali et al., 2019; Pettit et al., 2010). It is worth mentioning that, the output and discussions in both preceding sessions and session 4 were all relevant to the framework. Therefore, we combined results from all sessions to modify the conceptual framework, for example, categories of comfort/discomfort that were identified in session 1 and 3, discussed differences in user comfort in automated driving compared to a taxi (session 2), and experts’ direct comments on the original conceptual framework (session 4). The refined version of the framework was drafted by the lead author and revised based on the co-authors’ feedback.

Appendix B

Questions and instructions used in the pilot session

Session: Warm-up questions

Do you think understanding and defining driving comfort for AVs is important? (Slido).

Do you think it’s easy to measure comfort in AVs? (Slido).

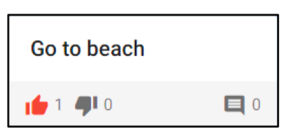
Do you think it’s easy to manipulate driving comfort in AVs? (Slido).

Quick tutorial to Padlet

Session A: UNDERSTANDING DRIVING COMFORT (Padlet)

Imagine, you are being driven in a vehicle, e.g., taxi, train, and bus etc., not in control. A) During this journey, you feel comfortable … B) During this journey, you feel uncomfortable …

What terms can you use to describe these feelings? Use thumb up and thumb down reacting to all answers, for example,



How relevant is the term to describe comfort?

Session B: CREATING

First, let’s talk about your experience and feelings about the existing automation functionalities… (Slido)

Have you experienced adaptive cruise control (ACC) in real cars or in prototype? - Y/N

Have you experienced Lane Keeping Assistance (LKA), in real cars or in prototype? - Y/N

Have you experienced any other ADAS functionalities, regarding vehicle motions or distances to other objects? - WordCloud

Regarding vehicle motions/distance to other objects, how does the system behave when you felt comfortable or uncomfortable? Why do you like it, or dislike it? (No tool; just discussion in Teams)

Imagine. You are being driven, not in control, don’t need to monitor, can do NDRTs…

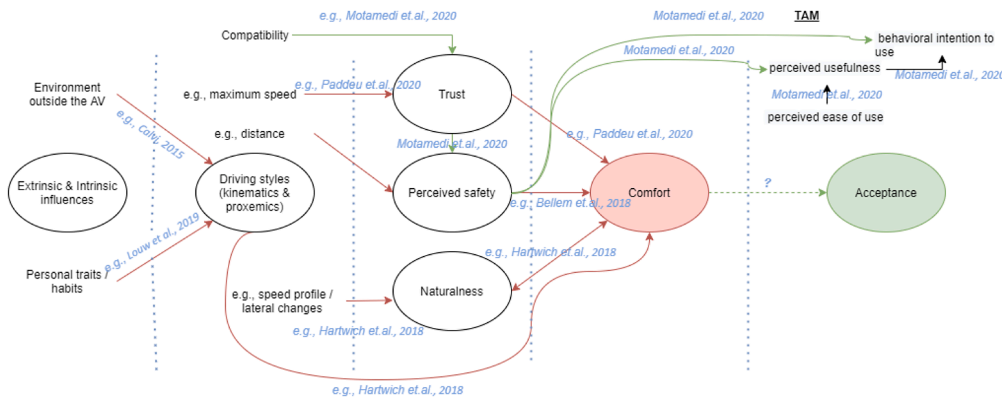
Regarding driving styles/environments, is there anything different in the L3/L4 automation, compared to the L1/L2 automation, about comfortable or uncomfortable experience?

Break

Consider the concepts - Trust, Perceived Safety, Naturalness, User acceptance - that are related to kinematics and/or proxemics, and this suggested conceptual framework…

Are there any other relevant concepts are missing? – add (Teams)

What are the relationships among them? – discuss (Teams)



Session C: LOOKING AHEAD

What else in this area, apart from kinematics and proxemics, are important to be understood? - Slido; word cloud

Are there any other different user groups that should be considered in this context? - If yes, please explain your answer – Slido

Session D: MEASURING

Among the range of measures to measure comfort in the driving context…

Which one is most successful?

Feedback question

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