VIRTUAL-ACOUSTICS LEAD-VEHICLE CONCEPT FOR SENSORY SUBSTITUTION TO ENHANCE ANTICIPATION OF DRIVING MANEUVERS

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ABSTRACT

Reduced access to motion-relevant information during highly automated driving can impair occupants' ability to anticipate upcoming vehicle maneuvers, reducing situational awareness and ride comfort while increasing the likelihood of motion sickness symptoms. To address this issue, a lead-vehicle-inspired anticipatory information concept is proposed that continuously represents future vehicle states rather than communicating predefined maneuver categories. Information about a virtual lead vehicle is transferred to either an auditory three-dimensional display or a peripheral visual display using sensory substitution principles. The concept was evaluated in a real-world driving experiment with 46 participants performing a visually demanding non-driving-related task. Participants were assigned to an auditory condition, a visual condition, or a control group without anticipatory support. Both substitution systems improved participants' ability to anticipate upcoming maneuvers and enhanced subjective route orientation, with the auditory implementation showing the strongest benefits. This advantage may be attributed to the fact that the auditory system enabled a true three-dimensional spatial representation of upcoming events, whereas the visual implementation was limited to a considerably lower-dimensional spatial encoding. Participants were also able to distinguish different maneuver classes from the continuous lead-vehicle representation. However, no significant reduction in motion sickness was observed. The results demonstrate that continuous lead-vehicle representations can successfully communicate future vehicle dynamics and improve anticipation during automated driving. The proposed approach provides a promising alternative to conventional event-based cueing systems and may support the development of future anticipatory in-vehicle interfaces.

Keywords: Automated vehicles, situational awareness, anticipatory cueing, sensory substitution, auditory display, ambient lighting, motion sickness, human-machine interaction.

1 INTRODUCTION

In recent years, auditory displays and acoustic information systems have received increasing attention in the automotive domain. Modern vehicles already incorporate a wide range of auditory interfaces for navigation, warning systems, infotainment, and human-machine interaction [1]. However, the growing number of in-vehicle information systems also increases the amount of sensory input presented to vehicle occupants. Previous studies have shown that auditory warnings are not always perceived positively, with a substantial proportion of users reporting annoyance and frequently disabling such systems [2]. At the same time, the transition from conventional driving to highly automated vehicles

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fundamentally changes the role of the vehicle occupant. As automated driving systems assume increasing responsibility for vehicle control, occupants gradually transition from active drivers to passive passengers. This development has two important consequences. First, many auditory information systems that currently support the driving task, such as driver assistance warnings or navigation-related cues, become less relevant as the occupant is no longer directly responsible for vehicle operation. Second, increasing levels of automation are expected to promote engagement in non-driving-related tasks (NDRTs), such as reading, working, or multimedia consumption [3]. While this enables occupants to make productive use of travel time, it also reduces their situational awareness of ongoing vehicle dynamics and the surrounding driving environment [4].

Situational awareness is commonly defined as the perception of elements in the environment, the comprehension of their meaning, and the projection of their status into the near future [5]. However, as occupants increasingly engage in NDRTs, they may lose continuous access to visual information about the roadway, surrounding traffic, and future vehicle behavior [6]. This reduction in available information can impair an occupant's ability to anticipate upcoming driving maneuvers and vehicle motions. As a result, sensory conflicts, or sensory mismatches, may occur when information from the visual, vestibular, and proprioceptive sensory systems no longer corresponds to the experienced vehicle motion [7]. Such conflicts are considered a primary mechanism underlying motion sickness (MS) and substantially increase the risk of symptoms such as headache, drowsiness, cold sweating, hypothermia, and nausea [8]. MS is regarded as one of the major challenges limiting comfort and user acceptance of highly automated vehicles. It affects approximately 59% of the population at least once during their lifetime [9]. Even in the absence of pronounced symptoms, reduced awareness of upcoming vehicle motions may negatively affect passenger comfort. For example, occupants performing NDRTs may need to stabilize mobile devices during cornering, compensate for unexpected lateral accelerations, or react to unanticipated vehicle movements. Such events can interrupt ongoing activities and reduce the perceived quality of the travel experience. Beyond comfort considerations, reduced situational awareness also raises safety-related concerns. Previous research [10] has shown that operators of automated systems tend to lose track of the current system state when automation assumes responsibility for task execution, resulting in a diminished ability to intervene appropriately when required. This issue is particularly relevant for highly automated vehicles, where occupants may still be required to resume control under certain circumstances. Examples include construction zones, narrowed lanes, complex merging scenarios, system limitations, unusual traffic behavior, or other unexpected road events [11]. Providing passengers with information about upcoming vehicle maneuvers may therefore not only improve comfort and reduce sensory conflicts, but also help maintain an appropriate level of situational awareness that supports effective re-engagement when necessary.

The importance of situational awareness in driving has been demonstrated extensively in previous research, as drivers continuously utilize environmental information, including road geometry, vehicle speed, lane position, and the behavior of surrounding traffic participants, to anticipate upcoming events and adapt their actions accordingly [12]. Among these information sources, preceding vehicles play a particularly important role, as their velocity changes, heading changes, lane changes, and braking behavior provide predictive cues about upcoming traffic developments [13]. Human anticipation in traffic is therefore largely based on the continuous observation of dynamic states rather than on explicit symbolic instructions. For example, even when navigation systems provide symbolic guidance such as directional arrows, drivers often supplement this information by comparing the displayed route geometry with the observed road geometry. This suggests that humans naturally utilize spatial and kinematic information to form expectations about future vehicle movements. Previous research further indicates that drivers actively gather information about the surrounding traffic situation before temporarily diverting their attention from the roadway [12]. In particular, information obtained from relevant traffic objects contributes to the formation of expectations about future developments in the traffic environment [13]. A vehicle initiating a lane change, for example, allows observers to anticipate subsequent vehicle movements and potential traffic interactions before they occur. A comparable source of predictive information is already available in automated vehicles, yet it remains largely underutilized for anticipating upcoming vehicle maneuvers. Surrounding traffic objects, and particularly preceding vehicles, are continuously tracked as part of environmental perception, trajectory prediction, and motion-planning processes. Consequently, information on future vehicle movements can already be estimated by the vehicle and could be communicated to occupants to support anticipation and maintain situational awareness during automated driving.

Research has explored multimodal cueing concepts including tactile, visual, and auditory displays [14] to compensate for the loss of situational awareness, particularly the reduced ability to anticipate upcoming driving maneuvers. These approaches often aim to reduce the sensory mismatch through the provision of motion-related sensory cues, thereby alleviating symptoms of MS. Such cues aim to adapt the occupant's expectation of future vehicle dynamics before the corresponding motion occurs [3]. In contrast to the visual modality, which is frequently occupied by NDRTs, the auditory modality typically remains available. As a result, it represents a promising channel for conveying anticipatory information without interfering with visually demanding activities. Early systems employing so-called auditory cues primarily relied on simple spoken instructions such as “left”, “right”, “brake”, or “accelerate”, typically implemented within relatively simple spatial configurations and restricted to one- or two-dimensional guidance paradigms [15, 16, 17]. Furthermore, the use of Wizard-of-Oz paradigms is not uncommon in this context, with some systems being manually triggered by an experimenter rather than operating autonomously [18]. More recent evidence suggests that non-speech auditory signals, such as beeping tones, may be more effective than verbal instructions in mitigating MS and communicating anticipatory information [19]. This is also supported by findings of Dam and Jeon [20] as well as Reuten et al. [18], who reported no significant reduction in MS when employing a speech-based anticipatory auditory system in their experiments. The simplification of cue design further enables intuitive spatial localization through auditory scene construction. For example, stereo audio systems can leverage spatialized sound to communicate left-right directional information more naturally and efficiently [21, 17]. However, properties such as pitch or frequency ranges can also be utilized in such systems as intuitive and easily interpretable markers for the occupant [22]. This approach exhibits strong parallels to visual cueing concepts, where simple pictograms, such as directional arrows, effectively convey movement direction and intended vehicle actions [21]. Similarly, spatial information can be visually communicated through distributed ambient lighting within the vehicle cabin, thereby exploiting the spatial dimension of the visual modality to guide occupant expectations and improve situational awareness [23]. Beyond the choice of information modality, anticipatory cueing critically depends on the temporal relevance of the presented information. Since occupants require sufficient time for cognitive processing of the cue prior to the onset of the anticipated motion event, cue timing constitutes a key design parameter. Current findings indicate that presenting the cue approximately two seconds before the occurrence of the anticipated event yields the most favorable results [19]. However, it should be noted that the term ”event” itself remains insufficiently defined within the literature. In the context of anticipatory driving maneuvers, it is often unclear at which precise instant a physiologically relevant stimulus begins to affect the occupant. More specifically, the onset of sensory mismatches may not coincide with the initiation of the vehicle maneuver, raising the question of which acceleration threshold must be exceeded before the occupant actually perceives the event. This issue is further complicated by the well-established frequency dependence of human well-being, whereby the physiological impact of vehicle accelerations depends not only on their magnitude but also on their spectral characteristics [24]. Furthermore, it is important to emphasize that existing anticipatory systems have demonstrated substantial effect sizes in experimental studies [15]. However, the available evidence is not entirely consistent. For example, Reuten et al. [17] reported no significant differences in participants well-being using anticipatory cues in a comparable sled setup of [15]. In addition, anticipatory systems generally do not eliminate MS symptoms entirely. Instead, they primarily reduce the subjective severity of symptoms and/or delay their onset. In this context, the contribution of placebo or psychological effects remains insufficiently understood. Many studies have investigated employing within-participant experimental designs, in which participants can readily recognize whether an external sensory system is active. Consequently, disentangling the true physiological effectiveness of the intervention from expectancy-driven placebo effects becomes challenging. Results obtained using non-functional systems [25] as well as research on so called ”well-being” systems [26] suggest that placebo or physiological effects may contribute meaningfully to the observed effectiveness of anticipatory systems and therefore warrant further investigation, see also [27, 28]. In addition, a study investigating an actively tilting vehicle as a MS mitigation strategy suggest that prolonged habituation periods may also be required before novel passenger assistance systems achieve their full effectiveness [29]. These finding may also explain why other research studies, such as [30], have not identified an optimal anticipatory latency. If the effectiveness of anticipation in reducing MS depends on learning and adaptation processes, differences in timing of warning signals may be masked by the generally limited short-term effectiveness of anticipatory information. Regardless of their effectiveness in mitigating MS, anticipatory cueing systems have consistently been associated with improvements in perceived ride comfort and user experience [17].

Despite the promising results reported for anticipatory motion cueing, most existing approaches remain event-driven and communicate future vehicle behavior through predefined maneuver categories such as braking, accelerating, or turning. While intuitive and easy to interpret, these representations compress inherently complex and continuous vehicle dynamics into a limited set of discrete events. As a consequence, information about the intensity, temporal evolution, and multidimensional characteristics of upcoming motion may be lost. In real-world driving, vehicle motion evolves continuously across multiple degrees of freedom and is characterized by simultaneously occurring longitudinal, lateral, and vertical accelerations that vary in magnitude, direction, and timing. Therefore, predefined maneuver categories can only provide a simplified representation of the motion ultimately experienced by occupants. Human anticipation of traffic situations follows a fundamentally different principle; Rather than relying on explicit maneuver announcements, drivers continuously observe the dynamic states of surrounding traffic participants and infer future vehicle behavior from changes in position, speed, and direction. Based on these observations, they form an internal prediction of the future traffic situation, allowing them to estimate those aspects of upcoming vehicle motion that are most relevant to their current task and context [12, 13]. To date, however, little research has investigated whether anticipatory motion information can be conveyed in a comparable manner through a continuous representation of future vehicle states. It therefore remains unclear whether occupants are able to derive meaningful information about upcoming vehicle dynamics from such a representation without receiving explicit maneuver descriptions. To address this research gap, the present work proposes a lead-vehicle-inspired anticipatory information concept that continuously represents the dynamic state of a virtual lead vehicle, through sensory substitution, instead of communicating predefined maneuver classes. The approach is based on the assumption that occupants may utilize information about the motion of a preceding vehicle in much the same way as drivers naturally anticipate future traffic developments during car-following [13]. To realize this concept, information that would ordinarily be obtained through visual observation of a lead vehicle is transferred to alternative sensory modalities [31]. While this sensory substitution has traditionally focused on compensating sensory impairments by transforming visual information into auditory or haptic representations [32, 33, 34], the present work applies the same principle to provide access to motion-relevant information that may be unavailable because occupants are engaged in NDRTs or no longer observe the traffic environment directly. The primary implementation focuses on the auditory modality, in which changes in the virtual lead vehicle's dynamic state are mapped onto a spatial three-dimensional acoustic representation. A visual implementation based on ambient lighting is additionally realized as a comparison condition. While visual displays are generally effective for conveying motion-related information, visual resources are frequently occupied by NDRTs in highly automated vehicles. Auditory resources, in contrast, become less critical for vehicle control and may therefore offer a particularly suitable channel for anticipatory motion communication. Moreover, occupants are already accustomed to processing auditory driving-related information, such as navigation instructions and driver-assistance warnings, potentially facilitating the interpretation and acceptance of auditory anticipatory displays. The objective of the present study is to investigate whether future vehicle dynamics can be communicated through a continuous lead-vehicle representation and whether occupants can utilize this information to anticipate upcoming vehicle motion. Specifically, it is hypothesized that (i) occupants receiving anticipatory lead-vehicle information will predict upcoming maneuvers more accurately than occupants without anticipatory support, (ii) report higher levels of route orientation and situational awareness, and (iii) successfully distinguish different maneuver classes from the continuous state representation. In addition, the potential influence of improved anticipation on subjective MS ratings is explored.

2 MATERIALS & METHODS

2.1 Lead-Vehicle Concept

To design a display for representing vehicle movements that is accepted by passengers of automated vehicles, several aspects must be considered. First, the system has to integrate seamlessly into the existing environment of the vehicle while still ensuring that relevant future vehicle actions can be communicated reliably. In contrast to conventional displays that reflect the currently experienced vehicle dynamics, the proposed auditory system conveys information about a predicted future trajectory. In doing so, it aims to exploit the underlying cognitive mechanisms of anticipatory car-following behavior. Previous research [12] has shown that drivers actively prepare themselves for short periods without visual access to the roadway by deliberately acquiring information about traffic conditions, vehicle speed, and surrounding traffic participants before diverting their gaze. Such preparation strategies are adapted to both the current traffic situation and the expected duration of the distraction. In particular, cues derived from relevant traffic objects, such as a vehicle initiating a lane-change ahead, play an important role in forming expectations about upcoming traffic developments [13]. These findings suggest that humans naturally use information from surrounding traffic participants to generate expectations about future vehicle movements. A comparable source of information is already available in automated vehicles, where surrounding traffic objects, especially preceding vehicles, are continuously monitored as part of perception, prediction, and trajectory-planning processes. Thus, information related to a leading vehicle can provide a meaningful link between established human anticipation strategies and the internal planning mechanisms of automated driving systems. Since the generation of trajectory expectations based on the behavior of preceding vehicles is already an established process in human driving behavior, the proposed system seeks to leverage this cognitive mechanism, see Fig. 1. Rather than communicating the planned ego-vehicle trajectory directly, the system presents information derived from a simulated lead vehicle that serves as a predictive traffic reference. Consequently, the transmitted information is derived from characteristics that humans naturally monitor during car-following tasks, namely the relative movement of the leading vehicle and its velocity. To preserve this familiar form of information processing, the proposed display does not communicate maneuver classes explicitly. Instead, it provides information about the motion state of the simulated lead vehicle, allowing occupants to generate their own expectations regarding upcoming vehicle behavior. More specifically, the relative movement of the lead vehicle is represented by the angle between the ego vehicle and the lead vehicle, α_{lead}, which indicates how the lead vehicle moves with respect to the ego vehicle. In addition, the velocity of the lead vehicle is communicated, reflecting the importance of speed estimation during human car-following behavior. Drivers continuously monitor the velocity of preceding vehicles and use this information to anticipate future actions. A prominent example is the activation of brake lights, which immediately creates the expectation that a reduction of one's own speed may soon become necessary. Besides the selection of suitable information, user acceptance constitutes a central design requirement. The display should therefore remain as unobtrusive as possible during normal driving

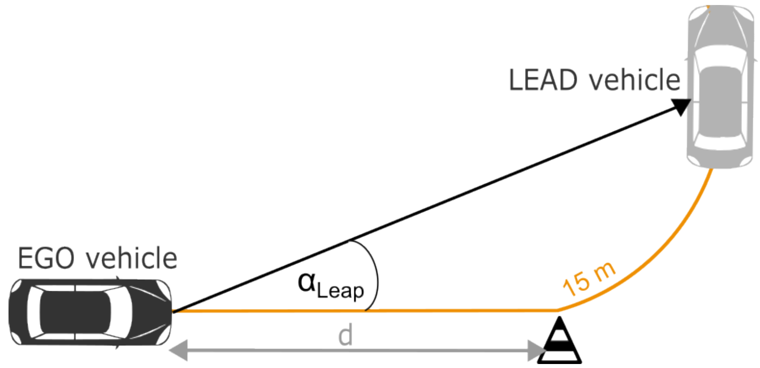


Figure 1: Simulated lead vehicle located 15 m ahead of the ego vehicle, illustrating the relative heading angle α_{lead} and the distance d to the upcoming maneuver.

conditions while still being capable of attracting attention whenever a relevant trajectory change or critical maneuver is imminent. This requirement is particularly important, as perceived annoyance has been identified as one of the reasons why users deactivate driver assistance systems such as lane-change assistants [35]. Rather than providing continuous warnings, the proposed concept aims to establish an ambient representation of the simulated lead vehicle that remains present in the background and becomes salient only when substantial changes in the predicted vehicle motion occur. The feasibility of such an anticipatory display is supported by the trajectory-planning processes employed in automated vehicles. Depending on vehicle speed and the driving situation, future maneuvers are typically planned several seconds before execution, commonly within a horizon of approximately 2 s to 8 s, although shorter horizons may occur at higher speeds [36]. This predictive information creates the opportunity to communicate forthcoming vehicle actions before they are physically experienced by the occupants. In the present work, anticipatory information is therefore provided approximately 1 s to 3 s before the corresponding vehicle motion occurs. To ensure a well-defined and consistent anticipation interval throughout the experiment, only two constant speed levels (8 km/h and 20 km/h) were employed in the experiment.
The complete test track, see section II.D, was determined and saved in advance by performing previous test drives, as reference map. Based on GPS location and inertial positioning reference algorithm, the calculated position of the ego vehicle is projected onto the stored reference map. Based on the ego position the position of the lead vehicle is determined and the current information about target velocity is retrieved. Afterwards, the calculation of all angles and distances is done. Bad weather conditions or object reflections can occasionally disturb the GPS signal. For correct triggering of the anticipatory cues, an additional stabilization algorithm (including a Kalman-filter) was applied to filter the GPS signal which should prevent double activations or skipping of certain events.

2.2 Acoustic Substitution System

The systems was implemented inside a test (ego) vehicle, a family van (VW Touran 2nd gen. 2017, Type: 1 T/CJSAAF, 1.8TSI, 132 kW). In the trunk of the vehicle a DATALynx ATX3 automotive Dual-CPU Car-Server is installed to control all hardware components. The setup consists of five small speakers (hama Stereo Speaker SONIC MOBIL 185 (USB, 3W), Hama GmbH & Co KG, Germany) placed with identical distances of 1 m to the participant, four of which are placed on a common plane. Two of them are positioned at the front and two at the back, directed towards the participant, see Fig. 2 (blue circles). The fifth speaker is positioned in the footwell in front of the participant (between the feet) directed upwards. The speakers are controlled via a Focusrite (Scarlett 18i20) audio interface.

The audio control was implemented using *Resonance Audio SDK* [37], *RTAudio* [38], and *Boost C++ Libraries* [39] implemented in C++ code. The speakers were interfaced to create a virtual sound source about 50 cm in front of the participant's head between both front speakers, continuously emitting a short loop of interior sounds (recorded inside vehicle while at idle). Spectrum characteristics of the sound signal are provided in Appendix Fig. 7. When the lead vehicle reaches the onset of a maneuver, the virtual sound source approaches the participant over the first 5 m along the longitudinal axis until it reaches the center of the four-speaker arrangement, see Fig. 3. This dynamic movement is intended to evoke the perception of an approaching object and thereby implicitly signal an imminent driving maneuver to the occupant. In parallel to the system behavior described above, three types of driving maneuvers, namely braking & acceleration, cornering, and speed bumps, were conveyed according to the three corresponding spatial directions. As described in Section II.D, the study was designed such that each real-world maneuver consisted of only a single motion component, thereby allowing the three spatial directions to be investigated independently.

Figure 2: The VISUAL substitution system (red circle; left light bar of the system) illuminated the passenger-side footwell using colored light cues. The AUDIO substitution system (blue circles, 4 of 5 speakers) generated a spatial auditory cue via a dedicated loudspeaker setup (The right light bar and the fifth footwell speaker are not visible in the figure).

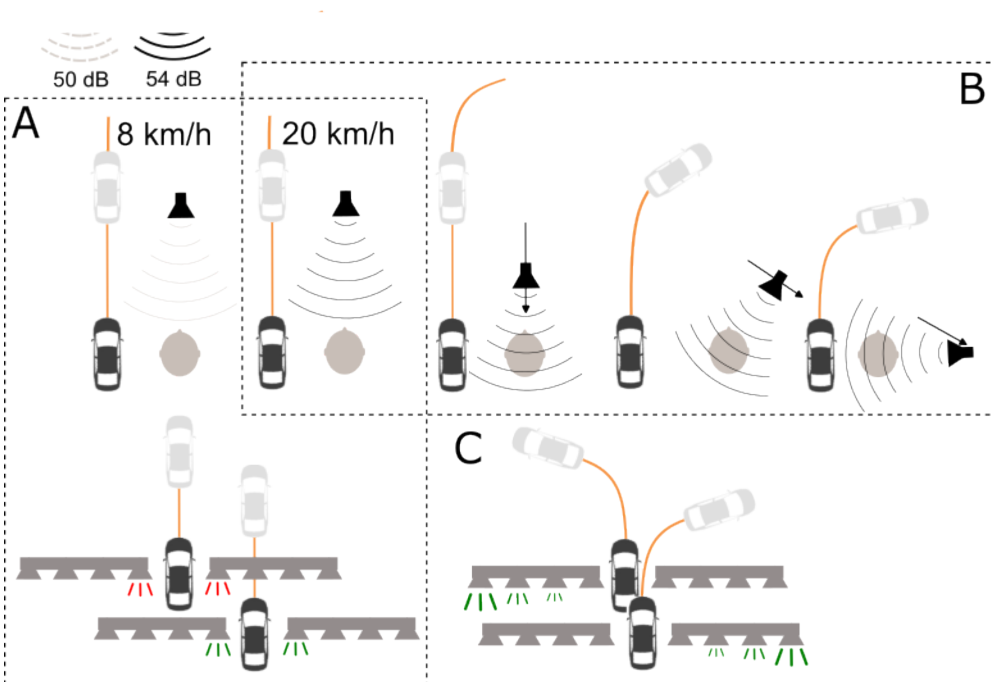


Figure 3: Illustration of the operating principles of the substitution systems. (A) Representation of longitudinal maneuvers through changes in sound volume (top) and color coding (bottom). (B) Sequence of a curve maneuver in the three-dimensional auditory environment. The virtual sound source first approaches the participant and subsequently moves toward the participant's right side as the lead vehicle enters the curve. (C) Simplified representation of curve maneuvers in the visual system, where the direction of the upcoming turn is encoded by shifting the light cue to the left or right side.

1) Longitudinal direction (braking and acceleration): The target velocity of the lead vehicle v_{lead} was continuously encoded by the sound level of the auditory substitution system. Under nominal conditions, the lead vehicle traveled at a constant target velocity of $20\,\mathrm{km/h}$, corresponding to a maximum sound pressure level $Vol_{\max}$ of $54\,\mathrm{dB}$ SPL. During braking maneuvers, the target velocity was reduced to $8\,\mathrm{km/h}$, and the sound level was decreased to a minimum sound pressure level $Vol_{\min}$ of $50\,\text{dB}$ SPL, see Fig. 3 (A). Conversely, acceleration maneuvers were represented by an increase in sound level from $Vol_{\min}$ to $Vol_{\max}$. Both volume levels were determined experimentally to ensure reliable perception while remaining comfortable and non-intrusive during driving. As the virtual sound source is designed to appear in front of the passenger while simultaneously supporting dynamic spatial movement, the required loudspeaker gains varied as a function of the maneuver onset distance d. Consequently, the front and rear loudspeaker pairs were controlled independently to maintain the desired perceived source position. The volume of the front and back speakers (Vol_{Front}, Vol_{Back}) was continuously adapted with:

$$Vol_{Front} = Vol_{min} + \frac{v_{lead} - 8[km/h]}{12[km/h]} \cdot 4[dB] \tag{1}$$

$$Vol_{Back} = \begin{cases} Vol_{min} + \Delta Vol(d) & ; d \leq 12.5m \\ Vol_{min} & ; d > 12.5m \end{cases} \tag{2}$$

, with

$$\Delta Vol(d) = (1 - \frac{d}{12.5[m]}) \cdot 4[dB] \cdot 0.9 \tag{3}$$

, where the correction factor of 0.9 applied to the rear loudspeaker prevents the virtual sound source from being perceived behind the occupant's head when minor forward head displacements occur during driving.

2) Lateral direction (cornering, U-turns, and lane changes): During cornering, the angle between the lead vehicle and the ego vehicle, α_{lead}, increases, see Fig. 1. This geometrical change between both vehicles is conveyed to the passenger through a corresponding lateral movement of the virtual sound source, see Fig. 3 (B). Internally, α_{lead} is transformed into the corresponding x-coordinate (eq. 4) shift of the virtual sound source, which is used for spatial projection and lateralization within the *Resonance Audio SDK*. Based on preliminary experimental testing, α_{lead} was nonlinearly scaled to improve the perceptual mapping within the 3D audio environment (eq. 5). Small, unintended steering fluctuations were suppressed within a deadband of $\pm 4°$ to avoid distracting or noisy movements of the auditory image during straight driving. For moderate steering inputs between $\pm 4°$ and $\pm 10°$, a steeper piecewise-linear scaling was applied to increase spatial sensitivity, ensuring that medium-range maneuvers already produced a clearly perceptible lateral displacement. Beyond $\pm 10°$, a flatter scaling segment limited the growth of the perceived displacement, resulting in a smooth and controlled progression as the angle approached larger deflections. Values exceeding $\pm 90°$ were clamped, as a lateral displacement of $90°$ already represents the maximum meaningful auditory indication of a cornering maneuver. Additional information indicating that the lead vehicle was located outside the passenger's field of view was not considered beneficial for the present experimental setup and would therefore not have provided further relevant spatial information. Combined with the longitudinal movement of the sound source based on the distance to the maneuver, the sound source initially moves toward the participant and subsequently transitions into a lateral movement. This motion pattern creates the impression of a continuous trajectory curving around the occupant toward the left or right side.

Let

$$x = s\frac{\theta}{90°} \tag{4}$$

, where $s \in \{-1, +1\}$ denotes the direction indicator, with

$$\theta = \begin{cases} 0° & ; |\alpha_{lead}| \in [0°, 4°] \\ \frac{41}{6}\alpha_{lead} - \frac{70°}{3} & ; |\alpha_{lead}| \in [4°, 10°] \\ \frac{9}{16}\alpha_{lead} - \frac{315°}{8} & ; |\alpha_{lead}| \in [10°, 90°[\\ 90° & ; |\alpha_{lead}| \in [90°, \infty) \end{cases} \tag{5}$$

3) Vertical direction (speed bumps): The employed version of the *Resonance Audio SDK* supports only two output channels, resulting in two stereo signals (four loudspeakers). To enable the use of additional output channels, a four-channel mode was implemented by duplicating the two audio sources through two auxiliary streams. Furthermore, a dedicated fifth audio stream was introduced for an additional loudspeaker used to represent vertical driving events. This implementation allows identical auditory cues to be rendered on front and rear speaker pairs while modifying their spatial positions and relative amplitudes independently. The fifth loudspeaker, mounted below and in front of the participant, was used exclusively to convey speed-bump maneuvers. Under normal conditions, the virtual sound source is positioned within the horizontal x-y-plane. However, once the vehicle enters the critical region preceding a speed bump, an additional displacement along the z-axis is introduced (eq. 6). At large distances, the vertical loudspeaker operates at a barely perceptible level and is effectively inaudible under typical driving conditions. The introduction of the vertical offset at the beginning of the critical region initially creates the impression that the auditory cue has disappeared, thereby indicating to the occupant that a change in the driving environment is imminent. As the lead vehicle approaches the speed bump and the onset distance d decreases, the calculated gain increases continuously while the virtual source gradually shifts back toward its original position within the x-y-plane. Consequently, the playback level of the lower loudspeaker increases, creating the perception of an approaching vertical event. The combined effect of the spatial displacement and the continuously increasing sound level provides a clear auditory indication that a vertical maneuver is imminent and approaching, reaching its maximum intensity when the speed bump is encountered. Since the driving maneuvers were conducted independently, the speed bumps were traversed without prior braking, such that the perceived cue was exclusively related to the vertical event. The mapping function and its scaling parameter were empirically tuned based on subjective assessments collected during active driving in the test vehicle and optimized for operation at the minimum track speed of $8\,\mathrm{km/h}$.

$$z = \begin{cases} \frac{d}{3} & ; d \in [0m, 12.5m] \\ 0 & ; d \in \,]12.5m, \infty) \end{cases} \tag{6}$$

2.3 Visual Substitution System

The visual substitution system consisted of two light bars [Cameo PixBar 500 Pro (6×12 W RGBWA+UV), Adam Hall GmbH, Germany] mounted to the left and right of the passenger approximately $50\,\mathrm{cm}$ above the footwell, see Fig. 2. The system illuminated the passenger footwell and was controlled using the same information as the auditory substitution system, namely the lead-vehicle heading angle α_{lead}, target velocity v_{lead}, and distance to the upcoming maneuver d. In contrast to the auditory system, which generated a three-dimensional virtual acoustic environment, the visual system was limited to a one-dimensional spatial representation along the two light bars. Presenting the information within the participant's peripheral visual field was a deliberate design choice, as previous research [40] has shown that information about upcoming vehicle maneuvers does not necessarily need to be presented in the central field of view. To convey information about multiple maneuver characteristics simultaneously, additional non-spatial dimensions of the light stimulus, namely intensity and color, were utilized. During straight driving, a continuously illuminated light spot was presented at the center position, closest to the participant. To indicate the distance to the next maneuver, the light intensity increased continuously from 0% at a distance of $25\,\mathrm{m}$ to 100% at a distance of $10\,\mathrm{m}$ from the upcoming event.

1) Longitudinal direction (braking and acceleration): Changes in the target velocity of the lead vehicle were encoded by color. For the higher velocity level ($v_{lead} = 20\,\mathrm{km/h}$), the light spot was displayed in green, whereas the lower velocity level ($v_{lead} = 8\,\mathrm{km/h}$) was indicated by red illumination, see Fig. 3 (A). Consequently, braking and acceleration maneuvers were represented by transitions between the two colors.

2) Lateral direction (cornering): Cornering maneuvers were represented by moving the light spot from the center position toward the respective side of the upcoming curve, see Fig. 3 (C). The movement was implemented using discrete angular steps of $8°$, matching the angular arrangement of the light sources, instead of a continuous transition. As each side consisted of six individual light sources, the selected step size resulted in a maximum displayed angular offset of approximately $48°$, reflecting the geometric placement of the light sources within the occupant's field of view. This stepwise implementation was motivated by preliminary observations inside the test vehicle suggesting that discrete spatial displacements are more salient and can be perceived more reliably in peripheral vision while participants are engaged in a visual NDRT. Because the increase in light intensity began between $25\,\mathrm{m}$ and $10\,\mathrm{m}$ before the maneuver, while the lead vehicle started turning only at approximately $15\,\mathrm{m}$ before entering the curve, longitudinal and lateral information partially overlapped but were presented largely sequentially. As a result, participants perceived the light spot as gradually increasing in brightness in the center position before moving toward the left or right side, reaching maximum intensity approximately halfway through the lateral displacement.

3) Vertical direction (speed bumps): Speed bumps constituted a special case and were represented by a brief color transition from green to red and back to green while the lead vehicle traversed the obstacle. Similar to the cornering condition, the light intensity increased with decreasing distance to the upcoming maneuver. The characteristic color change occurred shortly before maximum brightness was reached, thereby providing a salient visual cue indicating the speed-bump event.

2.4 Experimental Design

To validate the substitution systems during real driving and to determine whether the provided information improved passengers' ability to anticipate upcoming maneuvers, an experiment was conducted on a closed driving area. A total of

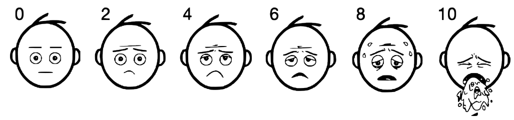


Figure 4: Pictograms depicting the various stages of MS symptoms according to the MISC were presented at 90-second intervals, enabling participants to continuously evaluate their current SMSL throughout the driving task.

46 volunteers (26.4 $\pm$ 3.8 years; 20 females) participated in the study and were assigned to one of three groups in a between-participant design. One group used the auditory substitution system (AUDIO, n=15), another group used the visual substitution system (VISUAL, n=16), and a third group served as a control group (CONTROL, n=15) without any substitution system. All groups exhibited comparable mean MS susceptibility scores (mean Q.Score of AUDIO: 5.8 $\pm$ 3.3; VISUAL: 5.8 $\pm$ 3.6; CONTROL: 5.8 $\pm$ 3.5), indicating comparable baseline conditions across the groups. These susceptibility scores were derived for each participant from the pre-experimental 8-item MS questionnaire [41, 42] (Appendix, Table 3), which yields MS susceptibility ranging from 0 (highly resistant to MS) to 12 (highly susceptible to MS). Participants assigned to the AUDIO and VISUAL conditions were informed about the general operating principles of their respective substitution systems. Although participants with hearing impairments, visual impairments, or color vision deficiencies (e.g., red-green color blindness) were excluded during recruitment, the functionality of the systems was additionally demonstrated prior to the experiment to verify that the presented auditory and visual cues could be perceived reliably. Rather than providing an explicit description of individual maneuver types, the conceptual functioning of each system and the relationship between the presented cues and vehicle movements were explained. Furthermore, participants were able to observe the systems during the baseline laps and directly relate the presented cues to the experienced vehicle motions. This familiarization procedure was implemented to ensure that auditory and visual information could be perceived and interpreted correctly, thereby minimizing the risk of information transfer failures caused by individual perceptual or operational factors. Although no substitution system was active in the CONTROL group, participants were informed that a non-specific MS mitigation system was being used in order to induce similar treatment expectations across all groups and thereby control for expectancy-related placebo effects.
During the experiment, participants sat in the center back seat of the test vehicle (see Fig. 2). The main task was to read a text, visible on a tablet PC placed on the lap, while the car was being driven by a pre-trained driver familiar with the track. During the experiment, participants reported their Subjective Motion Sickness Level (SMSL) every 90 s using an analog visual scale, see Fig. 4. The scale depicted the established MISC (0 = no symptoms, 10 = vomiting) through pictograms, which are considered easier and more intuitive to interpret and rate during driving compared to the original text-based MISC descriptions. Brief interruptions of the NDRT for symptom reporting are not expected to substantially affect situational awareness itself [43].

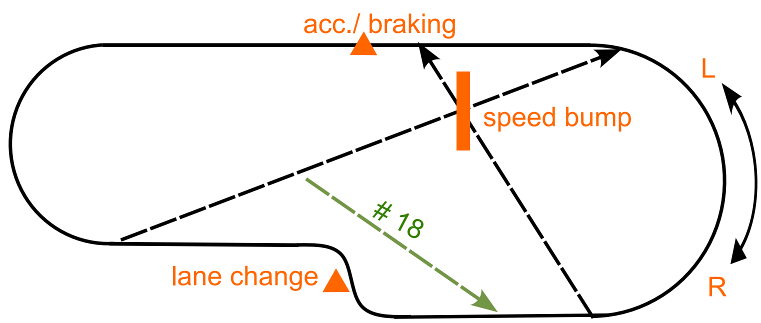


Figure 5: Driving route of the experiment. The route was driven in both directions (L-left; R-right) with diagonal drives (dotted lines) to change direction in a randomly generated sequence, but similar for all participants. Accelerating or braking, speed bumps, and lane changes are marked in the route. U-turns were performed at every end of the route. The 18th lap (green) out of the 22 driven laps was slightly altered, with the speed bump and the corresponding direction change being skipped. After each change of direction, except the last one, the velocity was changed from $20\,\mathrm{km/h}$ to $8\,\mathrm{km/h}$ and vice versa.

The experimental route comprised 22 laps on a 250 m circuit, each completed at a target velocity of $20\,\mathrm{km/h}$. This velocity was selected to ensure safe vehicle operation within the spatial constraints of the test track while allowing all maneuver types, including cornering, accelerating, braking, lane changes, and speed-bump traversals, to be performed without additional speed adjustments. Across the course of the experiment, the driving direction alternated between left-hand (L) and right-hand (R) loops according to the predefined sequence LLRRLLLLRRLLRRRRRL*LRRR. At designated maneuver locations, the vehicle reduced its speed to $8\,\mathrm{km/h}$ before executing a figure-eight trajectory to reverse the driving direction. After completing the maneuver, the vehicle accelerated back to $20\,\mathrm{km/h}$ and proceeded along the track. The transition sections of the figure-eight trajectory contained a speed bump, thereby introducing additional vertical motion stimuli. To minimize habituation effects and reduce predictability of the maneuver sequence, one lap (L*) deviated from the standard pattern. In this case, a change of direction was indicated, and the figure-eight maneuver was initiated, but subsequently terminated before reaching the speed bump, after which the vehicle resumed the normal route. All driving maneuvers were executed by a pre-trained test driver following a standardized driving protocol that separated longitudinal and lateral control inputs, thereby avoiding braking during steering actions and steering during braking phases. Laps 1 to 4 were considered baseline driving and were completed before participants lowered their gaze and started the NDRT. The final route design placed a strong emphasis on lateral vehicle dynamics, with 80 maneuvers primarily involving directional changes, whereas longitudinal and vertical motion events occurred less frequently, accounting for only 25 maneuvers in total. Each participant completed the same driving route, which comprised a total of 105 maneuvers.

After the measurements, participants completed a questionnaire addressing the overall driving experience, the perception of the substitution system (if applicable), situational awareness, predictability, and orientation (see Appendix Table 4). In contrast to the brief interruption of the NDRT required for monitoring of participant well-being, questions related to situational awareness were collected only after the driving session. This decision was made for two reasons. First, uninterrupted engagement in the NDRT was considered essential to ensure a realistic level of task immersion. Second, repeated assessments of situational awareness during the drive could have introduced demand characteristics and attentional biases. Since participants were aware that the study investigated a motion-sickness countermeasure, repeatedly prompting them to reflect on their awareness of the driving situation might have encouraged them to focus more strongly on the substitution system and the vehicle's behavior rather than on the NDRT itself. To minimize such observer effects and preserve natural interaction with the system, all subjective ratings of situational awareness were therefore obtained retrospectively after the experimental drive, see [43].
During some measurement days, temporary GPS signal disturbances were observed. Consequently, some participants were exposed to a system configuration affected by reduced localization accuracy. These disturbances impaired the vehicle's position estimation on the test track and occasionally led to delays in maneuver planning. Consequently, the anticipatory cues were, in some cases, presented after event onset or more than 10 seconds prior to the event, causing deviations from the predefined anticipation interval. Therefore, participants for whom fewer than 85% of the cues were presented within a time window of up to 10 s before the corresponding maneuver were excluded from the analysis. This resulted in a group size of 13 participants in the AUDIO group and 9 participants in the VISUAL group. In addition, three measurements were excluded due to corrupted signals caused by a server failure. Consequently, data from 12 participants were available for analysis in the CONTROL group.

3 RESULTS

Table 1, depicts the responses of all participants to the questions regarding driving experience and substitution system asked after the measurement. The results show in general very similar responses across conditions. E.g., the most uncomfortable maneuver was across all conditions the U-turn (Questions A5). When asked about expected nausea and actual nausea after the measurement, across all conditions about half of the participants said that the nausea was better than expected (Questions A6). Participants in both system groups reported that they perceived the provided cues at least occasionally during the drive (Question B1), although some participants, particularly in the VISUAL group, reported being distracted by the system (Question B2). The functionality of the system was generally understood by the participants (Question B3), and differences between both speed phases were rarely noticed (Question B4). Although participants did not report an increased sense of orientation (Question C2), route orientation performance improved, reaching statistical significance in the AUDIO condition (Question C1). Furthermore, participants were able to anticipate upcoming maneuvers significantly more often (Question C3). Anticipation performance for cornering maneuvers increased substantially in both experimental groups (Question C6). The visual system showed the highest recognition rates for longitudinal maneuvers; acceleration and braking events, whereas the auditory system achieved the highest recognition rates for the vertical maneuvers; the speed bumps.

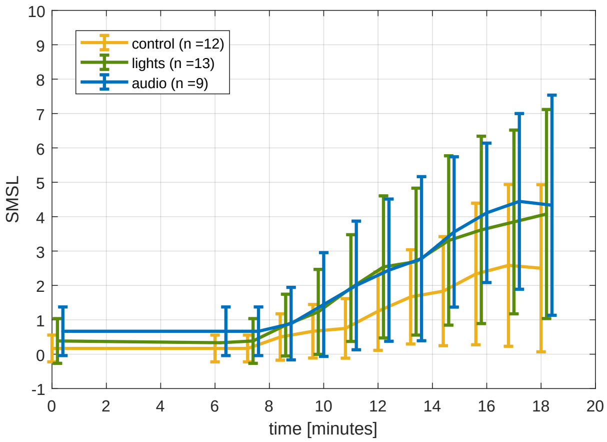
Table 1: Descriptive results of the post-drive questionnaire. Results are mentioned as absolute number of participants and in percentages related to their condition.

Question / Item	**Audio** ($N = 9$)	**Visual** ($N = 13$)	**Control** ($N = 12$)
A. General comfort and driving experience			
1. Comfortably seated prior to motion? (Yes)	8 (88.89%)	13 (100.0%)	12 (100.0%)
2. Comfort of vehicle motion (mean, 0–10)	4	4	4
3. Comfort of overall driving experience (mean, 0–10)	4	4	4
4. The drive felt too… (multiple answers possible):			
– Fast	0 (0.0%)	1 (7.7%)	2 (16.67%)
– Slow	2 (22.22%)	1 (7.7%)	1 (8.33%)
– Shaky	4 (44.44%)	6 (46.15%)	7 (58.33%)
– Spinning	6 (66.67%)	8 (61.54%)	7 (58.33%)
– Dark	0 (0.0%)	2 (15.93%)	1 (8.33%)
– Bright	0 (0.0%)	1 (7.7%)	0 (0.0%)
– Noisy	0 (0.0%)	0 (0.0%)	1 (8.33%)
– Quiet	0 (0.0%)	1 (7.7%)	1 (8.33%)
– Warm	0 (0.0%)	**5 (38.46%)**	0 (0.0%)
– Cold	1 (11.11%)	0 (0.0%)	2 (16.67%)
5. Most uncomfortable maneuver (multiple answers possible):			
– Acceleration	1 (11.11%)	2 (15.93%)	3 (25%)
– Braking	1 (11.11%)	4 (30.77%)	4 (33.3%)
– Curves	0 (0.0%)	1 (7.7%)	0 (0.0%)
– Speed bump	2 (22.22%)	4 (30.77%)	1 (8.33%)
– U-Turn	6 (66.67%)	9 (69.23%)	9 (75%)
– Lane change	4 (44.44%)	3 (23.08%)	4 (33.3%)
6. Nausea compared to expectation:			
– Better	4 (44.44%)	8 (61.54%)	7 (58.33%)
– Worse	3 (33.33%)	1 (7.7%)	2 (16.67%)
– As expected	2 (22.22%)	5 (38.46%)	4 (33.3%)
B. Perception of the additional system			
1. Perception of an additional system:			
– Always	**2 (22.2%)**	**3 (23.08%)**	0 (0.0%)
– Mostly	**4 (44.44%)**	**5 (38.46%)**	0 (0.0%)
– Sometimes	**3 (33.3%)**	**4 (30.77%)**	0 (0.0%)
– Never	**1 (11.11%)**	**2 (15.93%)**	12 (100.0%)
2. Have you been distracted by the system? (Yes)	3 (33.33%)	**6 (46.15%)**	0 (0.0%)
3. Mode of operation was clear? (Yes)	**9 (100.0%)**	**13 (100.0%)**	0 (0.0%)
4. Difference in system perception between fast/slow driving? (Yes)	1 (11.11%)	2 (15.93%)	0 (0.0%)

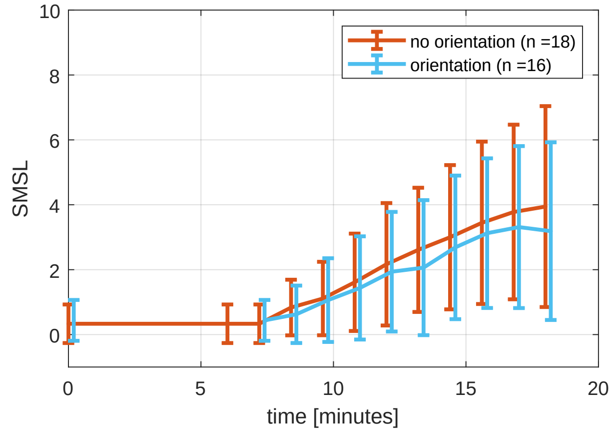
C. Situational awareness and predictability			
1. Were you able to orient yourself on the route:			
– All of the time	**1 (11.11%)**	0 (0.0%)	0 (0.0%)
– Most of the time	**1 (11.11%)**	2 (15.93%)	1 (8.33%)
– Now and then	**5 (55.55%)**	4 (30.77%)	3 (25%)
– None	**2 (22.22%)**	8 (61.54%)	9 (75%)
2. Did the system supported orientation? (Yes)	3 (33.33%)	1 (7.7%)	0 (0.0%)
3. Could you correctly predict if a maneuver approaches?			
– All of the time	**3 (33.33%)**	**4 (30.77%)**	0 (0.0%)
– Most of the time	**3 (33.3%)**	**7 (53.85%)**	1 (8.33%)
– Now and then	**2 (22.22%)**	**0 (0.0%)**	2 (15.93%)
– None	**1 (11.11%)**	**3 (23.08%)**	9 (75%)
4. Could you identify the type of maneuver correctly (for all maneuvers)? (Yes)	3 (33.33%)	2 (15.93%)	0 (0.0%)
5. If no, which maneuvers could you identify? (multiple answers possible):			
– Acceleration	1 (11.11%)	6 (46.15%)	1 (8.33%)
– Braking	1 (11.11%)	5 (38.46%)	1 (8.33%)
– Speed bump	3 (33.33%)	1 (7.7%)	0 (0.0%)
– U-Turn	2 (22.22%)	**8 (61.54%)**	1 (8.33%)
– Lane change	2 (22.22%)	4 (30.77%)	1 (8.33%)
6. C4 + C5:			
– Acceleration	4 (44.4%)	**8 (61.53%)**	1 (8.33%)
– Braking	4 (4.44%)	**7 (53.84%)**	1 (8.33%)
– Speed bump	**6 (66.66%)**	3 (23.07%)	0 (0.0%)
– U-Turn	**5 (55.55%)**	**10 (76.92%)**	1 (8.33%)
– Lane change	**5 (55.55%)**	6 (46.15%)	1 (8.33%)

Group differences were evaluated using two-sided Fisher's exact tests for categorical response variables. For Questions B1, C1, and C2, which contained ordinal response categories, one-sided Wilcoxon rank-sum tests were used. Comparisons were restricted to system-versus-control contrasts; no pairwise comparisons among the systems were performed. Statistical significance was defined as $p < 0.05$. Significant results are highlighted in bold.

The mean SMSL ratings did not reveal substantial differences between the three experimental conditions, see Fig. 6a. During the first approximately 500 s of the experiment, mean SMSL values remained close to zero in all conditions. This was expected, as the depicted interval also includes the baseline phase, consisting of 120 s of standing still followed by 300 s of low-demand driving without the execution of an additional task. Starting at approximately 600 s, SMSL ratings increased similarly across all three conditions. The mean SMSL ratings of the CONTROL group remained (non-significant) slightly lower than those observed in the AUDIO and VISUAL conditions; however, the average Q.Score was also lower in this group (see Appendix Table 2). When participants were grouped according to whether route orientation was reported (mean Q.Score = 6.00) or not reported (mean Q.Score = 6.06), (non-significant) slightly lower SMSL ratings were observed for participants who reported route orientation; see Fig. 6b. Furthermore, the error bars indicate a similar standard deviation across all conditions.



(a) SMSL by condition.



(b) SMSL by route orientation.

Figure 6: Average SMSL ratings across participants. (a) Comparison between AUDIO (blue), VISUAL (green) and CONTROL (yellow) conditions. (b) Comparison between reported (light blue) and not reported (orange) route orientation. Error bars indicate standard deviation.

4 DISCUSSION

Both substitution systems were deliberately designed to be intuitive and easy to understand. This is particularly reflected in the responses to Question B3 (Table 1), where all participants in both intervention groups reported that they understood the respective system. Furthermore, the systems were intentionally designed to be unobtrusive and minimally annoying. Nevertheless, a subset of participants reported perceiving the substitution system continuously throughout the entire experiment (Question B1, Table 1). This perception appeared to differ between modalities. In particular, participants in the VISUAL group reported being more distracted by the system than in the AUDIO group (Question B2, Table 1), suggesting that visual cues competed more strongly for attentional resources required by the primary NDRT. This observation is further supported by the slightly lower task performance observed in the VISUAL group, although the overall performance level remained high across all experimental groups (Appendix Table 2). However, as the visual modality was actively engaged by the NDRT, it may have been inherently more susceptible to distraction caused by the visual substitution cues than the auditory modality. Furthermore, it is conceivable that individuals with a high resistance to MS became deeply immersed in the NDRT and largely ignored their surroundings, whereas more susceptible participants allocated greater attention to the provided anticipatory information and actively processed it when necessary to maintain comfort and well-being during the ride.

The use of the sensory substitution systems enabled participants to anticipate significantly more driving maneuvers than those in the CONTROL group (Question C3, Table 1). In addition, the perceived level of route orientation was improved by system usage, with this effect reaching statistical significance for the auditory system (Question C1, Table 1). However, participants did not perceive the substitution systems as directly supporting their orientation (Question C2, Table 1). Although the study design primarily focused on lateral driving maneuvers, users of one of the substitution systems were also able to identify rarer, longitudinal motion events such as acceleration, braking, and speed bumps (Questions C4, C5, and C6, Table 1). The visual system appeared to communicate acceleration and braking particularly effectively through its red-green color coding. In contrast, the auditory system showed advantages in conveying speed bumps, as these events could be represented through a fifth loudspeaker in an additional spatial dimension, a capability that was not available in the visual system. These complementary strengths indicate that no single sensory modality is optimally suited for communicating all aspects of vehicle dynamics. Future systems supporting situational awareness should therefore adopt multimodal approaches that combine the strengths of different sensory channels in order to provide a robust, intuitive, and comprehensive representation of upcoming vehicle motions. As these findings are based on a between-participant design and are therefore not influenced by direct comparisons between experimental conditions by the same participants, it can be concluded that the systems, particularly the auditory substitution system, successfully conveyed relevant vehicle-state information and improved both orientation and maneuver anticipation. One limitation of the present findings is that participants were unfamiliar with the driving route. During real-world travel, occupants typically possess some degree of prior knowledge about the journey, including expected highway segments, salient landmarks, previous experiences with the route, or an estimated timeline of upcoming events. Such additional contextual information may substantially facilitate spatial orientation and route anticipation. Furthermore, the route used in the present study was intentionally designed to be difficult to predict. This design choice aimed to minimize anticipatory effects arising from route memory or the formation of an accurate mental model of the upcoming road geometry. Consequently, participants' anticipatory capabilities relied predominantly on the provided substitution cues rather than on prior route knowledge. Therefore, the reported findings should primarily be interpreted as reflecting improvements in the anticipation of upcoming driving maneuvers rather than genuine route anticipation. While the findings of Wijlens et al. [44] suggest that occupants do not naturally learn and anticipate simple repetitive patterns within a driving route, it cannot be ruled out that characteristic road geometries or route features familiar from everyday driving experience facilitate anticipatory behavior. As a result, the influence of route familiarity on the effectiveness of anticipatory assistance systems remains unclear. Future studies employing familiar or repeatedly traversed routes may therefore yield different results and provide further insight into the interaction between route knowledge and anticipatory support.

Although there was an increase in anticipation of events, the AUDIO and VISUAL groups exhibited slightly higher, albeit non-significant, average SMSL progressions than the CONTROL group, see Fig. 6a. One possible explanation is that the exclusion of several participants resulted in intervention groups with comparatively higher MS susceptibility (see corrected Q.Scores Appendix Table 2). Consequently, potential benefits of the anticipatory cueing systems may have been partially masked by differences in baseline susceptibility. An important limitation of the present study is the relatively small sample size associated with the between-participants design, which may have reduced the statistical power to detect the effects of anticipatory MS countermeasures. Nevertheless, the chosen design largely minimized placebo effects and other psychological influences that may arise when participants are repeatedly exposed to multiple experimental conditions or become aware of the intervention's intended purpose [25, 26]. But, an indication of a potential well-being effect can be observed across all experimental groups in the response trend for "nausea was better than expected" (Question A6, Table 1). Furthermore, if the effect sizes of anticipatory countermeasures were indeed as pronounced as suggested by earlier studies [15, 16], at least a tendency towards a reduction in MS would have been expected despite the limited sample size. The present findings therefore provide a modest indication that anticipatory countermeasures may be less (technological) effective than previously assumed, thereby supporting more recent studies that reported limited or no MS mitigation effects [17]. However, a small, albeit non-significant, reduction in average SMSL was observed when participants were grouped according to their reported level of orientation (in this case both groups exhibited a comparable Q.Score), as shown in Fig. 6b. This observation suggests that orientation and MS may indeed be related. It is therefore conceivable that the effectiveness of anticipatory systems depends less on the mere availability of anticipatory information and more on whether users can effectively process and use this information to anticipate upcoming vehicle motion. Consequently, the optimization of anticipatory countermeasures and the identification of suitable implementation strategies require further investigation. Future studies should additionally consider the role of habituation and familiarization periods [29], as well as the substantial inter-individual variability in MS susceptibility, both of which may strongly influence the effectiveness of such systems. Some participants in the CONTROL group were able to remain oriented and anticipate upcoming maneuvers without the aid of an anticipatory system (Questions C1 and C3, Table 1). Possible explanations include characteristics of the route design, learning effects arising from repeated maneuvers during the drive, a well-developed sense of timing, or the use of external environmental cues such as the position of the sun and the resulting shadow patterns in the peripheral field of view. This finding suggests that certain individuals may naturally develop alternative anticipation strategies, enabling them to infer upcoming vehicle motions even in the absence of dedicated support systems. If such individuals represent a distinct subgroup within the population, future research should investigate their characteristics separately. In particular, it remains unclear whether MS countermeasures can provide additional benefits for occupants who already possess a high degree of situational awareness and trajectory anticipation without external assistance.

5 CONCLUSION

This study investigated whether upcoming vehicle movements can be communicated through auditory and visual sensory substitution systems based on a lead-vehicle concept in real-world driving scenarios in which occupants are engaged in a visually demanding NDRT. The present findings demonstrate that occupants can successfully utilize a continuous lead-vehicle representation to anticipate future vehicle behavior. Participants were able to use the provided information to predict upcoming driving maneuvers, slightly increase route orientation, and distinguish between different classes of vehicle motion. These findings suggest that continuously representing the dynamic state of a lead vehicle constitutes a viable alternative to conventional event-based cueing approaches, which typically rely on explicit maneuver announcements. By leveraging principles of natural traffic anticipation, the proposed concept may offer a more intuitive and scalable framework for communicating complex future vehicle states to occupants. Among the investigated implementations, the auditory substitution system generally yielded the greatest benefits. This finding suggests that anticipatory information may be communicated most effectively when the (three dimensional) spatial characteristics of a sensory modality are fully exploited and when the selected sensory channel is not already occupied by a concurrent NDRT. At the same time, the complementary strengths observed for individual maneuver types indicate that future systems may benefit from multimodal implementations that combine the advantages of different sensory channels. In contrast, no statistically significant reduction in MS was observed. This finding is consistent with recent studies reporting weak, inconsistent, or absent effects of anticipatory MS countermeasures. Nevertheless, the interpretability of the present MS-related results is limited by the available sample size and should therefore be considered with caution. Importantly, the absence of a measurable MS mitigation effect does not necessarily imply the absence of a relationship between anticipation, orientation, and MS. Independent of their effects on MS, anticipatory systems in automated vehicles may foster trust in the automated driving system by improving the predictability of vehicle behavior, thereby contributing to greater passenger comfort [45]. Future work should therefore focus on improved information representations, refined experimental designs, longer familiarization periods, and more effective integration of anticipatory information into occupants' mental models of future vehicle motion. In this context, the continuous lead-vehicle representation using sensory substitution proposed in the present work may provide a promising foundation for the development of next-generation anticipatory in-vehicle systems to increase driving comfort.

6 APPENDIX

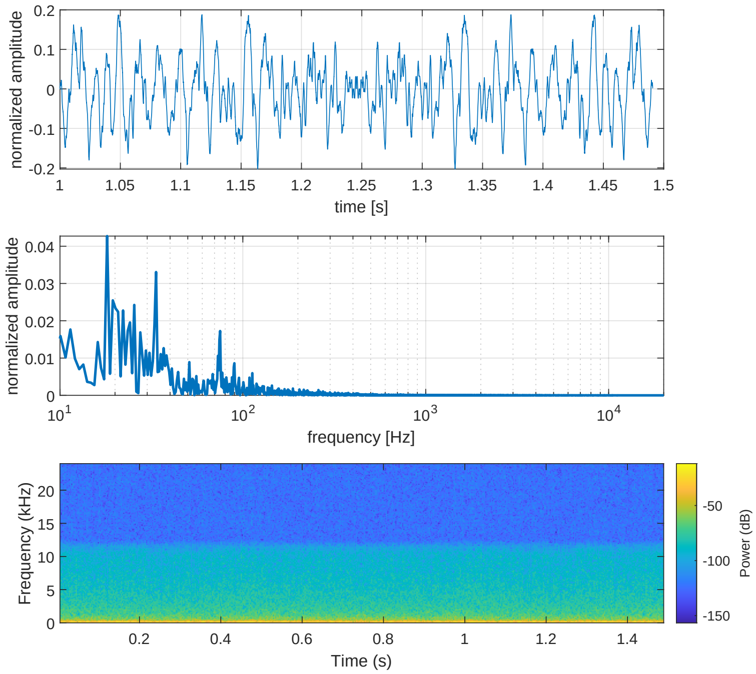


Figure 7: Sound profile and spectrogram of the AUDIO substitution system

Table 2: Task Performance and MS Susceptibility

	Audio ($N = 9$)	**Visual** ($N = 13$)	**Control** ($N = 12$)
Mean NDRT Performance Score	85.89%	78.38%	80.42%
Mean Q.Score	6.78	6.00	5.50
Std. Q-Score	2.73	3.37	3.73

Table 3: 8-Item MS Questionnaire with Scoring Rules [42]

Questionnaire Item	**Answer Options & Scoring**			
1. Do you see yourself as prone to motion sickness?	Not at all	Little	Moderate	Extreme
Score value:	0	1	2	3
2. Can you read or watch videos during a car trip without getting sick?	No		Yes	
Score value:	0		1	
3. How severe are your symptoms when they occur?	0–1	2–5	6–8	9–10
Score value:	0	1	2	3
4. Have you ever taken medication for motion sickness symptoms?	No		Yes	
Score value:	0		1	
5. Do you have any tricks to avoid the occurrence of motion sickness?	No		Yes	
Score value:	0		1	
6. Does sitting in the front or back seat affect motion sickness?	No		Yes	
Score value:	0		1	
7. Does the way of sitting affect motion sickness?	No		Yes	
Score value:	0		1	
8. Do factors such as attention or fatigue influence motion sickness?	No		Yes	
Score value:	0		1	
Classification Criteria	**Susceptibility Status**			
Sum of scores (Q.Score) < 6	Not susceptible to motion sickness			
Sum of scores (Q.Score) ≥ 6	Susceptible to motion sickness			

Table 4: Post-drive questionnaire assessing comfort, system perception, and situational awareness.

Item	**Response options**
A. General comfort and driving experience	
1. I was comfortably seated in the stationary vehicle prior to motion.	Yes/No
2. Comfort of vehicle motion.	0–10
3. Comfort of the overall driving experience.	0–10
4. The drive felt (e.g., too fast/slow, unstable, too dark/bright, too loud/quiet, too warm/cold).	Free text
5. Most uncomfortable maneuver.	Speed bump, braking, acceleration, lane change, U-turn
6. Nausea compared to expectation.	Better/Worse/As expected
B. Perception of the additional system	
7. Perception of an additional system.	Always/Most/Sometimes/Never
8. Distraction from NDRT due to system.	Yes/No
9. Understanding and consistency of system behavior.	Yes/No
10. Difference between fast and slow driving modes.	Yes/No
11. Additional comments.	Free text
C. Situational awareness and predictability	
12. Ability to orient along the route.	Always/Most/Sometimes/Never
12.1 If yes: Did the system supported this orientation?	Yes/No
13.Could you correctly predict if a maneuver approaches?	Always/Most/Sometimes/Never
13.1 Could you identify the type of maneuver correctly? (Yes) .	Yes/No
13.1.1 If not all maneuver, which maneuvers.	Speed bump, braking, acceleration, lane change, U-turn

7 ACKNOWLEDGMENT

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During the preparation of this work, the author used Microsoft Copilot in order to improve the readability and language of the manuscript. After using this service, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

All procedures were conducted in accordance with the Declaration of Helsinki and were approved by the local ethics committee (Identification number: 149/23 Ärztekammer des Saarlandes; Medical Council of the Saarland). Informed consent was obtained from all participants involved in the study.

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