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Designing With Motion: Exploring Vestibular Cues as a Subtle Awareness Nudge Modality in Automated Vehicles

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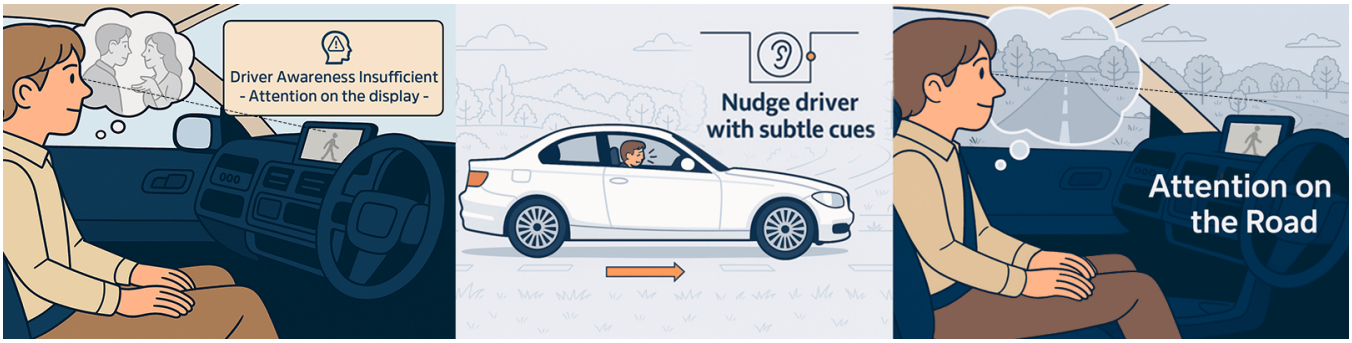


Figure 1: Using vestibular cues as a subtle awareness "nudge" modality in L3 automated driving scenario.

Abstract

Automated driving systems, particularly at SAE Level 3, present new challenges in managing driver attention to ensure smooth transitions from automated to manual control. This paper reports on a qualitative investigation of vestibular cues—implemented via subtle deceleration events—as a form of a dynamic Human-Machine Interface (dHMI) that subtly "nudges" a user's attention away from a non-driving related task (NDRT) and towards the driving environment. Conducted as a test-track study (N=25), we explore awareness, acceptance, and design considerations related to these cues. Findings reveal that while participants showed positive attitudes toward vestibular nudges as safety features, they were unable to differentiate nudges from necessary vehicle deceleration during automated driving. The study reveals how drivers interpret the implicit interaction with the dHMI during realistic NDRT and potential limitations. The study highlights the need for multimodality HMI approaches and customisation to optimise user experience in conditional automated vehicles.

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CCS Concepts

• **Human-centered computing → User studies**.

Keywords

Automated Driving, Dynamic Human-Machine Interface, Attention Management, Nudge, Vestibular Cues

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1 Introduction

Automated vehicles (AVs) promise to reduce road crashes and improve transport efficiency by minimising human error and enabling drivers to engage in non-driving-related tasks (NDRTs) such as watching videos or using mobile devices. However, in SAE Level 3 (L3) conditional automation [30], where the vehicle handles most driving but the driver must resume control when prompted, managing driver attention becomes a critical safety challenge [18].

When drivers disengage from the road to perform NDRTs, their situational awareness may degrade, widening the readiness gap between passive monitoring and active control [31, 33]. This gap has led to growing interest in Human-Machine Interface (HMI) strategies that subtly reorient driver attention in preparation for potential transitions.

Prior HMI solutions have relied heavily on explicit visual, auditory, or haptic alerts [20, 27, 32]. However, these modalities can disrupt the user experience or compete with NDRTs, especially when delivered during pre-transition periods where driver readiness is low but system takeover is not yet required.

This study investigates an underexplored modality for implicit attention management: vestibular cues. By introducing subtle deceleration events as motion-based signals—referred to here as a dynamic HMI (dHMI) [18]—we explore whether such cues can nudge driver attention without explicit prompts or interface clutter. Vestibular feedback has shown potential in L2 contexts [8] but remains largely unexplored in L3+ automated driving. Figure 1 shows the concept of using vestibular cues for attention management in highly automated driving scenarios.

1.1 Contribution Statement

This paper presents an exploratory qualitative study (N=25) examining how drivers experience subtle longitudinal deceleration cues used as a dHMI during L3 automated driving with NDRTs. Our research questions are: *How do drivers experience a vestibular nudging dHMI during automated driving with NDRTs, and what are the user attitudes and needs in relation to this dHMI application?*

Our findings contribute empirical insights into driver perception, interpretation, and acceptance of vestibular motion cues in AVs, informing future HMI designs aimed at enhancing driver readiness without explicit disruption.

2 Related Work

2.1 Attention Management in Automated Driving

Attention management (AM) refers to "the ongoing process by which a driver allocates and focuses attention among competing objectives, activities, decisions, and information elements to meet specific goals within a driving context" [22]. In Level 3 automated driving, AM is particularly critical during the *pre-transition* phase, before the system requests a manual takeover [18]. This phase is often overlooked despite growing evidence showing that drivers need more time and support to return to a sufficient level of awareness for safe manual intervention [17, 24].

Existing strategies to support AM frequently use explicit alerts delivered through visual, auditory, or haptic modalities [5, 20, 27, 32]. However, these channels are limited in automated contexts: Visual prompts can conflict with screen-based NDRTs [10]; auditory cues may be perceived as annoying [27]; and haptic feedback may be masked by environmental vibrations or ignored altogether [12].

These challenges have led to increased interest in implicit attention cues that operate more subtly, preserving user experience while gradually re-engaging awareness [1, 34]. This study examines such a modality using motion cues as a dynamic form of interaction.

2.2 Vestibular Interfaces and Vehicle Dynamics

Dynamic HMI (dHMI) refers to the use of vehicle behaviours (e.g., speed, pitch, deceleration) as communicative signals [18]. While traditional driving relies heavily on motion cues for situational awareness and comfort judgments [19, 35], such dynamics remain underutilised as communication tools in AV design [3].

Past research in L2 contexts has shown that pitch, roll, and longitudinal deceleration can improve vigilance and lane-change performance [8, 25]. In L4 research, deceleration nudges influenced driver decision-making more reliably than acceleration [37]. Importantly, studies have also shown that the presence or absence of vehicle motion itself can significantly affect driver responses. Sadeghian Borojeni et al. [29] found that simulator studies with motion generated faster driver reactions compared to static setups, suggesting that awareness and behavioural response may be underestimated in non-motion contexts.

These findings collectively support the potential of motion as an implicit cue, yet few have investigated its role in attention management under NDRTs in Level 3 driving.

This work draws on findings from both motion sickness and driving style optimisation [15, 28], as well as vestibular perception research [21], to explore deceleration as a subtle nudging mechanism for reorienting driver attention without explicit instruction.

2.3 Summary

While prior research has addressed attention management through visual and auditory channels, few studies explore vestibular cues as an implicit HMI for AVs. Within the AV HMI framework [3], vestibular nudges represent a promising form of dHMI for enhancing readiness in the pre-transition phase—without compromising the in-cabin experience. This study fills that gap by evaluating user

experiences and design expectations for motion-based feedback during L3 automated driving.

3 Method

3.1 Study Design

This study adopts a design-oriented, exploratory qualitative approach to investigate how subtle vestibular cues—implemented as longitudinal deceleration nudges—may support attention management in Level 3 automated vehicles. Rather than evaluating task performance or detection accuracy, the study focuses on capturing participants' situated experiences, interpretations, and attitudes toward this form of dHMI.

Conducted on a closed test track using a highly automated prototype vehicle (Figure 2a), the study involved 25 participants who experienced a 35-minute conditional automated drive while engaging in a non-driving-related task (watching short video clips) (Figure 2b). The experience comprised three distinct route sequences ("Drives"), each lasting approximately 10 minutes: two featured non-overlapping clockwise laps, and one involved non-overlapping counterclockwise laps. These Drives ran with seamless transitions at the start/end position. The three Drives were combined in counterbalanced order to form six driving scenarios.

Each Drive included two subtle deceleration events (programmed nudges) triggered at predefined locations, yielding a total of six nudges for each scenario to which participants were randomly assigned. Contextual decelerations occurred naturally as part of the vehicle's automated operation. Immediately following the drive, participants completed semi-structured interviews to reflect on their experiences.

3.2 Participants and Recruitment

Twenty-five licensed drivers (13 female, 12 male; mean age = 53.8 years, SD = 20.1) participated in this study. Participants were required to have at least two years of driving experience and were screened to exclude those with medical conditions affecting driving or balance perception (e.g., vestibular disorders), colour blindness, or conditions related to fatigue or drowsiness. The occupational background of participants was diverse, including higher-degree research students, engineering professionals, research personnel, and retirees.

Participants were recruited through multiple channels, including university communication channels, community organisations, social media, and snowball sampling. The study received ethical approval from the university ethics committee (approval number 8522), and all participants provided informed consent prior to participation.

3.3 Design Intervention

During the automated drive, participants experienced two types of longitudinal deceleration events reflecting different roles in the driving interaction:

Contextually necessary decelerations occurred naturally as part of the vehicle's automated driving behaviour. These were triggered by standard driving scenarios such as approaching intersections, navigating curves, or adapting to dynamic road conditions (Figure 2c). They were not introduced for experimental purposes

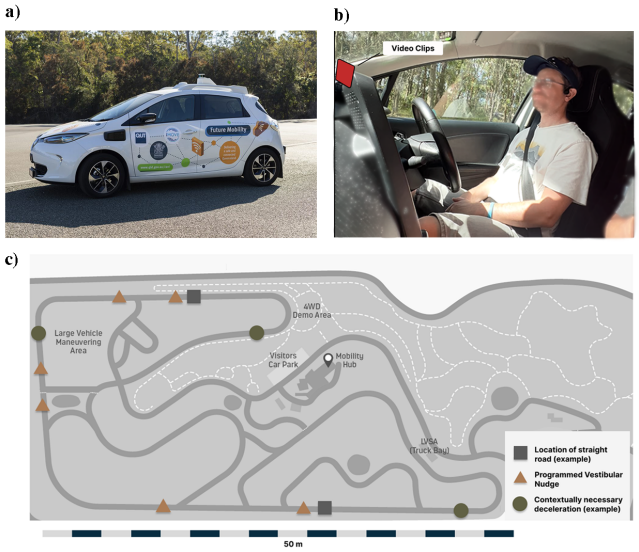


Figure 2: (a) The L3+ automated vehicle prototype. (b) The participant is watching video clips during automated driving. (c) Nudge locations at the test track.

but reflected the real-world driving dynamics of a Level 3 AV (Figure 3).

Programmed vestibular nudges were extra subtle deceleration events, intentionally introduced to prompt participant awareness. These nudges were designed to sit on the border of conscious perception, engaging the vestibular sense without triggering overt recognition. The goal was to explore whether such low-level, embodied cues could subtly redirect attention without requiring explicit system intervention. The design motivation is that additional vestibular cues, beyond those occurring during regular driving context, may naturally redirect attention toward the driving environment.

These nudges were implemented on straight road segments, selected because they allowed decelerations to be introduced in isolation—without overlap with contextually necessary decelerations (Figure 2c). The design of the nudges was informed by pilot testing conducted on the test track, which evaluated different speed profiles. A "uniform" deceleration profile was selected for its ability to produce a consistent two-phase motion: a gentle deceleration followed by a return to cruising speed. This profile was found to be perceptible yet unobtrusive and reliably reproducible within the automated vehicle platform.

During the drive, participants experienced a series of subtle longitudinal decelerations at different locations, each lasting 4-8 seconds. Each nudge generally followed a two-phase structure: (1) an initial deceleration phase lasting approximately 2-4 seconds, during which the vehicle slowed to a bottom speed; this was followed by a brief hold phase, during which the vehicle maintained the lower speed until a return-to-speed command was issued. In the experiment, this resulted in deceleration (calculated from example vehicle telemetry data recorded at a sampling rate of 50 Hz) ranging from approximately -1.74 to -0.77 m/s^2. This range has

been validated in pilot studies and supported by driving literature as being perceptible [16, 36]; and (2) a re-acceleration phase where the vehicle resumed its original cruising speed.

Although the nudges followed pre-programmed timing, the vehicle's onboard control logic dynamically adjusted actual speed trajectories based on environmental conditions, for example, road friction or the total weight of people inside the car. Unlike motion simulator settings, the resulting speed profiles were not completely uniform across instances; instead, they reflected the inherent variability of real-world AV control and environmental dynamics. The nudges, therefore, varied in speed reduction and profile shape (Figure 3), producing a brief but physically perceptible change in motion without disrupting the automated driving flow.

These events generated distinct acceleration-deceleration patterns using controlled brake torque and throttle modulation. The resulting motion was experienced as a mild backward force followed by a release—subtle, but physically perceptible within the seated driving context.

To simulate a realistic scenario of attentional disengagement, participants engaged in an NDRT during the drive. This task involved watching a series of pre-selected, engaging video clips on a dashboard-mounted device within their forward line of sight. The use of video watching—and the content itself—was informed by prior research [14].

3.4 Procedure

Each participant took part in a single test-track session involving a Level 3 automated driving experience with integrated programmed nudges. The session followed a structured sequence consisting of onboarding, familiarisation, the automated driving trial, and a post-drive interview.

The session began with a briefing and consent process, during which participants were introduced to the study objectives, safety protocols, and system features. This included an explanation that the vehicle may perform extra subtle decelerations—referred to as "nudges"—in addition to regular slowing for intersections and curves. Participants were told these nudges were designed as subtle reminders to glance up and check the environment, without issuing an explicit alert. However, they were not informed of the number, timing, or specific locations of these events.

This was followed by a warm-up phase, where participants completed two familiarisation laps in the vehicle's automated mode under the supervision of an expert safety driver. This phase allowed participants to experience the vehicle's dynamics and become comfortable with the automated system.

Participants then began the main automated driving session, which included six programmed vestibular nudges interspersed throughout the drive at predetermined straight track segments. The full drive lasted approximately 35 minutes and incorporated naturalistic driving elements such as curves, intersections, and contextually necessary decelerations.

Participants were asked to engage in the NDRT but were free to do so at their own discretion. They were not explicitly alerted to the timing or purpose of the nudges during the drive.

After the drive, participants returned to a quiet room and completed a semi-structured interview.

3.5 Data Collection

All participants completed the driving experience, including exposure to six programmed vestibular nudges. The study was conducted during daylight hours (08:40–17:00) over several days. One session was partially affected by light to moderate rainfall, though vehicle and nudge behaviour remained consistent.

Immediately after the drive, participants engaged in semi-structured interviews lasting approximately 10 to 20 minutes. These interviews were conducted in a quiet preparation room and focused on understanding participants' subjective experiences and interpretations of the vehicle's deceleration behaviours, with an emphasis on their awareness, perceived function, and potential acceptance of subtle motion cues.

The interview design followed a structured progression:

(1) **Warm-up** – Participants answered introductory questions about their background and general driving experience.
(2) **Initial impressions** – Participants were asked to describe their overall experience of the vehicle's deceleration behaviour during the drive, including whether any moments felt unusual or unnecessary (Q1).
(3) **Reflections on perception** – If participants reported noticing unexpected decelerations, follow-up questions (Q2) explored how they interpreted and responded to those experiences.
(4) **Disclosure of nudges** – Disclosure of nudges – The researcher clarified the design intent of the programmed nudges and disclosed their specific locations. This prompt was used to support retrospective reflection and elicit participants' awareness (Q3) and interpretation before concluding the interview.
(5) **Acceptance and future use** – The interview concluded with questions about acceptance and preferences, including perceived usefulness, safety, ease of use (annoyance), and willingness to use such a feature in future automated vehicles (Q4+).

All interviews were audio-recorded with consent and later transcribed verbatim for thematic analysis. Observational field notes were also captured during and after each session.

4 Analysis

Interviews from 24 of the 25 participants were transcribed, with one participant (P29) excluded due to lack of consent for automated transcription. Thematic analysis was conducted using a reflexive approach, following Braun and Clarke's framework as adapted for applied qualitative HCI contexts [4]. The analysis was inductive and semantic in nature, with a focus on capturing participants' expressed experiences and meaning-making in relation to the subtle deceleration cues.

The first author led the initial coding and theme development, drawing on prior experience in automotive HMI research and qualitative user studies. A co-author with extensive AV and HCI expertise reviewed and refined the themes, and both authors engaged in iterative discussions to co-construct the final thematic structure. In line with the reflexive approach, the goal was not to seek coding consensus but to acknowledge researcher subjectivity as an

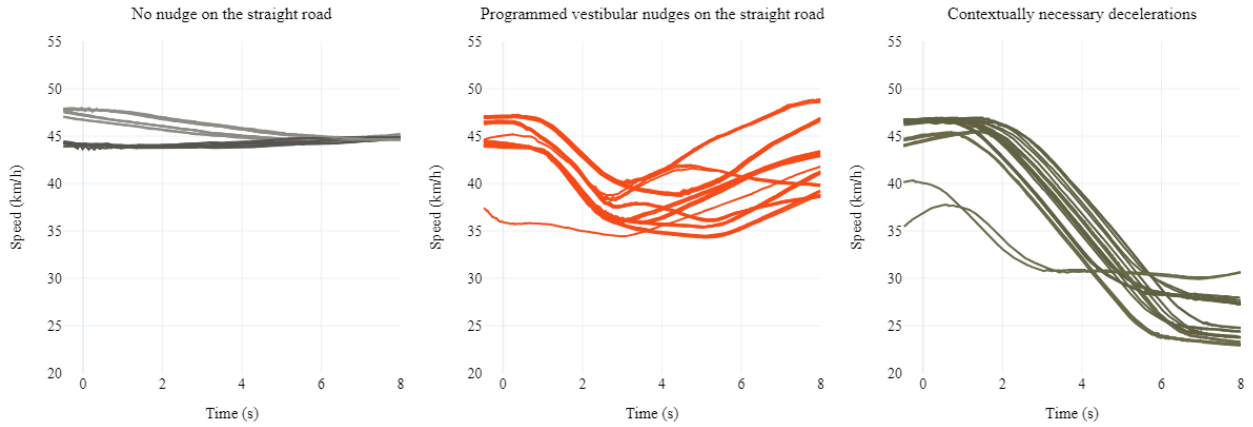


Figure 3: Examples of vehicle speed profiles in a real-world automated driving environment, illustrating cases of no nudge on straight roads, programmed vestibular nudges on straight roads, and contextually necessary decelerations.

interpretive asset. This orientation aligns with the constructivist paradigm underpinning the study.

Transcripts were read iteratively, and open coding was conducted using MAXQDA[1]. Meaningful segments of text were coded without a pre-existing framework. Initial codes were reviewed across transcripts and progressively grouped into candidate themes.

Themes were refined through multiple iterations, guided by thematic maps and discussion between authors. Some candidate categories (e.g., comments about NDRT content) were dropped to focus on aspects more central to the research aims. Final themes were selected based on their relevance to the study's exploratory goals and their coherence across cases.

The analysis focused on three interconnected areas:

(1) Participant awareness and interpretation of subtle deceleration cues, including differences before and after disclosure of the intervention.
(2) Cognitive and behavioural responses to vestibular nudges while engaged in a non-driving-related task.
(3) Participant attitudes and design expectations related to implicit safety features in Level 3 automated vehicles.

5 Findings

Participants' experiences coalesced into five key themes: *Awareness & Interpretation of Vestibular Nudges*, *Attentional Dynamics & Behavioural Responses*, *Trust Impact from Ambiguity*, *User Attitudes & Acceptance Factors*, and *Design Requirements: Multimodality & Customisation*. The interrelations of themes are synthesised in the Figure 4.

5.1 Awareness and Interpretation of Vestibular Nudges

5.1.1 Limited Explicit Awareness. Participants often struggled to explicitly identify the programmed nudges during the drive. Although they had been told that such events might occur, many

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

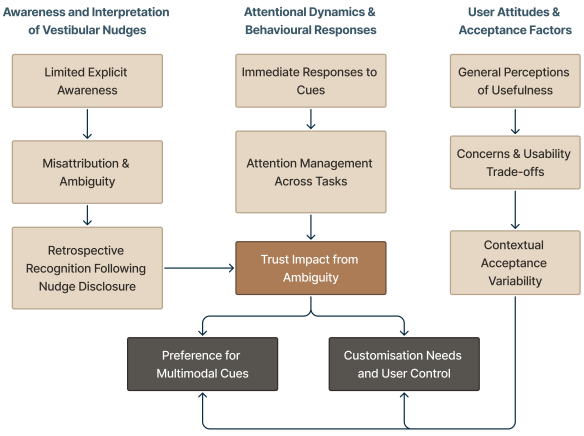


Figure 4: The relationships between themes of exploring implicit nudge dHMI.

were uncertain whether they had actually experienced them, or were unable to recall when or where they happened. This theme reflects the intended subtlety of the intervention and highlights the challenges of designing implicit cues that register without drawing undue attention.

Most participants (16 of 24) reported either failing to notice the nudges or being unsure if they had occurred at all:

> **P49**: *"No. I can't really remember. Because it did that a bit, it did it a few times, that sort of thing..."*

Some participants recalled that a subtle change might have happened but were unable to specify when:

> **P25**: *"...yes, I felt some, when we were travelling through a straight road, sometimes you suddenly drop the speed. Mm-hmm. I can remember, but I can't remember when it was."*

Others reflected on the difficulty of noticing subtle cues without having them explicitly pointed out after the fact:

> **P84**: *"I think I picked up on most of them, or maybe all of them. Why are you doing this?"*
> **P50**: *"Perhaps they need to make it a little bit more of an obvious one. Yeah. Because it does so many juddery bits around other parts of the course."*

These responses illustrate that even when participants were primed to expect something unusual, the nudges often remained below the threshold of conscious detection. This limited explicit awareness supports the idea that vestibular cues can operate as implicit feedback—but also reveals a risk: if cues are too subtle, they may fail to register at all, especially in environments with multiple background movements or distractions.

5.1.2 Misattribution and Ambiguity. Participants often misinterpreted the programmed nudges, conflating them with other expected or unexpected vehicle behaviours. This theme highlights the interpretive ambiguity that arises when deceleration cues are subtle and embedded in a context full of natural vehicle dynamics. It shows how participants drew on prior expectations and environmental assumptions to make sense of motion they could not easily attribute.

Some participants misattributed a wide range of vehicle behaviours to the nudge functionality, including speed drops (P80), manoeuvres before turns (P02, P36), speed variations inconsistent with their driving preferences (P84), jerky steering wheel motion (P12, P89), or even the car coming to a stop at signposts (P84).

In several cases, participants described how these different types of deceleration blended together, making it difficult to isolate any specific cue:

> **P79**: *"Because the car was jittery anyway. Sort of blended in with it."*

Other participants attributed the sensations to plausible environmental causes such as subtle impacts (P50), wildlife avoidance (P39), or road surface irregularities like bumps (P25, P07). One participant, who maintained road attention instead of engaging with the video task, interpreted the motion as a vehicle quirk:

> **P62**: *"Because they were on the stripes and because I wasn't watching the video. I knew exactly what was in the environment. So yeah, I just put it down to an idiosyncrasy in the car."*

Several participants interpreted these events as evidence of imperfect or malfunctioning automation. For instance:

> **P80**: *"I've got a little robot thing at home that's got a line following thing, and it's sort of very reminiscent of that behaviour."*
> **P50**: *"Because I've got a car which I've now discovered [has an issue with] the transmission gears, and it's automatic to listen, and it's starting to do what I call a grind, and they tell me it's called a shudder."*

These responses suggest that when cues are delivered implicitly, users may misattribute their source based on existing mental models or past driving experience. Even when participants are aware that something unusual might happen, the lack of a clear perceptual or semantic signal leads them to fill in the gaps with their own assumptions. This can reduce the effectiveness of the cue or undermine confidence in the system.

5.1.3 Retrospective Recognition Following Nudge Disclosure. After the drive, participants were informed about the specific locations and purpose of the programmed nudges. This prompted several to reflect on their earlier experiences and reinterpret moments of subtle deceleration that they had initially attributed to other causes—or not noticed at all. This theme captures how post-hoc disclosure influenced participants' understanding of the system and reframed their interpretation of ambiguous motion events.

Participants who had initially experienced confusion or surprise often described how the disclosure helped clarify what had happened. Some, like P01 and P04, linked this process of reinterpretation to their sense of trust in the system and how they made sense of its behaviour:

> **P01**: *"The main downside is that it reduces the trust in the system, so you think it's a glitch, despite I was told it was inserted deliberately, you think it's some sort of a problem going on now with the system."*

Others reflected on the mental effort of reconciling what they felt with what they were later told. These participants reported initial uncertainty that later gave way to understanding:

> **P04**: *"I got more alert, but then very quickly I realised it's okay... then I had to process the fact that they are happening, because I was informed that they would be happening, and then I would relax..."*

These accounts show how implicit interventions often require interpretive work by users, especially when feedback is subtle. The post-drive disclosure offered a moment of sensemaking that, for some, reduced confusion, while for others, it revealed a gap in communication that had briefly undermined trust or created discomfort during the drive.

5.2 Attentional Dynamics and Behavioural Responses

5.2.1 Immediate Responses to Cues. Participants exhibited a range of immediate reactions to the vestibular nudges—some subtle, others more noticeable—spanning from proactive attentional shifts to passive disregard. This theme explores the diversity of responses and illustrates how implicit motion-based cues were received in the moment of experience.

Some participants responded proactively by attempting to scan the environment, adjust their posture, or interpret the event as a meaningful signal. For example, several reported looking around to assess the driving situation (P04, P12), while one participant even attempted to brake in reaction to the deceleration (P25). Others, like P01, described the experience as momentarily unpleasant.

> **P04**: *"So, the immediate response was just to alert first and look around, so try to find the..."*
> **P25**: *"...because I was trying to brake. I thought, some kind of thing is going on."*

In contrast, six participants explicitly noted that they noticed the nudge but chose not to respond, suggesting either a lack of salience or a decision to disregard it.

> **P80**: *"I did specifically notice that, but it didn't make me want to do anything, or panic, or touch anything."*

These behavioural responses illustrate the variable effectiveness of implicit motion cues. While some participants interpreted the cue as a prompt to reorient their attention, others did not consider it meaningful or actionable.

5.2.2 Attention Management Across Tasks. Participants navigated the competing demands of engaging with a NDRT while also maintaining some awareness of the driving environment. This theme captures how they managed this balance, revealing variations in attentional strategies, self-regulation, and task prioritisation.

Several participants reported fluid transitions between watching video content and scanning the environment, often depending on how mentally engaging they found the media. These transitions were sometimes triggered by perceived fatigue, information overload, or a sense of obligation to monitor their surroundings. One participant described how cognitive saturation from intense or complex videos led to disengagement:

> **P01**: *"Videos were really intense, frankly, so they-they were more—they overwhelmed me, um... [recalled video contents] ...I was noticing I was switching on, but majority of them, they are above my usual, uh, threshold."*

Similar experiences were shared by P03, P62, P80, and P92, who described how their attention fluctuated—sometimes withdrawing from the video altogether, sometimes toggling between screen and road.

A smaller group (5 out of 24) adopted selective sensory strategies, reporting they engaged with audio content while still visually monitoring the environment. For example:

> **P49**: *"There were some interesting stories, but I refused to take them all in... I'm a great one for podcasts while I'm driving. I do watch a lot of, particularly the ABC conversations. I'll not watch them, listen to them."*

Participants P03, P16, and P62 also noted treating the video as background noise rather than a fully engaging task.

Overall, these patterns illustrate how participants dynamically allocated attention between the in-vehicle task and their surroundings, either disengaging entirely, switching focus periodically, or maintaining low-effort environmental monitoring. These findings reflect the dual-task nature of Level 3 automation scenarios and suggest a need to consider how system design can better support natural attentional rhythms during non-driving engagement.

5.3 Trust Impact from Ambiguity

Participants' trust in the automated system was shaped by how they interpreted—or struggled to interpret—the meaning of subtle deceleration cues. This theme explores how ambiguity in system behaviour influenced driver confidence, particularly when cues were misread, unacknowledged, or overinterpreted.

Some participants experienced immediate confusion or uncertainty about whether the vehicle's actions were intentional or malfunctioning. These initial reactions led some to question the system's reliability:

> **P04**: *"If I wasn't told that I should expect them, that would affect me trusting the system."*

Participants P01, P04, and P16 all reported that their trust was impacted by not knowing how to interpret the vehicle's deceleration at the time it occurred. P16, in particular, described how repeated unexplained behaviour led to ongoing concern:

> **P16**: *"Because I guess when the car's slowing down, you're kind of like going, what's it seeing? What's it doing? So if it keeps doing it for nothing, then it might mean that you're not trusting its decisions."*

At the same time, several participants raised concerns about the opposite problem: that overly noticeable nudges might also reduce trust by seeming intrusive or overly cautious. P16 captured this trade-off:

> **P16**: *"If it became something that you're too aware of, you might mistake it for being overly cautious... that might impact your level of trust. But if you're used to it doing what it does, then it's better than a sound or light or alarm... "*

One participant, P39, who encountered an unrelated vehicle malfunction during the session, expressed that such issues—compounded by media reports of automated driving incidents—would further diminish their overall trust in the technology.

Others framed trust as a prerequisite for ignoring subtle feedback altogether. For instance:

> **P85**: *"There were a couple of times with some suggestion of uncertainty in the car... but nothing worrying—just a fractional moment of dissociation between the drive and whatever."*

Together, these accounts show that ambiguity in system behaviour—whether through subtle cues, unexpected repetition, or lack of clarity—can introduce uncertainty that affects user trust. Designing for trust may require striking a balance between too much and too little feedback, and understanding how different drivers respond to ambiguity under automation.

5.4 User Attitudes and Acceptance Factors

5.4.1 General Perceptions of Usefulness. Participants' general attitudes toward the vestibular nudging functionality ranged from enthusiastic to cautious, with most seeing some value in its intended purpose. This theme explores perceived benefits, conceptual appeal, and participant impressions related to awareness, safety, and fatigue reduction.

A majority of participants (15 out of 24) described the functionality as useful or interesting. A smaller group (6 out of 24) described it as "controversial" or conditional in its usefulness, while two participants found it odd or questionable.

Several participants interpreted the feature as a subtle but helpful safety reminder, particularly in situations where attention might wane (P16, P25, P85, P95). Others suggested it could help reduce driver fatigue or drowsiness (P08, P39, P85). One participant highlighted its role in bringing awareness to uncertain manoeuvres:

> **P05**: *"The advantages would be that it makes people a bit more aware of what's going on with manoeuvres that aren't 100 percent certain."*

These attitudes suggest a general openness to motion-based feedback as part of automated driving experiences, particularly

when framed as a non-intrusive support mechanism rather than a command.

5.4.2 Concerns and Usability Trade-offs. Despite general openness to the concept, participants expressed concerns about how such functionality would play out in everyday use. This theme captures perceived risks, edge cases, and discomforts associated with vestibular feedback.

Some participants framed the feature in terms of trade-offs, balancing subtlety against possible ineffectiveness (P12). Others voiced concerns about its impact on nearby road users (P04, P05, P80), or noted that it might not be equally effective for all individuals (P84).

A few participants cautioned that too much subtle deceleration could lead to overreaction or misinterpretation (P62, P95). Motion sensitivity (P31), attentional fragmentation (P08), and potential stress were also cited. One participant worried the intervention could reduce the overall enjoyment of driving.

Habituation and annoyance were raised as practical concerns in sustained use:

> **P04**: *"But I'm quite sure that people will get used to it very quickly and will stop noticing them like in hours after starting driving."*
> **P95**: *"Then noticing it over and over might sort of become annoying."*

These concerns reflect real-world usability questions: how noticeable is "just enough"? And how long will it stay that way?

5.4.3 Contextual Acceptance Variability. Perceived acceptance of the nudging feature varied depending on the driving context, individual disposition, and expected use case. Several participants noted that its perceived value might change depending on whether they were commuting or taking a long-distance trip.

> **P25**: *"Maybe for a long drive, I think, it might be annoying. So if I'm the driver, I might switch off the automated mode if I'm travelling a long distance, but for the commuter travellers, day-to-day travelling in the city, it might be very useful."*

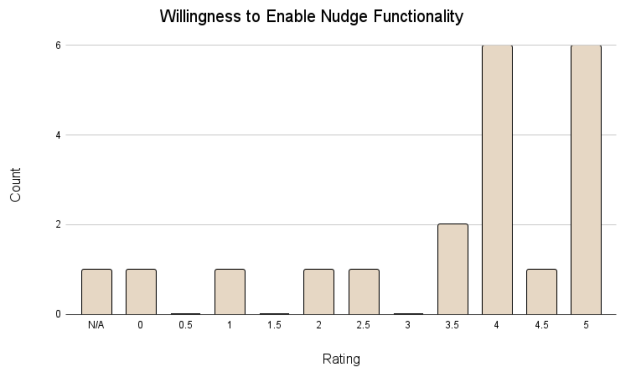


Figure 5: The rating of willingness to enable the nudging functionality.

Although the study was qualitative in focus, participants were also asked to rate their likelihood of using the feature in a future automated vehicle. As Figure 5, willingness-to-use ratings (on a 0–5 scale) were generally positive (N = 20, M = 3.7), although some found it difficult to commit to a number in a hypothetical context:

> **P79**: *"[The car] It's going to be driving itself, I think the more features you can have, the better."*

These responses point to the importance of context-aware design and flexible implementation strategies that adapt to different user goals and usage scenarios.

5.5 Design Requirements: Multimodality and Customisation

5.5.1 Preference for Multimodal Cues. A recurring design suggestion across interviews was the integration of additional feedback channels alongside vestibular cues. Many participants (8 out of 24) expressed a preference for multimodal approaches, indicating that combinations of sensory modalities could improve the salience and interpretability.

> **P12**: *"But having the nudge puts that natural body ..., and put that on instead of just one sense, multiple senses. So, yeah, I think something like a light with it would be good, just to keep in another sense there. Also, it then means, you know, one happens without the other."*

Participants offered specific ideas, including dashboard light indicators, auditory beeps, voice prompts, or haptic vibrations embedded in the seat. One participant described the physical sensation metaphorically, emphasising its intensity and purpose:

> **P85**: *"It was like someone hitting your back to wake you up."*

These preferences point to a broader desire for redundancy and clarity—where the nudging signal is supported by complementary cues that aid interpretation, reduce ambiguity, or reinforce urgency depending on context.

5.5.2 Customisation Needs and User Control. Beyond multimodality, many participants expressed a desire for greater control over when, how, and in what form nudging feedback would be delivered. For some, this meant the ability to toggle the functionality on or off entirely if it became irritating or unnecessary (P80, P08). Others framed it as a secondary, customisable feature—something helpful, but not universally required.

Several participants suggested preferences for tailoring the modality (e.g., light, sound, vestibular) or the message framing depending on the situation. P03 noted the appeal of being able to select the type of reminder best suited to their needs. P05 similarly conceptualised it as a supportive function that could be configured or adapted.

A particularly creative suggestion came from P16, who recommended randomising the nudges to maintain their effectiveness:

> **P16**: *"I don't think it would be annoying. I do feel like it shouldn't be on... like it needs to be semi-randomised. It can't be just like a constant, right?"*

Together, these findings emphasise that a one-size-fits-all implementation is unlikely to satisfy a broad user base. Instead, effective vestibular cue design may require configurable options that align

with user preferences, situational needs, and potential long-term use patterns.

6 Discussion

6.1 Design with Motion: Implicit vs. Explicit

The findings reveal exploratory implications for the design of motion-based communication in automated vehicles. Participants demonstrated varied perceptions regarding the programmed vestibular nudges, often conflating them with contextually necessary decelerations and mechanical vehicle behaviours. This perceptual ambiguity highlights a fundamental challenge in designing implicit interaction: the difficulty of distinguishing intentional communicative cues from incidental vehicle movements. As one participant noted, the effectiveness of such nudges might diminish once they get used to the car's driving style, suggesting that familiarity with vehicle behaviour influences cue interpretation. Prior research on dHMI in L2 has similarly noted that vehicle dynamics, such as pitch movement, are often underperceived or misattributed if not supported by additional contextual framing [7].

These findings also relate to Endsley's model of situation awareness [9], in which perception and comprehension are precursors to appropriate action. When participants did not clearly perceive the cues (Section 5.1.1) or misinterpreted them (Section 5.1.2), the intended increase in awareness was diminished. This mirrors concerns in earlier work on visual and auditory HMI strategies that failed to support reliable awareness during high-workload NDRTs [10, 26].

The tension between implicit and explicit interaction represents a critical design consideration for vestibular communication. Our analysis indicates that participant responses typically fell into three distinct categories: no conscious perception, implicit recognition with appropriate response, and explicit awareness accompanied by confusion. This tripartite classification suggests the need for adaptive systems capable of detecting user responses and modifying feedback accordingly. When participants consciously perceived nudges, many expressed a desire for explanatory feedback—a preference that highlights the limitations of purely implicit interaction paradigms. As observed in the interviews, participants who explicitly registered the nudges often sought clarification rather than simply directing attention to potential hazards, undermining the effectiveness of the nudging strategy.

In practical deployment, whether decision-makers should rely solely on implicit nudging strategies without incorporating additional modalities may depend on the potential drawbacks of such interactions. However, our findings indicate that purely implicit vestibular cues can create ambiguity that affects trust in the automated driving system. This suggests that implicit modalities for attention management require more explanation.

6.2 Trust and Transparency

Vestibular cues are primarily intended to intervene during engagement with demanding NDRTs. A key distinction between Level 2 and Level 3+ automation lies in driver positioning within the control loop. In L2 scenarios, the driver remains "in the loop" [23], meaning that vestibular interventions may more directly influence tactical-level behaviours [8]. In contrast, L3+ systems introduce greater challenges, as the driver is likely to be "out of the loop" during the pre-transition phase. Here, vestibular cues must first compete with cognitive and perceptual demands of the NDRT before influencing tactical-level or strategic-level awareness.

In this context, the vestibular cues introduced in our study appeared to create a "transparency gap"—a discrepancy between system behaviour and user comprehension that potentially undermines trust formation processes [13]. While such gaps are often framed as design shortcomings, our findings raise the possibility that, when appropriately timed and bounded, this ambiguity may serve a productive function. Specifically, a transient reduction in trust could prompt re-engagement with the driving environment by introducing uncertainty [2]. In our case, the uncertainty triggered by the programmed nudges may be interpreted similarly to how drivers experience uncertainty about an AV's interpretation of crash risks from the surrounding environment.

However, this effect is not without risk. Prolonged or unexplained gaps in transparency could erode confidence in the system over time. Yet, given participants' generally high willingness-to-use ratings for vestibular nudging, our results suggest that short-term ambiguity is not necessarily unacceptable, particularly when the cues are framed as subtle rather than directive.

Our findings further suggest that effective vestibular communication requires careful calibration between the implicit alerting strategy and transparent feedback. As with prior research on driver intention cues [11] and pitch feedback [7], participants in our study expressed a desire for clarifying signals, particularly when motion cues were consciously detected. Designing for transparency may involve combining subtle motion with just-in-time supplementary feedback (e.g., ambient lights, low-level audio), activated only when driver state or behavioural markers (e.g., delayed glances) suggest misinterpretation.

The challenges identified in this study support broader calls for adaptive, multimodality systems in AV HMI design. In line with AM frameworks and the SAT model [6, 22], future research should explore how vestibular cues can be dynamically adjusted or contextualised to better support trust and understanding, especially under varying user states, NDRT loads, and environmental conditions.

7 Limitations and Future Work

This study was conducted in a controlled, closed-track environment, which, while beneficial for methodological consistency, lacked the variability of real-world traffic conditions. Additionally, the study was an exploratory investigation using a prototype vehicle rather than a production-ready model. This means the vehicle may have exhibited technical limitations in its control maneuvers that do not reflect the fluidity and precision of state-of-the-art AV systems. These limitations may have amplified the perceptibility of programmed nudges, potentially overestimating their salience.

Participant selection criteria also excluded individuals with vestibular disorders or other conditions affecting motion perception, which may limit the applicability of findings to broader populations.

Moving forward, future studies would benefit from incorporating quantitative measures—such as eye-tracking—to validate the attentional effects of such interventions. Additionally, we plan to explore escalation strategies for vestibular cues, investigate multimodal cue

combinations, and develop adaptive interactions that dynamically respond to user states and contextual demands—ultimately supporting safer and more intuitive AV-human communication systems.

8 Conclusion

This study investigated vestibular nudging as an implicit driver–vehicle communication modality during Level 3 automated driving. In a test-track study with 25 participants engaged in NDRTs, we examined how subtle deceleration cues—implemented as a form of dHMI—were experienced and interpreted. Thematic analysis revealed mixed levels of awareness, with participants showing both appreciation for the concept and challenges in perceiving and interpreting the cues. These findings contribute to our understanding of implicit driver–dHMI communication within the AV HMIs framework and highlight the potential of vestibular cues to support attention management. They offer empirically grounded implications for designing intuitive, safety-supportive interfaces in future automated vehicles.

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