Encountering Automation Surprise in Everyday Automated Driving: An Exploratory Phenomenological Inspired Study Using A Wizard-of-Oz Vehicle on Real Motorways

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Automation Surprise (AS) has traditionally been studied as a system- or user-induced failure in high-risk or safety-critical domains. However, as automated vehicles (AVs) enter everyday mobility, we argue for a shift in perspective: from AS as failure, to AS as a lived experience. This study explores how AS unfolds during non-critical automated driving, using a phenomenologically informed, design research approach. We conducted a Wizard-of-Oz study in which participants experienced automated driving on real roads. By mainly interpreting interview data, we show how subtle mismatches between AV behaviour and user expectations can trigger surprise, even when the system performs technically correctly. These moments involved embodied sensations, attentional shifts, and sensemaking of the environment. We propose that AS in AVs should be reframed as a situated experience. We contribute an expanded conceptualisation of AS, and identify design considerations for future design and research, expanding from merely preventing AS.

Keywords: Automated Driving, Automation Surprise, Wizard of Oz, Experience Prototype, Phenomenology, User Experience, Design Research, Human-Vehicle Interaction

1 Introduction

As automated vehicles (AV) become integrated into daily life, new questions emerge, not only about technical performance or safety, but also about how people experience and interpret these automated systems as part of their everyday life (Detjen et al., 2021; Flemisch et al., 2011; Lindgren et al., 2020; Strömberg et al., 2018). With AVs progressing to higher levels of automation (specifically SAE levels 3, 4, and 5 (SAE International, 2021)), drivers (hereafter referred to simply as ‘users’ of AVs) transit from being actively control and monitor the vehicle, to being fallback driver (SAE level 3) or even passenger (SAE levels 4 and 5) during certain or all parts of their ride (Rydstrom et al., 2022). This shift enables users to engage in various non-driving-related activities (NDRAs) (Pfleging, 2017), often framed as a key benefit of highly automated driving (Carsten & Martens, 2018; König & Neumayr, 2017).

While users are engaged in NDRAs, their attention shifts away from the driving context. If the vehicle performs an unexpected action, such as braking or changing lanes, users may be startled or surprised, even if the AV is functioning correctly. There is no guarantee that they will place complete trust in AVs and feel comfortable enough to be fully "out of the loop" (Flemisch et al., 2014; Lindemann et al., 2018; Merat et al., 2012). One concept that helps describe such moments is the Automation Surprise (AS) (Carsten & Martens, 2018). Originally developed in the field of human factors and studied primarily in human-automation interaction (e.g., aviation), AS refers to instances where users encounter unexpected system behaviour, resulting in breakdowns in awareness and potentially safety-critical errors (Flight Safety Foundation, 2014; Rivera et al., 2014; Sarter et al., 1997).

However, as user experience researchers and interaction designers, we are interested in AS as a phenomenon that reflects how emerging automation technologies influence users' felt experiences. Even when no failure occurs, users may still encounter moments of surprise that may influence their feelings of comfort, as well as their long-term acceptance, trust, and relationships with automation (Carsten & Martens, 2018; Reilhac et al., 2017; Strömberg et al., 2018). Yet, this experiential dimension of AS has been largely under-explored (Meschtscherjakov et al., 2016). Most existing research took a human factors and cognitive psychology perspective, focusing on emergency situations and transitions of control between users and automated systems. However, many AV journeys in daily life will be routine and uneventful, occurring under non-critical conditions, where the vehicle performs the driving tasks reliably and the user is not required to intervene. In such conditions, we ask: does AS still occur? Adopting a phenomenological perspective (Zahavi, 2020), we explored how users notice, interpret, and make sense of AV behaviours that surprise them, even if everything works correctly technically.

To guide the exploration, we draw on established HMI design principles aimed to reduce AS, namely observability, predictability and timeliness proposed by (Carsten & Martens, 2018). Rather than treating these qualities as design requirements for systems, we reframed them as experiential qualities from the user's perspective that can be related to AS. These qualities informed the design of the interview questions and thematic analysis. Methodologically inspired by methods from design research (Boehner et al., 2007; Buchenau & Suri, 2000; Gaver et al., 2004; Millen, 2000) and phenomenological approach (Tufford & Newman, 2010; Zahavi, 2020), we leveraged a Wizard-of-Oz (WoZ) vehicle setup driving on actual motorways, for the participants to experience how it may feel like to be in an AV (Baltodano et al., 2015; Wang et al., 2017). To gently anchor participant attention and support reflection, we introduced a haptic cue via a wristband, used as a research probe (Buchenau & Suri, 2000). Data were collected through interviews, behavioural video, and demographic surveys.

Our findings suggest that AS does arise in non-critical automated driving conditions, but not always a clear failure or error. Instead, participants described momentary reactions that unfolded across embodied sensations, attention shifts, and contextual understanding. These experiences were shaped not only by the AV's behaviour, but also by the driving environment and each user's personal expectations and engagement. We, therefore, frame AS as a situated, multi-layered phenomenon, best understood through the lens of sensemaking (how users try to make sense of what the system is doing and why).

By shifting the focus from "AS as system failure" to "AS as lived experience," we open up new ways to study and design for AS in everyday human-automation interaction. Using phenomenological interpretation, we examine a traditionally human factors concept through the lens of experiential HCI. In doing so, this work contributes: (1) empirically, by showing how AS emerges in non-critical driving conditions and the interpretive activities it entails; and (2) conceptually, by offering an experiential framing of AS and speculating on future direction for research and design.

2 Related Work

2.1 AS and Human-Automation Interaction

AS has traditionally been studied as a critical safety issue, particularly within aviation and other high-risk domains with automated systems (Meyer et al., 2022; Rivera et al., 2014; Sarter & Woods, 1995; Sarter et al., 1997). In such contexts, AS refers to the cognitive-emotional response to the situation when the behaviour of an automated system deviated from operator expectations, resulting in confusion, loss of situational understanding and delayed responses (Campbell et al., 2018; Trippe & Mauro, 2015). It was also defined as a weakness in the operator's mental model, caused by inadequate training or poor mode awareness (Bureau, 1998).

Trippe and Mauro (2015) identified multiple causes of AS, including mode confusion, sensory misalignment, and insufficient feedback. Notably, they also described a category of "nuisance surprises", events that do not endanger safety but still impose cognitive and emotional burdens on operators. This distinction resonates with potential issues that may arise in daily automated driving, while road safety is not at stake due to AS. Guidance from Flight Safety Foundation (2014) emphasised that the surprise itself can be disruptive, regardless of its causes or intensity. So while original studies framed AS as a cognitive problem with safety consequences, other works increasingly acknowledges the emotional, experiential, and subtle impact of AS events. Building on this foundation, de Boer and Dekker (2017) identified a fundamental divide between two conceptual models of AS: what they described as the "normative model" and the "sensemaking model". The normative model, which de Boer and Dekker (2017) referred to the work of Parasuraman and Manzey (2010) understood surprise as the result of complacency and automation bias, related to attention levels. In this view, AS is framed as a preventable performance error, and mitigation focuses on correcting human limitations through training, or improved transparency in HMI design (Parasuraman & Manzey, 2010; Sarter & Woods, 1995). In contrast, the sensemaking model, developed by Rankin et al. (2016) framed AS not as a failure, but as an interpretive disruptions. It viewed cognition as a dynamic and distributed process of meaning-making, situated within a complex and often ambiguous operational context. From this perspective, AS arises when a user encounters system behaviour that does not align with their current implicit expectations, and followed by retrospectively reframe and reinterpret the situation.

This sensemaking model also was reflected in other recent work. In the domain of safety assessment for air traffic control, Meyer et al. (2022) highlighted AS as a side effect of increasing automation and the resulting complexity of socio-technical systems. However, rather than attributing AS only to "human performance limitation", they identified a broader set of contributing factors, including "workplace conditions", "personality factors", and "equipment and infrastructure". Together, these studies underscored the importance of studying AS not only as a failure, but shaped by user expectations, system behaviour and contexts, even in technically safe, non-critical conditions. Our study adopts a phenomenologically-inspired perspective aligned with such a sensemaking perspective.

2.2 AS in Automated Driving

The study of AS in automated driving has gained attention, yet remains relatively scarce. The bibliographic review by (Tillinghast & Duffy, 2021) pointed to a growing interest in AS-related constructs within human-AV interaction research, such as "cooperation" (Banks & Stanton, 2015), "shared control" (Inagaki & Itoh, 2007; Muslim & Itoh, 2019; Saito et al., 2021), and "trust" (Lee & See, 2004). However, most empirical studies have focused on safety-critical events such as transition of control, where AS is triggered by unexpected system actions, unclear feedback, or mismatched expectations (Banks & Stanton, 2015; Inagaki et al., 2007; Reilhac et al., 2017; Victor et al., 2018).

Carsten and Martens (2018) laid out HMI design principles for AVs, explicitly highlighting the importance of minimising AS to ensure safe operation. They first defined two main categories of AS in driving: the absence of expected actions, and the presence of unexpected actions. While positive AS can occur when a system handles a situation well, AS of the second kind ("negative surprise") needs to be avoided because of the safety risks involved. They also modelled AS as a consequence of increased system reliability, which is with potential negative safety impacts. This aligns with the traditional framing of AS as a preventable outcome of poor human-automation alignment. To reduce these occurrences, Carsten and Martens (2018) proposed four interface qualities: observability, predictability, timeliness, and directability. Our study built on and reframed these qualities that represent how users perceive, anticipate, and make sense of their experience under non-critical automated driving. Details of this reframing are elaborated in Section 3.4.1. This aligns with a sensemaking approach to AS.

Other studies further demonstrated phenomena related to AS. Pipkorn et al. (2021) investigated scenarios beginning with the driver's "surprise reaction" to a suddenly appearing obstacle in supervised automation, while Victor et al. (2018) explored how expectation mismatches affect supervision engagement. Banks and Stanton (2015) underscored the subjective nature of AS by using verbal reports to reveal surprise-related stress that was not evident in observable driving behaviour. They also argued that experienced users may be even more prone to AS than novices due to stronger mental models. Together, these studies revealed that AS is a multi-layered phenomenon and provides inspiration for the design of this study.

To summarise, non-critical conditions in which AS may still disrupt the NDRA engagement and use comfort are hardly studied. To our knowledge, there are no studies that looked at AS during non-critical automated driving conditions, and our study aims to fill this gap.

3 Methodology

This study adopts a phenomenologically inspired design research approach (Sas et al., 2014; Tufford & Newman, 2010; Zahavi, 2020) which allows users expression and our interpretation. We aimed to explore the situated and subjective nature of AS, rather than evaluating system performance or measuring AS against predefined metrics.

We understand experience as dynamic, complex, and deeply contextual. It is shaped by the perception of multiple sensory cues, which are interpreted through personal and environmental filters (Buchenau & Suri, 2000). Therefore, we designed an on-road study using a Wizard-of-Oz (WoZ) vehicle to provide context for imagining the experience of highly automated driving. Our methodological orientation draws from several design research traditions: design ethnography (Millen, 2000; Plowman & Laurel, 2004), experience prototyping (Buchenau & Suri, 2000), technology probes (Boehner et al., 2007; Gaver et al., 2004), and the Needfinding Machine (Martelaro & Ju, 2019). All of these support rich, interpretive inquiry into user experience and needs with emerging technology. We adapted ethnographically inspired fieldwork to shorter engagements on real roads. Influenced by technology probes, tools intended not for functional refinement but for eliciting reflection and surfacing design opportunities, we treated the WoZ vehicle as a speculative probe (Baltodano et al., 2015; Wang et al., 2017). Our field setup functioned as an experience prototype (Buchenau & Suri, 2000): an embodied intervention designed to elicit the experience of automated driving.

Unlike traditional lab-based WoZ simulations, the real-world contexts provide richness and unpredictability of actual environments that play a key role in shaping user experience (Habibovic et al., 2016; Wang et al., 2017). We selected motorways as the context for this study, reflecting scenarios where highly AVs are most likely to be implemented.

Moreover, we included the ‘haptic cue’ as an in-situ anchor, a nudge intended to gently draw attention to specific moments without interrupting the experience (Huang & Stolterman, 2014). Because AS in non-critical conditions can be subtle and difficult for participants to consciously recognise or articulate (Flight Safety Foundation, 2014), the cue was designed to mark moments (e.g., lane changes, roundabouts) that might later become meaningful in retrospective reflection.

This study has been approved by the Ethical Review Board at Eindhoven University of Technology.

3.1 Setup

We used a modified Renault Espace 2.0 WoZ vehicle developed at Eindhoven University of Technology (Karjanto et al., 2018; Yusof, 2019). The wizard driver sat in the driver’s seat driving the vehicle, and the experimenter sat in the front passenger seat. To create the illusion of automated driving, a partition hid the front seats, and a TV screen mounted to the partition displayed a live feed of the road and dashboard from an action camera. The participants sat in the back seat. A fake steering wheel was installed in front of the participants, which rotated in sync with the real steering wheel's movements. No further in-vehicle interfaces were added, and we intentionally study AV experience without adding further interface design, to foreground the user's sensemaking before such interfaces are designed or standardised. This approach allows us to better understand what kinds of experiential support users might need, to reveal what interpretive gaps future designs might need to bridge, not simply whether a particular interface is effective.

This setup was inspired by the RRADS protocol (Baltodano et al., 2015). We did not overtly deceive the participants about the existence of the wizard driver, but they were hidden from the participants until the end of the experiment (Fraser & Gilbert, 1991; Kelley, 2018). We asked participants to imagine themselves sitting in a highly AV and behave in context accordingly. The participant's perspective during the experience is shown in Figure 1, and the setup is shown in Figure 2.

The haptic cue was implemented using a wristband prototype placed on the palm side of the wrist. Haptic modality was chosen to reduce potential conflicts with visual and auditory sensors when participants were watching a video (Riener et al., 2017). The location of the wrist was chosen to avoid interference with vehicle-induced vibration and to leverage the wrist's sensitivity to passive touch (Zeagler, 2017). Each vibration lasted one second and was manually triggered by the experimenter just before predefined events. The triggering of the vibration was not precisely time-locked, as the study did not aim for strict variable control.

Figure 1. The view from the participant's perspective during the experience.

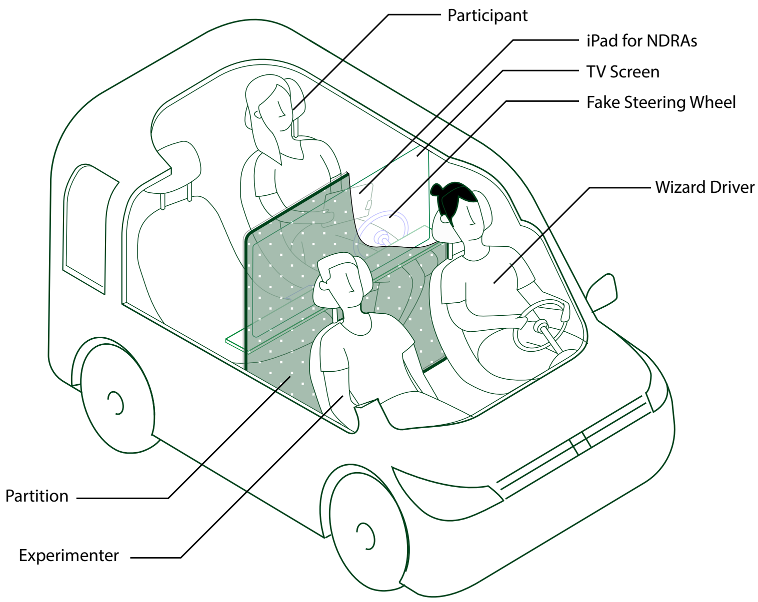

Figure 2. The setup illustration.

Four wizard drivers were trained to operate the vehicle, using human pre-agreed feedback to follow the correct driving habits. It should be emphasised that we embrace the experience variations the

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Figure 3. (a) The map of the route; (b) The illustration of the procedure.

participants encountered throughout the experiment given the real-world context. Hence, it was not imperative for all wizard drivers to follow the exact same driving pattern.
The NDRA was watching a pre-selected video preloaded on a 10.2-inch iPad (a compilation of short humorous animal clips[1]). This video was selected for its universal appeal and relaxed pacing, ensuring that participants remained engaged without cognitive overload.

3.2 Participants

A total of 20 participants (16 males and 4 females, range of age=23 to 54) completed the experiment. All participants have driving licenses valid in Europe. An overview of the participants is shown in the Appendix. The participants were recruited through flyers, social posts and personal networks. Individuals susceptible to motion sickness were excluded using a shortened version of the Motion Sickness Susceptibility Questionnaire (who scored above 50%) (Golding, 2006) . Participants affiliated with Eindhoven University of Technology received €10/hour, external participants received €12/hour.

3.3 Route and Procedure

The study took place on the predefined 17-km motorway route near Eindhoven, the Netherlands, as shown in green line in Figure 3 (a). The route excluded pedestrian crossings, traffic lights, and intersections, as representative of non-critical automated driving scenarios. Each participant experienced the

[1]https:youtu.beseDX-MwoMJc?si=Ygf9BcaK_FUweHU

same route twice, one with the haptic cue, and one without. The order was counterbalanced.
On average, each session lasted approximately 1.5 hours. This duration includes a 10-minute preparation phase, up to 55 minutes of on-road driving (the specific duration depends on road conditions), and a 20-minute post-interview (Figure 3 (b)). Preparations and post-interview were held on the campus (point A). Through the link drive (grey line in Figure 3), the route that started data collection began at a roundabout (point B), then an 80 km/h motorway, merged onto a 100–120 km/h highway (point C), and later exited via another roundabout (point D) and ramp (point E) onto a second 70-80 km/h motorway, finally ends in point F. Then through the link drive back to B, and start the second rounds.
Several scripted manoeuvres were created along the route. These included lane changes (to the adjacent or furthest left lane), overtaking (merging left and returning right), motorway merging, and sudden deceleration near a speed camera. Participants were not explicitly informed of these scripted manoeuvres.
The participants wore the haptic wristband throughout both rides, but vibrations were activated only during the cue condition. The session with the cue introduced subtle moments of guided attentional anchoring, supporting participants in noticing and reflecting on their reactions. The session without the cue allowed for a more naturalistic experience of automated driving. The order of these rounds was randomised to avoid priming effects or unintentional framing based on initial experience. Two rounds were complementary and analysed together.
The haptic cue are triggered before the predefined road condition (e.g., roundabout at point D) and scripted manoeuvres (e.g., lane changing on motorway). While these were predefined, natural variability in traffic conditions meant that not all participants experienced them identically, and each instance unfolded with contextual differences. Before the experiment, participants were informed that the wristband would vibrate before certain events. However, they were not told which specific events would trigger it, and no actions or responses were expected from them.
After informed consent and a pre-questionnaire (demographics, trust propensity, tech attitudes), participants were introduced to the setup and the cue. They were informed that the steering wheel and pedals were non-functional and that they would watch a video while the vehicle drove itself. Participants then completed the two rides, after which they were guided to inside of the building for the structured interview.

3.4 Data Collection and Analysis

To explore how the participant experienced AS, we collected data from three sources: structured interviews, video recordings, and questionnaires. The post-interview served as the primary data source, while the video and questionnaire data provided additional context.

3.4.1 Structured Interview

The structured interview was designed to elicit reflection on the experiences. In line with phenomenological research practices, we intentionally avoided defining the phenomenon of AS for the participants (Tufford & Newman, 2010). This allowed them to describe the experiences in their own terms, without being biased by researcher-imposed interpretations. AS was interpreted retrospectively through thematic coding of the interview recording. Therefore, our interview focused on facilitating reflections of moments that aligned with characteristics of AS, such as unexpected or absent vehicle behaviour, disruptions in attention, emotional states, and sensemaking of what occurred.

The interview questions first based on the three qualities proposed by (Carsten & Martens, 2018): observability, predictability, and timeliness, originally intended as HMI design principles to mitigate AS. The fourth quality, directability (*"ability to influence and be influenced to come to the best joint performance"* (Carsten & Martens, 2018) was excluded as it was not applicable to the passive user role in our setup. We reframed these as experiential qualities, and the comparison of the original and reframed definitions are provided in Table 1.

In addition to this, participants were also asked about their general experience, distractions from NDRAs, or any moments they found surprising or difficult to interpret, as we aim to emphasise on the participants' lived experiences in AVs while conducting NDRAs.

Table 1. Original and Reframed Definitions of Observability, Predictability, and Timeliness

Quality	**Original Definition (Carsten & Martens, 2018)**	**Reframed Definition (This Study)**
Observability	Whether the system status (e.g., system mode) can be understood or detected.	Participants ability to detect and understand system state and intent within their specific context of use.
Predictability	Whether system actions is sufficiently observable, understandable and reliable allowing users to plan their own actions accordingly.	Participants' ability to anticipate vehicle actions and plan for their own expectations and actions accordingly.
Timeliness	Whether the system provides information early enough for users to understand and respond appropriately.	Whether participants can timely understand and react appropriately

All interview recordings were transcribed verbatim, and analysed using qualitative content analysis in MAXQDA software [2]. The transcription was first organised into six primary codes corresponding to the interview questions: 'observability', 'predictability', 'timeliness', 'general experience', 'interpretation' and 'distraction'. Two authors coded the data iteratively, inductively identifying additional codes as needed. Then we refined the coding scheme through discussion and consensus (Kuckartz, 2014). A final round of discussion was conducted with input from an external researcher. This process finally generate a coding scheme with 6 categories, 13 codes and 21 sub-codes (see Table 2).

3.4.2 Video Recording and Coding

The video recordings include two parts: the front view of the on-road conditions (out-videos) and the participants' in-vehicle behaviour (in-videos). We used the open-source event-logging software for

[2] https://www.maxqda.com

Table 2. Finalised Coding Scheme from Structured Interviews

Categories & Codes	Definition	Segment
A. Experiential Qualities		
Observability	Description of the experience of perceiving, detecting, or interpreting vehicle actions and intentions.	79
Predictability	Description of the experience to anticipate the situation and plan for their own expectations and actions accordingly.	10
Timeliness	Description of the timing for receiving information, weather early enough for sense-making or not.	18
B. Sensing and Observation Behaviour		
Triggers	Events or cues that prompted participants to perceive, observe and glance the vehicle or the environment (e.g., car dynamic, curiosity, cue).	70
Sense-making	Participants describe how they made sense of the vehicle behaviour, context or other information by perceiving, observing and glancing.	20
Methods	Strategies or channels the participants used to gather information, through perceiving, observing or glancing.	
- Vehicle behaviour	Driving style, manoeuvrers, dynamics.	75
- Environment	E.g., road condition, traffic, other vehicle's behaviour.	18
- Car Interior	E.g., Steering wheel, rear mirror, side mirror.	3
- Periphery	Peripheral observation.	3
C. Distraction from NDRAs		
Perceived distraction	Descriptions of distraction or disruption, how and when their NDRAs was interrupted by internal or external prompts.	48
NDRAs factors	Reflection on how the nature of the NDRAs or personal preference influence immersion or distraction.	10
D. Interpreting Driving Behaviour		
Driving Style Impression	Overall impression of how the car behaved (e.g., smooth, cautious, harsh), or aligned with the participant's personal driving preferences.	34
Tactical Manoeuvrers	Specific vehicle decisions (e.g., lane changes, overtaking), including unexpected manoeuvrers or anticipated actions not executed.	25
Felt Dynamics	Immediate and bodily felt sensations of vehicle movements.	23
E. Role of the Environment		
Road and Traffic	Descriptions of the road type, traffic situation, other vehicles behaviour.	26
Context Familiarity	Reflection on how knowing or recognising the area and the route affected participants experience.	5
F. Emotional and Interpretive Reflections		
Emotional and Experiential Framing	Descriptions of how the ride felt emotionally (e.g., comfort, anxiety, boredom, detachment, trust), or experientially (e.g., out of the loop, on the train, in a taxi, just sitting).	65
Reflections on Info Needs	Reflections on felt informed, confused, or unsure about the experience, or broader expectations around how automation should communicate.	95

video annotation - BORIS (Friard & Gamba, 2016). The second author coded all video pairs. An external researcher independently coded ten video pairs with the coding protocol provided by the second author. The Inter-rater reliability was performed on these 10 video pairs and use discussion to solve any conflicts. Using the video annotation, we calculated the total duration of looking-around time (glances away from NDRAs lasting longer than 3 seconds) and the total count of glance-up (glances lasting less than 3 seconds).

3.4.3 Questionnaires

The pre-questionnaire gathered the participant's demographic data, the propensity to trust, the driving experience, the propensity to trust, and the attitude toward technology.

4 Results and Findings

The findings are structured around the categories from the thematic coding of structured interviews, complemented by the behavioural glance data and demographic profiles. The categories reflect how participants encountered, interpreted, and reflected on AS during non-critical events in automated driving, particularly while engaged in NDRAs. While the haptic cue was sometimes referenced by participants, it is treated here not as a design solution, but as a contextual probe that anchored participants' reflections on information needs and attention shifts.

4.1 Experiential Qualities: Observability, Predictability, Timeliness

Participant reflections were analysed through the lens of the three experiential qualities. These show participants frequent effort to understand and anticipate the vehicles' behaviour and driving contexts, also considering the timeliness of such process.

Observability: Observability emerged as a central quality, as participants frequently reflected on their understanding, by interpreting felt dynamics and the environment in relation to the AV's actions. For example, N03 stated *"Physical movements make me aware of I am turning left or right."* Moreover, N16 stated *"...you look in the environment, then you (knew) it's gonna brake, because there is a red light."*

Predictability: Participants varied in their ability to anticipate vehicles actions and the context. Some formed expectations based on repeated patterns (N02), while others felt detached from the system's decisions, as N20 stated they were engaged in NDRAs and *"... didn't really look up and notice stuff, so I didn't really have to predict anything. Just go with the flow."* Moreover, N16 considered their potential prepared actions: *"if you have a vibration for instance, you can say ok now it's gonna do something. Then I can track it doing it, I can grab the steer or something."*

Timeliness: participants described timeliness in subjective and embodied terms—such as "sudden," "harsh," or "smooth" Several participants described moments where they felt they had sufficient time to observe and orient themselves with the cue. Others noted context-dependent variation, such as N04 remarked it was "too late" in city traffic but "enough" on highways. Moreover, Harsh vehicle actions were often perceived as untimely (N14: "Abrupt... there was no warning").

These results suggest that experiential qualities were actively constructed through sensory input, situated context and attentional levels.

4.2 Observation and Sensing Behaviour

Participants often engaged in active or passive observation and sensing, to interpret and reflection on the experiential qualities (i.e., observability, predictability and timeliness). Video data revealed significant individual variation: looking-around time ranged from 0.4% to 66% of each rounds of driving, and glance-up counts from 4 to 88. But these patterns remained consistent across two rounds ($r =$ .84 and .55, respectively), suggesting stable personal behavioural patterns. Participants reported being prompted to observe by vehicle dynamics, environmental factors, or internal states like curiosity or concern. N11 described, *"When there was a sudden movement, like a braking deceleration, ... then I would look up."* Several participants said glancing made them more situationally aware (e.g., N02, N06, N13).

These sensing and observation behaviours were not only reactions to immediate changes, but also means of gathering information to interpret vehicle behaviour and situate themselves within the unfolding driving context. The participants also described what they attended to. Car dynamics were mostly mentioned, as well as environment observations, such as seeing the exit on the highway (N16). Immediate physical surroundings within the car, such as the movement of the steering wheel (N03), others mentioned attempting to check the rear-view mirror or turning indicators, despite these not being functional or not present in the setup, as part of a habit. Peripheral vision also played a role as described by N09 and N10.

Moreover, the cue were often tied to increased observation. For example, N19 said, *"When I felt the vibration, I tended to look up."* These references are interpreted as reflections on sensemaking.

4.3 Disruption and Distraction

As this study focuses on the scenarios when the participants were primarily engaged in NDRAs, therefore, distraction from NDRAs was a recurring topic.

Participants described moments of being pulled out of their NDRAs by curiosity, uncertainty, or the need to verify what was happening. In which the cue also definitely plays a role in it, as a prompt for such distraction. For example, N14 stated: *"I had no idea when the car would warn me. I actually spend most of the time observing the road, because I was so concerned."*. Others, in contrast, describe being distracted by choice to observe the environment to regain situational understanding. N04 stated, *"... unless I want to be distracted by myself, I actively want to look outside."*. Distraction from NDRAs was not uniformly considered negative. For some, it coincided with a sense of growing confidence or trust. N18 noted: *"(with the cue), I got more distracted, but at the same time, I felt more confident."*.

Behavioural data reveal only weak to moderate correlations between perceived distraction scores and glance behaviours (no cue: $r = .52$ for glance-up count; $r = .43$ for look-around time; with cue: $r = .17$ and $r = .00$, respectively). These values do not support strong statistical conclusions but may reflect tendencies in how participants oriented attention during distraction. Interview narratives suggest that

some participants looked frequently without necessarily reporting high distraction, and vice versa—indicating that glancing alone does not equate to experiential disruption.
Furthermore, preferences for NDRAs shaped their attentional shift and perceived disruption. Some (e.g., N09, N15) prioritised the video over situational understanding, others (e.g., N11) became bored and redirected attention away from NDRAs.

4.4 Interpreting Driving behaviour

Participants' interpretations of vehicle behaviour played a central role in how they experienced and made sense of automated driving. The participants frequently reflected on how these matched or mismatched their expectations. Bodily sensations often initiated this awareness. N12 noted, "*When (the car) makes a move, then I know it will change the lane.*" However, subtle actions were sometimes missed, as N16 mentioned: *"...because you were watching a video, you don't notice the car is moving from lane to lane."* Participants described driving styles as *"smooth"*, *"calm"*, *"what I expected"*, and *"what I would do"*, indicating alignment with personal expectations. Conversely, unexpected or unnecessary actions, such as harsh braking, often led to confusion or discomfort. N01 stated: *"...harsh braking, I did not understand why that was happening because I didn't see any car in front."* Participants also mentioned the absence of expected action. N12 said, *"Sometimes, I noticed the car in front of me is driving rather slow. And I expected the car to take over, but it didn't."* These moments often occurred when participants were paying attention to the driving and forming their own interpretations of the context.

4.5 Role of Environment

When observing the environment, the participants have more situational understanding, potentially contribute to a better understanding of the car's behaviour. Road type, traffic patterns, and familiarity with the route, all contributed to such understanding. However, sometimes this also means that the participants formed their own assessments of what the car should do more consciously. As a result, a mismatch behaviour of the AV would be more noticeable to them. N06 described: *"... when the front road is very clear, means that... you just need to keep the same speed, but then the vehicle decided to suddenly slow down, (and this) makes me (feel) a little bit dangerous."* Participants interpreted situations based on perceived complexity or urgency, sometimes expecting feedback even when no objective risk was present (e.g., N14 expect a warning when other road users getting close to their own car). Moreover, familiarity with the environment further shaped the understanding. Participants who knew the area often used their prior knowledge to predict upcoming manoeuvres. N20 described: *"I come from around here, so I knew like that we weren't going to drive very far. The switch lanes was like, ...I expected that to happen."*

4.6 Emotional and Interpretive Reflections

Participants reflected on a wide range of emotional and experiential responses, such as ‘related’, ‘nervous’, ‘stressed’, ‘confused’ and ‘confident’. These reactions were shaped by how participants interpreted the driving context and their role in it.

Some described passive states of engagement, N01 described the experience as *“I was there”*, while others used metaphors such as being on a train (N20), in a taxi (N03), or at home (N14). Some participants welcomed the passive experience (e.g., N01, N05, N07), others described moments of uncertainty with statements such as *“I don’t know what’s happening”* or *“I don’t understand why”* due to the non-attentiveness. N04 felt *“overwhelmed”* when they realised how disengaged they had become, they recalled such feeling when they noticed that the car had moved to a new location.

Reflections on the cue often centred on informational appropriateness. Some found the cue useful, as it provides a reminder to be more attentive, others felt it unnecessary and reflected on the appropriateness of being notified at all. Some expressed the cue given by the vehicle in such a simple situation is too much and not so fond of *“the constant report from the car”* (N03).

5 Discussion

In this section, we reflect on the findings and relate them to existing literature, aiming to expand how AS exist beyond safety-critical moments and how it can be understood, and suggest implications for future design and research.

5.1 AS in Non-Critical Automated Driving

This study confirmed that AS can happen even during non-critical automated driving, emergencies or obvious malfunctions are not needed for the participants to feel surprised. Participants reported momentary emotional responses, which is similar to the concept “automation startle”, triggered by surprising behaviours that may not evolve into a full cognitive failure (Landman et al., 2017). Beyond this, the participants also described longer and more reflective experiences, as manifestations of AS: feeling curiosity and uncertainty, redirecting attention, and noticing interpretive dissonance.

These moments arise from mismatches between what participants expected and what the vehicle did in responding to the environment, even when the response is “correct” from a technical perspective. Importantly, these were not always shown as clearly negative: sometimes surprise sparked reflection or learning. This suggests that AS is not always a breakdown to be prevented, but a natural part of how users come to understand and relate to automation.

Beyond system behaviour, the experience of AS was also shaped by broader contextual and environmental features. Participants frequently interpreted automation actions through cues from the road, traffic, and landscape. Familiarity with the route or expectations formed from environmental complexity similarly influenced how participants evaluated the vehicle’s actions. We also speculate that AS in automated vehicles differs from AS in aviation. Unlike trained pilots who work with clear mental models and formal technical knowledge, AV users rely more on habitual and perceptual reasoning.

We therefore suggest that AS in automated driving should be seen not only as a reaction to system behaviours, but as an ecologically situated experience, which is co-constructed through the interplay between automation, environment, and the user's evolving interpretation of both.

As AVs become more common, such subtle and context-dependent surprises may occur regularly. We suggest that AS should be seen not only as a technical failure, but as a normal part of how humans and automated systems interact.

5.2 Attentional Shifts in NDRAs

While full user engagement in NDRAs is often assumed or even encouraged in AV, prior research suggest that many still desire some level of involvement to maintain situational understanding for comfort (Frison et al., 2017; Merat et al., 2012; Roedel et al., 2014). Our findings also show that participants do not always remain fully engaged in these activities. Many participants shifted their attention back to the driving environment in response to sudden movements, curiosity, or the need to check what the car was doing.

These attention shifts may not be considered as signs of bad interaction design. Instead, they often reflected attempts to understand the situation, especially when something unexpected happened. Participants moved fluidly between being engaged in the NDRA and briefly re-engaging with the road. These transitions show that attention during AV use is not all-or-nothing. People make dynamic choices about when to look up (attention shifting) and what to notice (prioritising tasks) (Rankin et al., 2016). These attentional redirections marked key moments of interpretive engagement, which can be seen as experiential manifestations of AS.

Our behavioural data support this interpretation. Glance patterns were not always aligned with their perceived distraction. This suggests that visual attention alone does not guarantee cognitive engagement, and that participants may have been "looking but not seeing", a distinction also noted in prior work (Dehais et al., 2015; Rankin et al., 2016).

We speculate that that full immersion in NDRAs may not be ideal, or even possible, for all users. People appear to manage their attention in personally meaningful ways (Tinga et al., 2022; Wandtner et al., 2018). Designing systems that assume uniform attention patterns when addressing AS may not reflect real-life use.

5.3 Reframing AS as Situated Phenomenon

Our findings also support emerging perspectives propose in aviation that AS is not solely cognitive failure. Instead, it can be understood as a situated phenomenon: *"the element of surprise marks the cognitive realisation that what is observed does not fit the current frame of thinking."* (de Boer & Dekker, 2017; Rankin et al., 2016). Following this, experience of AS shaped by not only the AV's behaviour, but also user's expectations, bodily sensations and situated context. In our study, participants interpreted what the AV was doing using clues from the environment (like traffic or road layout), physical sensations (such as braking), and personal reasoning. This points to AS as a gap in shared understanding between the user and the AV. It is not just about whether the AV behaves correctly, but whether the user can make sense of that behaviour. These experiences echo ideas from ecological HMI design (Strömberg et al., 2019) and embodied interaction (Boelhouwer et al., 2019), which argue that understanding technology is a multimodal and context-dependent process.

By recognising AS as a lived experience, designers and researchers can better understand the sense-making process when encountering AS, and design systems that support people's understanding, not override it.

5.4 Design Considerations

We propose several directions for design. These are not specific interface solutions, but intermediate-level insights that can guide how we approach AS in everyday AV use:

1. Design strategies could go beyond preventing surprise toward supporting users' ongoing sense-making.
2. Interfaces should accommodate the natural flow between NDRA immersion and situational re-engagement when encountering surprising system behaviours, rather than enforcing constant attention or complete detachment. Moments of surprise can be used to gently re-engage users.
3. AS can reveal mismatches in understanding that point to design improvements. Studying and designing for AS from the user experience perspective can help uncover hidden misalignments and improve the understanding of AV systems in daily usage.

6 Limitations and Future Work

While this study offers valuable insights into the lived experience of AS, several limitations should be noted. First, participants were not given a formal definition of AS, nor asked to identify specific surprise events. AS was interpreted retrospectively from interview data and behaviour. This opens a rich space for user-led framing, aligned with the phenomenological study common sense, but reduce the precision with which different forms of AS could be compared. We see this work as laying an experiential foundation for future research that may develop more structured typologies of AS as lived experience in automated driving. Second, although the cue should not be considered a design solution in itself, participants reflected on how it conveyed information. We interpreted these reflections as indications of the kinds of information users might desire. However, such interpretations should be treated with caution, as they remain speculative and participants' reflections may have shaped their immediate perceptions and experiences of AS. Finally, while we outlined conceptual design directions, the study did not aim to produce concrete design concepts. Future work should build on these insights to prototype.

7 Conclusion

This study used a phenomenological and design research approach to explore if and how AS arises during non-critical automated driving. Rather than being limited to emergencies or system malfunctions, we found that AS often emerges from subtle mismatches between users' expectations, embodied sensations, AV behaviour, and the surrounding context. By shifting the focus from "AS as cognitive failure" to "AS as lived experience," we highlight the sensemaking processes that users engage in after moments of surprise. Our findings also show that attention during NDRAs is fluid. Attentional shifts are not simply distractions, but meaningful responses, can be understood as how users monitor, interpret, and adapt to automation when experiencing surprising event. We propose that researchers and designers reframe AS as a multi-layered experiential phenomenon, one that reveals misalignments in expectations and offers insights into users' interpretive needs. While AS has its roots in human factors, this study invites a broader, experience-centric perspective. Future research could build on this framing by treating AS as a designable condition, embracing ambiguity, attentional shifts, and narratives of technology, to develop richer typologies of AS in everyday automated mobility.

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9 Appendix

Table 1: Participants Overview

ID	Age	Gender	Exp. with ADAS	Attitude to AV	Trust tendency
N01	25	Male	3	4	4.17
N02	29	Female	1	3	2.67
N03	30	Male	2	1	3.17
N04	25	Male	2	2	3.00
N05	33	Male	3	1	4.17
N06	27	Male	3	3	2.00
N07	30	Male	3	2	3.33
N08	30	Female	2	0	4.67
N09	30	Male	2	2	3.67
N10	25	Male	4	2	3.17
N11	54	Male	2	0	4.83
N12	27	Female	2	1	2.20
N13	28	Male	3	0	3.83
N14	25	Male	2	0	2.67
N15	27	Male	3	0	4.33
N16	31	Male	2	2	3.67
N17	27	Female	4	2	2.83
N18	27	Male	2	1	3.5
N19	23	Male	2	1	3.83
N20	26	Male	2	1	4.00

Experience with ADAS

4- Yes, I use them quite often.

3- Yes, but only try them a few times.

2- No, I know about them but never tried them.

1- No, I had no ideas what that means.

Attitude to AV

0 - Look very much forward

5 - Highly sceptical

Trust tendency

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