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Tactile alert placement in driving contexts based on neurocognitive evidence and eight consensus based design guidelines

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Abstract

Tactile alerts can communicate spatial and temporal information in automotive human-machine interfaces while reducing reliance on visual and auditory channels. Evidence on appropriate body locations for such alerts remains distributed across automotive human-machine interface (HMI), haptic-interface, and somatosensory research. This study examines how body location may influence the perception and processing of tactile alerts in driving contexts. It adopts a sequential evidence-to-consensus design comprising a scoping review of automotive HMI studies, reported in accordance with PRISMA-ScR; an umbrella review

of systematic reviews and meta-analyses on tactile perception and processing; and a modified Delphi study with six specialists from automotive industry, design, and neuroscience. The scoping review identified fifteen eligible studies, while the umbrella review synthesized evidence from six eligible reviews. The integrated evidence indicates that body regions differ in tactile acuity and sensitivity and that spatial congruence between stimulation location and event direction may support alert interpretation and response. Ten preliminary design guidelines were formulated and subsequently evaluated and refined through expert consensus, resulting in eight consensus-supported guidelines.

Keywords: Tactile alerts; vehicles; interaction design.

1 Introduction

In driving, tactile alerts support time-critical decisions, including hazard warnings, lane-departure notifications, collision avoidance, and takeover requests in automated vehicles [1–3]. In this study, a tactile alert is defined as a deliberately designed warning conveyed through mechanical stimulation of the skin, whereas haptic is used as a broader term that may also encompass kinesthetic interaction [4]. Because tactile communication relies on direct physical contact, the perceptual salience, spatial awareness, and motor response of the driver depend fundamentally on where and how stimulation is applied across the body, such as the thighs, back, hands, wrists, or face, and through which vehicle interface [5–8]. Therefore, a critical distinction must be established between body location, which refers to the specific anatomical region receiving the stimulation, and actuator location, which refers to the physical position of the hardware device embedded within the vehicle (e.g., seat pan, seat back, steering wheel, seatbelt) or integrated into a wearable interface [9–11].

Tactile alerts constitute an important communication modality in automotive human–machine interfaces (HMI) because they can convey spatial and temporal information through the somatosensory system while reducing reliance on visual and auditory channels [12]. Figure 1 illustrates in-vehicle systems delivering tactile stimulation through contact points such as steering wheels, seats, pedals, and wearable devices. Although requiring drivers to don specialized wearable garments may be impractical and may reduce acceptance [13], researchers have increasingly investigated consumer wearables, such as smartwatches and smartbands, because they take advantage of devices that drivers may already own and wear in daily life [7, 8, 11]. Beyond avoiding the need for dedicated equipment, these devices may provide stable physical contact even when automated-driving postures reduce contact with built-in vehicle surfaces [7, 8, 11].

Tactile acuity varies across body regions, affecting the detection, discrimination, and localization of mechanical stimuli [12] [14]. Consequently, the same alert may produce different perceptual outcomes depending on its body location. In automotive contexts, this issue is particularly relevant when alerts carry directional information. Spatial congruence refers to the correspondence between the stimulated body location

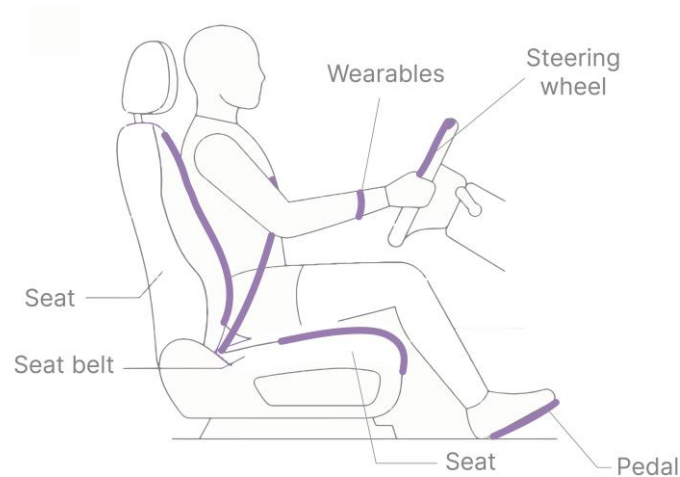


Fig. 1 Examples of tactile-alert locations in vehicle interfaces adjusted from 12

and the direction or location of a relevant driving event; for example, presenting a stimulus on the left side of the body to indicate a left-side hazard [15] [16] [17] [18]. Evidence from in-vehicle studies suggests that spatially congruent tactile warnings can facilitate interpretation and, in some conditions, reduce response time compared with non-directional stimulation [19] [12]. Under the visual, auditory, and motor demands of driving, such perceptual characteristics may be particularly important for timely and reliable responses [20] [21] [22].

Although the revised literature presents advances in haptic interfaces, the evidence remains distributed among different areas, covering technological aspects, performance in automotive HMIs and neurocognitive mechanisms of tactile processing [14] [23] [24]. The integration of these perspectives is important to guide the development of more efficient interfaces [25] [26] [27] [28] [29]. In the reviewed literature, a gap is observed in the integration between body location of haptic alerts, neurocognitive aspects, human-computer interaction and automotive design, limiting the understanding of how different body regions influence the effectiveness of these systems [23] [24] [25].

Given this gap, the present study combines a scoping review following PRISMA-ScR [30] with an umbrella review [31]; their synthesis informed a subsequent modified Delphi study [32] with an expert panel. This approach integrates evidence from the literature and expert knowledge to support the development of evidence-informed design recommendations. Accordingly, the following research questions were formulated:

RQ1. What is known about the use of different body locations for presenting tactile alerts in automotive human-machine interfaces, and what perceptual, cognitive, and behavioral outcomes have been investigated?

RQ2. What evidence from reviews and meta-analyses describes differences in tactile perception and processing across body regions?

Together, these questions guide the synthesis of evidence used to develop preliminary design guidelines, which are subsequently evaluated and refined through the Delphi study with an expert panel.

The remainder of this paper is organized as follows: Section 2 describes the materials and methods, Section 3 presents and analysis our findings, and Section 4 outlines the conclusions and future research directions.

2 Materials and Methods

The study is characterized as applied, exploratory, and descriptive, adopting a sequential evidence-to-consensus design that combines literature synthesis with a modified Delphi to translate dispersed evidence into design recommendations [33] [34] [35]. It is applied because it aims to translate scientific knowledge on tactile perception and body location into practical guidelines for haptic alerts in automotive interfaces [25] [36] [37]. It is exploratory because it addresses a multidisciplinary problem with conceptual and empirical gaps concerning the influence of body location on tactile perception [38] [36]. Finally, it is descriptive because the reviews systematically organize the available evidence according to observable characteristics of the phenomenon, including body location, stimulus characteristics, interface context, and perceptual and behavioral outcomes [39] [40] [41].

The scoping review was conducted in accordance with the PRISMA extension for Scoping Reviews (PRISMA-ScR) [30] [42] [43]. A scoping review was selected because it is appropriate for mapping a broad and heterogeneous body of literature [30] [44] [45], identifying key concepts and study characteristics [42] [46] [44], and identifying research gaps within an emerging or multidisciplinary field [44] [47] [48].

Complementarily, an umbrella review was conducted to synthesize evidence from existing systematic reviews and meta-analyses in the neurocognitive and somatosensory fields [49] [50] [51]. This review type was selected because it enables the integration of findings from multiple secondary reviews [49] [52] [31], providing a higher-level synthesis of the available evidence [52] [53] [51] while helping reduce fragmentation and inconsistency across related research domains by comparing and contrasting overlapping reviews [49] [50] [53].

Following the synthesis of evidence from the scoping and umbrella reviews, a modified Delphi study was conducted to evaluate and refine the preliminary design guidelines and establish expert consensus [54] [55] [34] [56]. This sequencing is consistent with modified Delphi designs in which preparatory literature reviews are used to generate the initial knowledge base, candidate items, or draft statements that are subsequently submitted to an expert panel for evaluation [38] [35] [55] [56] [57]. The modified Delphi procedure followed a structured sequence of steps:

1. **Expert panel selection:** The panel comprised six specialists from the automotive industry, design, and neuroscience. A panel size of five to ten specialists is considered appropriate for this type of expert evaluation [58]. Their distribution and professional backgrounds are presented in Table 1. Experts were selected according to their academic and/or professional expertise in the study domains [59] [57].
2. **Preparation of preliminary guidelines:** The initial guidelines were developed from the evidence synthesized in the scoping and umbrella reviews, providing the basis for expert evaluation.

3. **First-round evaluation:** Experts independently evaluated the preliminary guidelines using a predefined Likert scale and could provide qualitative comments or suggestions for modification [59] [32].
4. **Analysis and feedback:** The responses were quantitatively analyzed using measures of central tendency and agreement, complemented by a qualitative analysis of the experts' comments. Based on these results, the guidelines were revised and resubmitted to the experts in a second round for consensus evaluation. In this round, the revised Delphi questionnaire incorporated the comments received in the initial round and presented the median response for each guideline, allowing experts to reconsider their evaluations while maintaining independent judgment [57] [59].
5. **Consensus assessment and refinement:** Consensus criteria were established *a priori* based on the proportion of agreement within the predefined response categories. Items that did not reach the consensus threshold were reconsidered, reformulated, or excluded in subsequent round[59] [57].

Table 1 Professional background of the participating specialists.

ID	Years of experience	Position or Role
Specialist 1	25 years	Engineering coordinator at a Brazilian automotive manufacturer
Specialist 2	10 years	University design professor
Specialist 3	30 years	Neuroscience researcher and faculty member
Specialist 4	10 years	OTA manager at an automotive manufacturer in Brazil
Specialist 5	5 years	Researcher in design
Specialist 6	1 year	Medical doctor

The individual stages of the reviews are described in the following sections.

2.1 Scoping review

2.1.1 Information sources

The studies included in this review were identified through systematic searches conducted in two electronic bibliographic databases: Scopus and Web of Science. Both databases were selected due to their comprehensive coverage of peer-reviewed literature in engineering, human factors, and transportation research [60] [61] [62] [63]. The search was conducted on August 21, 2026.

2.1.2 Search strategy

The search strategy was developed using four concept blocks: vehicle context, alerts or warnings, haptic/tactile modality, and body location or stimulus placement: (vehicle* OR car* OR automobil*) AND (alert* OR warning*) AND (haptic* OR tactile* OR vibrotactile*) AND (body OR location* OR placement*).

2.1.3 Eligibility criteria

Inclusion criteria

- Studies published in English;
- Empirical studies;
- Peer-reviewed journal articles or conference papers.
- Full-text articles with open access or institutional-library access.

Exclusion criteria

- Non-automotive studies without direct driving relevance;
- Studies without a tactile alert, warning, cue, or feedback function or without a reported stimulation location;
- Non-empirical publications, duplicates, conference abstracts without full papers, editorials, protocols, or inaccessible full texts.

2.1.4 Selection process

The study selection process for the scoping review was reported using a PRISMA-ScR flow diagram Figure 2. A total of 135 records were identified through searches conducted in databases. Duplicate records were identified and removed using Mendeley reference-management software, leaving 93 records. The remaining records underwent three screening stages: (i) screening of titles, abstracts, and keywords; (ii) assessment of the introduction and conclusion sections; and (iii) full-text review.

After the predefined inclusion and exclusion criteria were applied, 15 studies were considered eligible and included in the final synthesis.

2.1.5 Data collection process

Data from the included studies were charted using a structured extraction spreadsheet [30?]. The spreadsheet was designed to capture information relevant to the objectives of the scoping review and to support comparison across heterogeneous study designs [?]. Data extraction covered bibliographic information, study design, driving context, participant characteristics, tactile-alert configuration, stimulated body location, outcome measures, and main findings.

2.1.6 Study risk of bias assessment

A formal risk-of-bias assessment was not conducted for the scoping review because its purpose was to map the extent, characteristics, and gaps of the available evidence rather than to estimate a pooled effect or determine the certainty of evidence [?].

2.2 Umbrella review

2.2.1 Information sources

To synthesize the available evidence from systematic reviews and meta-analyses addressing neurophysiological aspects of the research topic, this umbrella review was conducted using three electronic bibliographic databases: Scopus, Web of Science, and

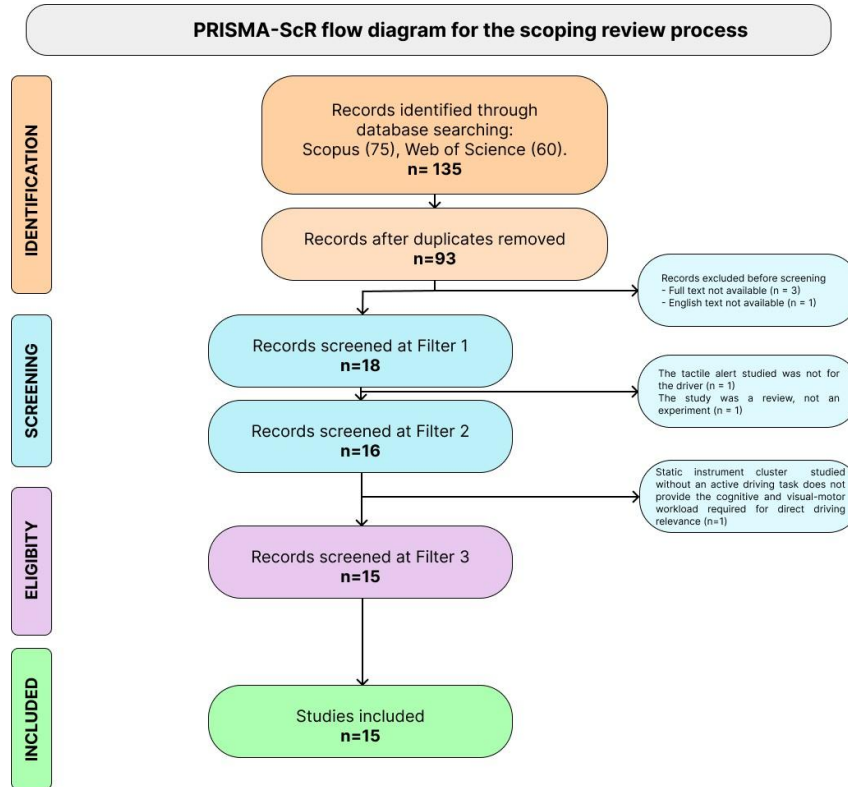


Fig. 2 PRISMA-ScR flow diagram for the scoping review process

PubMed. Scopus and Web of Science were selected for their broad multidisciplinary coverage [64], while PubMed was included to ensure comprehensive retrieval of literature in neuroscience, neurophysiology, and related biomedical fields, given its primary focus on life sciences and biomedical literature [64] [65]. The search was conducted on August 21, 2026.

2.2.2 Search strategy

The search strategy comprised four thematic blocks: tactile stimulation; tactile perception and processing; body and somatosensory representation; and review type: (tactile* OR vibrotactile*) AND ("tactile perception" OR "tactile processing" OR "tactile attention" OR "tactile localization" OR "spatial touch" OR "tactile acuity" OR "somatosensory perception") AND (body OR skin OR somatosensory OR "body representation" OR "body surface" OR "peripersonal space")) AND (review* OR "systematic review*" OR "meta-analy*").

2.2.3 Eligibility criteria

Inclusion criteria

- Studies published in English;
- Systematic reviews or meta-analyses with a defined search strategy, eligibility criteria, and selection process;
- Reviews addressing human tactile perception or somatosensory processing, including detection, discrimination, localization, sensory thresholds, or differences across body locations;
- Full-text articles with open access or institutional-library access.

Exclusion criteria

- Narrative or conceptual reviews, commentaries, protocols, or non-review publications;
- Reviews focused exclusively on engineering, materials, or device development;
- Reviews without evidence on human tactile perception or somatosensory processing;
- Duplicate reviews or inaccessible full texts.

2.2.4 Selection process

The selection process for the umbrella review was reported using a separate flow diagram Figure 3. A total of 277 records were identified through searches in databases. After duplicate removal, 124 records were sequentially evaluated through three screening stages: Filter 1 (title, abstract, and keywords), Filter 2 (introduction and conclusion sections), and Filter 3 (full-text review).

Following the application of the predefined eligibility criteria across these filters, a total of 6 reviews were ultimately included in the umbrella review.

2.2.5 Data collection process

Data from the included systematic reviews and meta-analyses were extracted using a structured spreadsheet [49, 50]. The extraction focused on the review objectives, populations or samples, tactile or somatosensory phenomena examined, body locations considered, included primary-study characteristics, outcome domains, principal findings, and methodological-quality assessment.

2.2.6 Study risk of bias assessment

The methodological quality of the included systematic reviews and meta-analyses was assessed using AMSTAR 2[66]. The assessment was used to identify limitations in review conduct, including the comprehensiveness of searches, transparency of selection and extraction procedures, risk-of-bias assessment of primary studies, and appropriateness of synthesis methods.

3 Results and Discussion

Fifteen studies were retained after the screening process conducted according to the PRISMA-ScR guidelines and the predefined eligibility criteria. The characteristics of the included studies, including the citation and a summary of the main findings, are presented in 2.

Table 2 Selected studies on tactile and vibrotactile alerts in driving contexts.

Citation	Summary and main results
[11]	Wearable vibrotactile devices on the finger or wrist significantly reduce emergency brake response times more effectively than temple-mounted devices.
[8]	Vibrotactile cues produce faster reaction and takeover times than ultrasonic mid-air haptic feedback, though the latter is valued for its contactless nature.
[2]	Drivers in automated vehicles react faster to takeover requests when tactile alerts are compatible with the required avoidance direction.
[7]	Vibration warnings delivered to the upper jaw result in shorter reaction times and higher driver preference compared to the wrist or shin.
[19]	Dynamic vibrotactile cues moving toward the torso significantly speed up braking reaction times compared to static cues or cues moving away from the torso.
[67]	Vibrotactile forward collision warnings are most effective when the signal providing upwards apparent motion is linked to the vehicle's closing velocity.
[13]	Vibrotactile warning signals significantly reduce driver braking response times and increase safety margins during potential rear-end collisions.
[6]	Tactile collision warnings result in faster driver reaction times compared to both visual and auditory warning systems.
[68]	Dynamic vibrotactile flow warnings reduce braking reaction times, but linear motion signals remain more effective for alerting drivers to collisions.
[3]	A specific back-to-seat vibration pattern resulted in the fastest driver response times during takeover requests in automated vehicles.
[9]	The study found that including a directional tactile alert of an imminent collision threat through seat vibration reduced drivers' response time by 257 milliseconds and significantly improved threat direction localization accuracy, from 32% to 84%, compared with purely auditory alerts.
[5]	The study found that although increasing the number of seat vibration alerts may cause confusion and delay driver reactions, configuring alerts in distinct seat areas significantly improves manual response time and helps rapidly redirect distracted drivers' attention to sudden road threats.
[69]	The use of tactile feedback in the driving simulator seat resulted in 100% accuracy in navigation responses, outperforming audio commands, and was preferred by more than 92% of the tested sample.
[10]	Demonstrated that vibrotactile feedback on the seat, combined with the rearview mirror, improved drivers' performance and spatial perception, reducing the time other vehicles remained in the blind spot during everyday traffic simulations and assisting in blocking opponents during racing exercises.

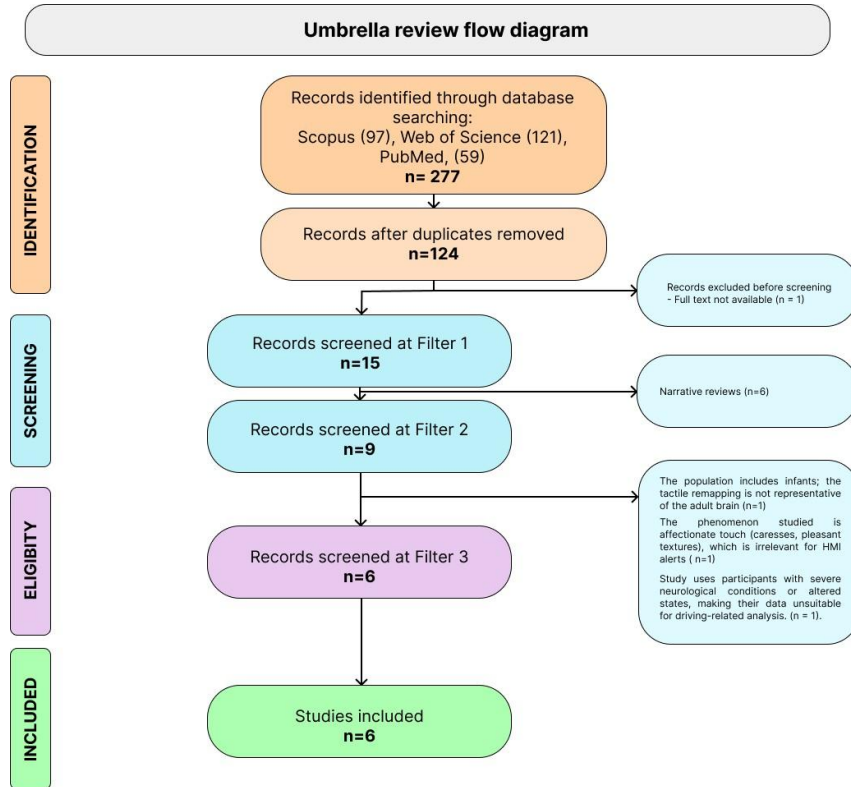


Fig. 3 Umbrella review flow diagram

Six systematic reviews and meta-analyses were included in this umbrella review following the screening process and application of the predefined eligibility criteria. The characteristics of the included reviews are presented in 3.

3.1 Thematic overview

The results are organized to move from applied ergonomic design to its underlying neurocognitive mechanisms. The Synthesis of the corpus provides an overview of the literature, followed by Body location as a design variable, which examines actuator placement on the driver's body. Reaction time, accuracy, and spatial congruence addresses how alert directionality affects performance, while Context-dependent placement considers these factors in Highly-Automated Driving (Level 3). Finally, Neurocognitive foundations links the empirical findings to human physiology.

Table 3 Summary and main results of the included studies.

Citation	Summary and main results
[70]	This demonstrates that the ability to pay attention and retain memory for tactile stimuli varies considerably depending on the region stimulated, being much more efficient and detailed in areas of the body with high spatial resolution (such as the hands and fingers) than in larger areas with lower sensitivity (such as the back).
[71]	Neuroimaging reveals that different body regions activate disproportionate cortical representations (the somatosensory "homunculus") and utilize distinct neural pathways, highlighting significant processing differences, for example, between glabrous skin (such as the palms of the hands, focused on high discriminative acuity) and hairy skin (such as the arms, more attuned to affective touch).
[72]	The meta-analysis reinforces that, in addition to baseline tactile acuity being intrinsically different between body segments (e.g., hands vs. arms or neck), the gain in tactile sensitivity obtained by looking at the body itself varies depending on which region is being viewed and stimulated.
[4]	It provides direct mappings proving that spatial discrimination thresholds (such as the ability to distinguish two points) differ drastically across the body, concluding that areas like the torso or thighs have much lower spatial resolutions than the fingertips.
[73]	The emergence of tactile awareness is shaped by the anatomy of the body, where parts with greater cortical magnification (higher density of receptors, such as hands and face) dominate conscious perception, while regions of lower sensitivity are more susceptible to spatial distortions, localization errors, and tactile "blindness".
[74]	Tactile processing differs significantly between body parts (such as between the fingers and the big toe) due to the strong somatotopic organization of the primary somatosensory cortex (SI), also revealing that perceptual decision time and neural inhibition vary strongly depending on the anatomical proximity of the stimulated regions.

3.2 Synthesis of the corpus

The integrated corpus of 21 documents reveals that haptic HMI design operates at the intersection between behavioral execution time constraints and the processing capabilities of the central nervous system. The 15 experimental studies primarily evaluate variables linked to direct vehicle performance (e.g., BRT, TRT, and LCT), investigating how actuator placement affects the driver's ability to respond to longitudinal threats or requests for resumption of control (TOR) [2, 13].

In contrast, the six reviews from the umbrella review demonstrate that these behavioral measures are profoundly limited and shaped by the physiology of cutaneous transduction and somatotopic representation [70, 71]. The reviews consolidate concepts such as Weinstein's two-point spatial discrimination threshold, the frequency specificity of mechanoreceptor channels (Meissner RA-I vs. Pacini RA-II), and the limitations of central attentional capacity (tactile subitization and change blindness) [4, 72, 74]. Thus, while haptic engineering proposes new channels (such as facial stimulators or textured steering wheels), neuroscience provides the basis for evaluating the cognitive cost and somatic robustness of these choices under high workload.

3.3 Body location as a design variable

The experimental literature focuses on the seat cushion and backrest [3, 5, 6], the steering wheel rim [75], wearable devices on the upper limbs [11] and on the face [7, 8].

The vehicle seat stands out as the most robust interface with guaranteed continuous contact [5, 6]. The seat cushion (seat pan) is very useful for 360° direction coding, achieving directional location accuracies of 92-93 percent under real traffic conditions, without detection losses even on roads with high secondary vibration (brick-road) [6]. However, its spatial resolution is limited for complex representations, being inadequate to discriminate more than a few discrete regions due to the sparse density of gluteal and thigh receptors [5, 10].

The vehicle's steering wheel provides direct contact with the palms of the hands, which have the lowest peripheral spatial discrimination threshold (10 mm) [75]. However, its effectiveness weakens in Highly-Automated Driving (HAD - Level 3) contexts, where the driver commonly removes their hands from the steering wheel to perform non-driving-related tasks [3].

The face (upper jaw and temple) elicits the lowest simple absolute reaction times (SRT) in the literature, due to peripheral conductive proximity to the brain and massive tactile innervation [7, 8]. However, facial recognition faces severe subjective rejection due to causing persistent discomfort, being described by users as excessively aversive and intrusive, which makes its application as a channel for frequent notifications or comfort unfeasible.

3.4 Reaction time, accuracy, and spatial congruence

Analysis of reaction times and accuracy highlights that tactile alerts reduce emergency braking latencies (EBR) and accelerate the resumption of safe control in HAD transitions [2, 13].

Experimental literature consistently supports that dynamic tactile signals (which mimic movement along the skin) offer advantages over static or fixed-intensity stimuli. Alerts that generate dynamic flow patterns towards the torso (toward-torso flow), sequentially activating the hands and then the waist (with 150 ms per stage), reduce EBR statistically more than concurrent static signals or the absence of alerts [1]. Similarly, dynamic tactile expansion flows on the back (expanding vibrotactile flow) reduce BRT more rapidly than centralized static stimuli [68]. However, amplitude modulation based on Time-to-Collision (continuous haptic looming) applied to a single isolated tator offers no advantage over constant intensity alerts [67].

The congruence between the physical direction of the stimulus and the required motor action is critical under high time pressure. In Level 3 Automated Driving Control (HAD) experimental scenarios, the driver experiences long periods of sensory disengagement [3]. Under a critical time-to-collision (TTC) of 4 seconds, the driver lacks the resources to interpret complex logical directions [2].

In this context, compatible/ipsilateral alerts (where the seat vibrates on the same side the driver should swerve) elicit significantly shorter control-taking times (TRT = 0.92 s) and greater maneuverability accuracy compared to mismatched/contralateral threat-directed (TRT = 1.12 s) or bilateral (TRT = 1.34 s) alerts [2]. This finding

contrasts with the classic manual driving paradigm, demonstrating that cognitive disengagement in HAD requires the direct facilitation provided by primary somatomotor compatibility [2].

3.5 Context-dependent placement

In highly automated vehicles (Level 3), the driver adopts resting postures or performs active secondary tasks (NDRTs), such as reading, typing, or dozing off [3]. These activities drastically alter physical contact with the thighs and buttocks due to leg crossing or extension, as well as moving the hands away from the steering wheel [3, 8]. In this context, channels such as the steering wheel become ineffective for immediate alerts[3]. Critical safety systems should be directed to surfaces that maintain firm and continuous mechanical contact, such as the seat back or the diagonal strap of the seat belt, using patterns such as back-first sequencing to robustly restore control awareness and mitigate lower postural noise [3].

High-criticality tactile alerts (FCW, LDW, immediate TOR) require rapid exogenous attention capture, justifying the synchronous activation of multiple shakers in the seat or seatbelt [1, 5]. In contrast, non-urgent or comfort notifications (autopilot status, infotainment messages) prioritize usability and the prevention of stress or startle effect. Mapping these low-criticality alerts to wrist-worn devices at frequencies of 200 Hz leverages the user’s pre-existing mental model with commercial smartwatches, ensuring high acceptance and keeping the seat channel free of false alarms [7, 8].

3.6 Neurocognitive foundations

The classic two-point discrimination threshold of Weinstein establishes the maximum spatial resolution of the body surface [72, 75]. While the human palm resolves spatial stimuli up to 10 mm, the lumbar region of the back requires a separation of at least 40 mm to avoid somatic fusion [72, 75]. Consequently, physical arrangements of actuators that do not respect these biological distances fail to transmit discrete spatial information to the driver [5, 10].

The somatosensory system processes mechanical transients through functionally segregated channels. The Meissner system (RA-I) is sensitive to low oscillation frequencies, often called flutter (range of 30 to 70 Hz), responding optimally to discrete pulses. The Pacini system (RA-II) responds preferentially to high-frequency vibrations (200 to 250 Hz), with a high capacity for capturing exogenous attention and lower spatial acuity, ideal for emergency transients.

The umbrella review establishes that the biggest bottlenecks in touch perception are not peripheral, but central. The somatosensory association cortex and posterior parietal areas have a strict tactile retention capacity of only 1 to 3 parallel stimuli (tactile subitization) [73]. The presentation of multiple simultaneous stimuli generates the phenomenon of tactile change blindness, causing the driver to fail to detect the change in alert patterns in up to 30 percent of occurrences if there is an intervening visual or tactile distractor [4].

Systematic cross-referencing of the literature reveals areas of strong scientific consistency, but also points to divergences between clinical/psychophysical tests and field ergonomics.

Points of convergence

- **Fitch’s 3-Alert limit and tactile subitization:** [5] empirically demonstrated that braking performance and comprehension of seat-integrated alerts decay substantially when the haptic portfolio is expanded from 3 to 7 different alerts. This limit coincides with the tactile working memory retention limits and subitization identified by [73], suggesting a potential relationship between the number of tactile alert categories and limitations in central cognitive processing.
- **Steering wheel spacing and tactile discrimination:** The successful recognition of tactile patterns on a steering wheel with 20 mm spacing between actuators [75] is consistent with psychophysical evidence concerning spatial tactile discrimination. This suggests that actuator spacing can influence the ability to distinguish spatially distributed stimuli and may support the perception of directional tactile patterns [71, 75].

Points of divergence

- **Single-Point Haptic Looming Illusion:** While neurobiological models suggest that dynamic tactile stimulation may contribute to the perception of approaching events, the findings of Gray et al. [67] and Meng et al. [1] reveal that continuous amplitude modulation through a single actuator does not necessarily provide benefits in braking reaction time compared with fixed-intensity alerts. This suggests that dynamic tactile information may require spatially distributed or sequential stimulation to effectively communicate movement or collision direction.
- **High Tactile Sensitivity Does Not Guarantee HMI Viability:** Although psychophysical and neurophysiological evidence indicates that tactile sensitivity varies across body regions, high perceptual sensitivity does not necessarily translate into suitability for automotive HMI applications. Driving-related experiments indicate that stimulation of facial or jaw regions may produce increased discomfort or negative subjective responses [7, 8]. Therefore, tactile alert placement should consider not only sensory acuity, but also comfort, acceptability, emotional response, task context, and practical integration into the vehicle interface.

3.7 Preliminary guidelines

Based on the cross-referencing of evidence and discussions presented, Table 4 presents the ten preliminary design guidelines proposed for the placement of haptic alerts in vehicles.

Table 4: Proposed preliminary design guidelines for the placement of haptic alerts in automotive HMIs.

Guideline	Recommendation	Neuro-Vehicular Rationale	Design Implication and Expected Benefit	Supporting Citations
1. Front Collision Warning (FCW) – Front Seat Pan	Consider synchronous stimulation by actuators positioned in the anterior regions of the seat to communicate imminent frontal collision situations.	The anterior regions of the thighs and seat generally exhibit lower spatial tactile acuity compared to the hands. Consequently, spatially complex patterns in this region may be less suitable for alerts requiring rapid and unambiguous detection. Perceptual responses to vibration are also influenced by the frequency, amplitude, contact area, and mechanical coupling of the stimulus, and not just by the stimulation frequency.	Broad and temporally coherent stimulation may be appropriate when the primary objective is to favor rapid detection rather than detailed spatial discrimination. The effectiveness of the selected stimulation parameters should be experimentally evaluated under representative driving conditions.	[1, 5, 9, 13]
2. Longitudinal vs. Lateral Warning – Seat Pan/Seat Back Segregation	Map longitudinal-criticality alerts, such as FCW, to the seat pan, while lateral-deviation alerts, such as LCW/LDW, are assigned to the seat back.	Processing multiple haptic stimuli within neighboring somatotopic regions may be affected by attentional limitations, including tactile masking and choice-response demands.	Use the seat pan and seat back as physically separated channels for different threat directions. This may reduce mental workload and choice-response latency while decreasing directional confusion.	[4, 5, 73]

Guideline	Recommendation	Neuro-Vehicular Rationale	Design Implication and Expected Benefit	Supporting Citations
3. Blind-Spot Directional Warning – Seat Back Spacing	Consider the distribution of actuators along the backrest with sufficient spatial separation to favor discrimination between different stimulation locations on the left and right.	The back generally has lower spatial tactile acuity than highly sensitive regions, such as the hands. Stimuli positioned very close together may, therefore, be more susceptible to perceptual integration or reduced spatial discrimination.	A more conservative spatial separation between actuators may favor the differentiation of the location of lateral threats. However, the most appropriate configuration should be determined empirically, since perceptual discrimination depends on stimulation parameters, body location, posture, and the characteristics of the mechanical coupling.	[6, 9, 10, 69]
4. Critical Collision Warning – Toward-Torso Flow	Sequentially activate actuators on the steering-wheel rim followed by actuators located around the waist, seat-belt, or torso region, creating a centripetal “toward-torso” pattern.	Dynamic tactile sequences can provide directional information and may interact with attentional mechanisms involved in monitoring the space surrounding the body.	Encode frontal collision information as an apparent movement toward the torso. Dynamic stimulation may increase threat salience and support faster attentional engagement than static stimulation.	[1, 67]
5. Takeover Request (TOR) – Ipsilateral Placement	For takeover requests requiring an immediate lateral evasive maneuver, present the haptic stimulus on the side corresponding to the intended direction of the maneuver.	Under severe time pressure, stimulus–response compatibility may facilitate response selection by reducing the need for cognitive remapping between threat location and required action.	Prefer spatially compatible haptic mappings when rapid steering is required. Ipsilateral stimulation may reduce takeover reaction time and directional errors.	[2, 3]

Guideline	Recommendation	Neuro-Vehicular Rationale	Design Implication and Expected Benefit	Supporting Citations
6. Information-Rich Alerts – Steering Wheel	Direct complex or spatially detailed haptic alerts preferentially to the hands, particularly through the steering wheel, rather than the seat back or legs.	Visual Enhancement of Touch (VET) can improve tactile processing when attention is directed toward the stimulated body region. This effect is particularly relevant to visually accessible regions such as the hands.	Reserve high-resolution haptic patterns for the steering wheel, where the hands are directly accessible to vision. This may facilitate discrimination of variations in frequency, rhythm, and spatial pattern.	[70, 72, 75]
7. Directional Navigation – Cutaneous Rabbit on the Steering Wheel	Consider tactile stimulation sequences along the steering wheel rim to communicate directional information through apparent tactile movement when the driver's hands are expected to make contact with the steering wheel.	Hands have high spatial tactile acuity, and appropriately designed stimulation sequences can produce perceptions of apparent tactile movement. Spatiotemporal patterns of this nature can therefore provide directional information without requiring continuous visual attention to a navigation interface.	Dynamic stimulation along the steering wheel can constitute an intuitive mechanism for directional communication. However, its use should be conditioned on the presence of contact between the hands and the steering wheel and evaluated considering different hand positions and different driving task demands.	[4, 75]

Guideline	Recommendation	Neuro-Vehicular Rationale	Design Implication and Expected Benefit	Supporting Citations
8. Low-Criticality Notifications – Wrist or Steering Wheel	Map non-urgent notifications, such as system-status information, to the wrist or steering wheel using relatively high frequencies around 200–250 Hz.	The upper limbs contain mechanoreceptors that are responsive to dynamic vibration, including Pacinian receptors, which are particularly sensitive to relatively high-frequency stimulation.	Reserve seat and seat-belt actuators for high-urgency warnings and use peripheral locations for routine information. This may support comfortable interaction while preserving the salience of urgent channels.	[7, 8, 11]
9. Re-engagement of Distracted Drivers – Back-First	For requests to regain control during non-driving tasks (NDRTs), consider initiating tactile stimulation in body regions that have relatively stable contact with the interface under the specific conditions of the task.	Posture and body movements during NDRTs can alter the mechanical contact between the driver and the haptic interface, potentially affecting stimulus transmission and detectability. The reliability of a tactile channel therefore depends not only on body location but also on posture, contact pressure, clothing, and movements associated with the task.	A haptic channel associated with a relatively stable contact region can contribute to greater consistency in stimulus transmission during periods of driver disengagement. The most suitable region should be determined considering the characteristics of the NDRT and the expected driver posture.	[3, 15]

Guideline	Recommendation	Neuro-Vehicular Rationale	Design Implication and Expected Benefit	Supporting Citations
10. Dynamic Intensity Compensation – Seat Back	Implement automatic modulation of actuator intensity according to clothing conditions, external temperature, or calibrated user preferences.	Thick clothing can mechanically attenuate vibration transmitted from the actuator to the skin, potentially reducing the effective amplitude of the stimulus.	Adjust actuation intensity to compensate for estimated mechanical attenuation. This may maintain perceptual reliability across different clothing conditions and improve the consistency of haptic alerts.	[3, 7, 9]

3.8 Modified Delphi consensus process

The six specialists who composed the original panel completed both Delphi rounds (Round 1: 6/6, 100.0%; Round 2: 6/6, 100.0%), with no attrition between iterations. Consensus was defined *a priori* as at least 80% agreement, operationalized as five or more experts assigning ratings of 4 or 5 on the five-point Likert scale, together with a median score of at least 4. Table 5 shows that eight of the ten preliminary guidelines met this criterion in Round 1. Guidelines 4 and 8 did not reach consensus and were therefore retained for reconsideration in Round 2.

Table 5 Evolution of agreement across the two Delphi rounds ($n = 6$). Agreement corresponds to ratings of 4 or 5.

Guideline	Round 1		Round 2	
	Median	Agreement	Median	Agreement
1. FCW – Front Seat Pan	4 (4–5)	5 (83.3%)	5 (5–5)	5 (83.3%)
2. Seat Pan/Seat Back Segregation	5 (4–5)	5 (83.3%)	4.5 (4–5)	5 (83.3%)
3. Blind-Spot Directional Warning	5 (4–5)	6 (100.0%)	5 (5–5)	6 (100.0%)
4. Critical Collision Warning – Toward-Torso Flow	4 (3–4)	4 (66.7%)	3.5 (3–5)	3 (50.0%)
5. TOR – Ipsilateral Placement	4.5 (4–5)	5 (83.3%)	5 (4–5)	6 (100.0%)
6. Information-Rich Alerts – Steering Wheel	4.5 (4–5)	5 (83.3%)	4.5 (4–5)	5 (83.3%)
7. Directional Navigation – Steering Wheel	4.5 (4–5)	5 (83.3%)	4.5 (4–5)	5 (83.3%)
8. Low-Criticality Notifications	4 (2–5)	3 (50.0%)	5 (4–5)	5 (83.3%)
9. Re-engagement of Distracted Drivers	5 (5–5)	6 (100.0%)	5 (4–5)	6 (100.0%)
10. Dynamic Intensity Compensation	5 (5–5)	5 (83.3%)	5 (5–5)	6 (100.0%)

The qualitative feedback from Round 1 was synthesized and used to revise the wording and explanatory material presented in Round 2. The revisions focused on clarifying anatomical references and actuator locations, delimiting the conditions under which a tactile channel should be used, and explicitly addressing the roles of posture, clothing, hand contact, individual sensory differences, and multimodal support. No new guidelines were added and no items were merged; therefore, all ten original statements were resubmitted after revision. The panel also received the median score for each item from Round 1 while preserving the independent and anonymous assessment of the revised statements.

The revised formulation of Guideline 8 produced the most substantial improvement between rounds, with agreement increasing from 50.0% to 83.3% and the median score increasing from 4 to 5. This change indicates that clarifying the intended use

of peripheral haptic channels for low-criticality information addressed concerns previously raised regarding wearability, habituation, and unnecessary interface complexity. Guidelines 5 and 10 also showed increased consensus, reaching unanimous agreement in Round 2. Guidelines 3 and 9 maintained unanimous agreement across both rounds, indicating stable support for spatially differentiated backrest stimulation for blind-spot warnings and for the use of body regions with reliable contact during driver re-engagement.

Guidelines 1, 2, 6, and 7 maintained agreement at the predefined consensus threshold in Round 2. For Guideline 2, the median decreased slightly from 5 to 4.5, while agreement remained stable at 83.3%. Guidelines 6 and 7 likewise retained a median of 4.5 and 83.3% agreement. The qualitative feedback indicated that this support was contingent on the driver's continued contact with the steering wheel and on empirical evaluation of the cognitive demands associated with more complex tactile patterns.

Guideline 4 was the only item that failed to reach the predefined consensus criterion in both rounds, with agreement decreasing from 66.7% in Round 1 to 50.0% in Round 2. The comments raised concerns regarding the potential complexity of sequential stimulation, interindividual variation in tactile interpretation, discomfort, and the possibility that dynamic patterns could distract or startle drivers during critical situations. Accordingly, Guideline 4 was not included in the final consensus-supported set and should instead be treated as an exploratory design proposition requiring dedicated experimental validation before application in automotive HMIs.

No formal stopping rule based on statistical stability was prespecified. Stability was therefore assessed descriptively by comparing medians, interquartile ranges, and proportions of agreement across rounds. The complete retention of the panel, the convergence observed for Guideline 8, and the stability of agreement for most other items supported the interpretation that consensus was achieved for nine of the ten guidelines after Round 2. These findings should nevertheless be interpreted as expert-informed design guidance rather than empirical evidence of effectiveness, particularly given the small and multidisciplinary composition of the panel.

3.9 Final design guidelines

The final guideline set was established from the revised statements evaluated in Round 2 and the accompanying qualitative feedback. Based on the predefined consensus criterion of at least five of the six specialists assigning a rating of 4 or 5, eight guidelines were retained. These guidelines showed agreement ranging from 83.3% to 100.0%, with median ratings ranging from 4 to 5.

Guideline 4, concerning dynamic tactile patterns for communicating the trajectory or evolution of external threats, did not reach consensus (median = 3.5; agreement = 50.0%). Expert comments raised concerns about the cognitive complexity of sequential patterns, potential discomfort, startle effects, and uncertainty regarding their interpretation under time pressure. Guideline 8, concerning low-criticality notifications through secondary haptic channels, also did not meet the predefined agreement threshold (median = 4.5; agreement = 66.7%). Although its revised wording removed the previously proposed wearable interface, experts continued to question its added value relative to visual and auditory channels and highlighted concerns about habituation

and unnecessary interface complexity. Consequently, both guidelines were excluded from the final consensus-supported set.

The qualitative feedback was incorporated as boundary conditions for the retained recommendations. Experts emphasized that tactile alerts should complement, rather than replace, visual and auditory channels and active vehicle safety systems. They also highlighted the importance of maintaining simple and immediately interpretable patterns for critical alerts, while considering the effects of posture, clothing, contact conditions, and individual sensory differences. These aspects, together with the potential for startle responses, should be investigated through empirical evaluation. The final guidelines are presented in Table 6.

Table 6: Final consensus-supported design guidelines for tactile alerts in automotive HMIs. **ID**

Guideline recommendation		Round 2 agreement	
G1	FCW – front seat pan	For imminent frontal-collision warnings, consider broad and temporally coherent tactile stimulation through actuators positioned in the front region of the seat, near the thighs. This stimulation should function as a complementary warning component and not as a substitute for visual, auditory, braking-assistance, or other active safety systems when these are appropriate.	5/6 (83.3)
G2	Longitudinal and lateral warning segregation	Consider assigning longitudinal threats, such as forward-collision warnings, to the seat pan and lateral threats, such as lane- or lateral-collision warnings, to the seat back. The spatial separation should provide an additional perceptual cue for differentiating event categories and should be empirically evaluated against, or in combination with, established visual and auditory alerts.	5/6 (83.3)
G3	Blind-spot directional warning	For blind-spot warnings, consider spatially separated actuators on the left and right sides of the seat back to support discrimination of lateral threat location. The selected spacing, stimulation parameters, and mechanical coupling should be tested under representative driving conditions, different postures, and relevant clothing conditions.	6/6 (100.0)

ID	Guideline	Final recommendation	Round 2 agreement
G5	Spatially compatible takeover requests	For takeover requests requiring an evasive manoeuvre, design tactile or haptic mappings in which stimulus location and direction correspond directly to the body region and direction of the required action. Spatially compatible stimulation should be embedded in a progressive multimodal takeover strategy and evaluated according to automation level, driver activity, and time available for response.	6/6 (100.0)
G6	Information-rich alerts in high-acuity regions	Present spatially or temporally complex tactile information preferentially in body regions with higher tactile acuity, particularly the hands. Alert interpretation should remain possible through tactile perception alone and should not require visual inspection of the stimulated region or interfere with the mechanical control of the vehicle.	5/6 (83.3)
G7	Directional navigation through the steering wheel	Tactile sequences along the steering-wheel rim may be used to communicate non-critical directional navigation information when sustained hand contact with the wheel is expected. Their use should be limited to situations in which their benefit over conventional visual or auditory navigation cues is demonstrated and should not impose complex decoding demands during time-critical events.	5/6 (83.3)
G9	Driver re-engagement through stable-contact regions	When requesting the return of control from a disengaged driver, initiate tactile stimulation in body regions that maintain relatively stable contact with the interface under the expected task and posture conditions. The alert should be integrated into a progressive multimodal strategy that considers posture, clothing, contact pressure, individual differences, and the avoidance of excessive startle.	6/6 (100.0)

ID	Guideline	Final recommendation	Round 2 agreement
G10	Context-dependent haptic calibration	Consider adaptive calibration of haptic stimulation to account for meaningful variations in clothing, posture, contact conditions, interface materials, and individual perceptual preferences. Because direct evidence for automatic compensation remains limited, adaptive calibration should be treated as a design opportunity requiring experimental validation before adoption as a general system requirement.	6/6 (100.0)

These guidelines represent expert-supported design recommendations rather than evidence of direct effectiveness in real driving conditions. Their operational parameters, including actuator placement, spacing, intensity, temporal pattern, multimodal integration, and effects on driving performance, should be validated in controlled and ecologically representative studies.

4 Conclusion

This study examined how the location of tactile stimulation on the driver’s body may influence the design of tactile alerts for automotive human–machine interfaces. By integrating evidence from a scoping review of automotive studies, an umbrella review of tactile-perception research, and a two-round modified Delphi process, the study translated dispersed findings into a set of design-oriented recommendations. The final consensus-supported guidelines emphasize the relevance of body location, spatial compatibility, tactile acuity, contact stability, contextual adaptation, and multimodal integration when designing tactile alerts for driving contexts.

The findings indicate that tactile-alert placement should not be treated as a purely technical decision concerning actuator installation. Instead, it should be considered in relation to the perceptual properties of each body region, the urgency and spatial meaning of the event, the driver’s expected posture and activity, and the availability of visual, auditory, and active vehicle-safety systems. The final guidelines provide a structured basis for distinguishing between high-criticality warnings, directional alerts, takeover requests, information-rich signals, and context-dependent haptic calibration. In this sense, the study contributes to the automotive HMI literature by connecting neurocognitive evidence on tactile processing with practical design decisions concerning in-vehicle interfaces.

The study also has important limitations. First, the evidence synthesized in the reviews was heterogeneous with regard to driving context, automation level, actuator configuration, outcome measures, and experimental setting. Consequently, the proposed guidelines should not be interpreted as universal specifications for actuator placement or stimulation parameters. Second, the Delphi panel comprised six

specialists with distinct professional backgrounds. Although this multidisciplinary composition supported the examination of the topic from complementary perspectives, the small and non-probabilistic sample limits the generalizability of the consensus. Third, agreement among specialists represents the perceived relevance and plausibility of the recommendations, rather than direct evidence of their effectiveness in real driving conditions. Finally, the literature searches were restricted to selected databases, English-language publications, and accessible full texts, which may have limited the coverage of relevant evidence.

Future research should empirically test the final guidelines in controlled simulator studies and, subsequently, in ecologically representative driving environments. Such studies should compare tactile-only, visual, auditory, and multimodal warning strategies while assessing reaction time, directional-response accuracy, workload, acceptance, discomfort, habituation, and startle effects. Particular attention should be given to differences in driver age, sensory characteristics, driving experience, clothing, posture, hand position, and automation level. Further research should also investigate the interaction between actuator spacing, stimulation intensity, temporal patterns, and contact reliability across different vehicle interfaces. Finally, replication of the Delphi process with larger and more diverse international panels may strengthen the external validity and practical applicability of the proposed recommendations.

Overall, the study advances an evidence-informed guidelines for designing tactile alerts in automotive interfaces. The resulting guidelines offer a foundation for future experimental validation and for the development of tactile systems that support driver awareness and response without imposing unnecessary cognitive or sensory demands.

Limitations

This study has limitations related to search coverage and access. The searches were restricted to the Scopus, Web of Science and PubMed databases, which may have excluded relevant studies indexed exclusively elsewhere. Eligibility was limited to English-language full texts available through open-access or institutional-library access, potentially introducing language and access bias. In addition, evidence from the umbrella review is indirect and does not by itself establish the effectiveness of tactile alerts in driving. The Delphi panel comprised only six heterogeneous experts; therefore, consensus should not be interpreted as empirical validation. Finally, if most included studies used simulators or laboratory tasks, the transferability of findings to real-world driving remains limited.

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Declarations

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Competing interests

The authors declare that they have no competing interests.

Data availability

All data generated or analysed during this study are included in this manuscript.

Author contributions

S.S.C.L.: Writing – original draft, methodology, analysis. L.O.: Conceptualization. All authors (S.S.C.L., I.W., I.S., M.C., L.O., Y.F.) contributed to Writing – review and editing.

Ethics approval

This study was approved by the Ethics Committee for Research in Human and Social Sciences of the Federal University of Paraná (CEP/CHS/UFPR), under CAAE No. 01182126.5.0000.0214 and Opinion No. 8.769.191.

Ethics accordance

The study was conducted in accordance with the guidelines of the Brazilian National Health Council (CNS) Resolution 510/2016.

Consent to Participate

Informed consent was obtained from all participants involved in the study.

Consent to Publish

Consent to Publish declaration: not applicable.

Clinical Trial

Clinical trial: not applicable.

Declaration on the use of AI tools

During the preparation of this manuscript, the generative artificial intelligence tool ChatGPT 5.6 Luna was used to support the writing and editing of the manuscript. The authors carefully curated, revised, validated, and edited all AI assisted content and take full responsibility for the final version of the manuscript.

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