Motion sickness in automated vehicles: Principal research questions and the need for common protocols

Cyriel Diels[1] Ying Ye[2],Jelte E. Bos[3,4], Setsuo Maeda[5]

1 Royal College of Art, Intelligent Mobility Design Centre, UK
2 University of Southampton, UK
3 TNO Human Performance, The Netherlands
4 Vrije Universiteit Amsterdam, Behavioural and Movement Sciences, The Netherlands
5 Nottingham Trent University, UK

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Abstract

Motion sickness in automated vehicles represents a key Human Factors concern that will negatively impact the passenger experience and, ultimately, public acceptance. Minimising or avoiding motion sickness altogether therefore becomes a strategic design goal. In this paper we propose principal research questions that need to be addressed as part of a concerted effort to understand the causative factors of motion sickness and the need to develop and apply common protocols to accelerate knowledge and subsequent innovation in this field. With the ultimate goal to provide guidelines to inform the design of future vehicles, the International Standard ISO 2631-1 (1997) is taken as the starting point. The current Standard provides estimates of the likelihood of motion sickness as a function of vertical motion input only. However, in the context of automated vehicles, and in particular in the light of anticipated Non-Driving Related Activities in such vehicles, the current standard is of limited use: The model has not been validated for horizontal and rotational motions or any potential multi-axes interactions; The Standard was derived on the basis of the percentage of passengers reaching the point of emesis while less severe levels of motion sickness are of greater interest and may show a different relationship between the frequency and acceleration; Modulating factors that are able to regulate, adjust or adapt sickness levels are not included, in particular vision and the associated concept of anticipation, passenger orientation and reclination angles. Finally, the accumulation of motion sickness knowledge in this field is severely hampered by the absence of consistent study protocols. We here propose the identification and development of appropriate vibration measurements and motion sickness assessment and evaluation methods.

Keywords: *automation, vehicle design, motion sickness, acceptance, Standards*

1. Introduction

Vehicle automation is widely anticipated to positively contribute towards a safer, greener, and more sustainable future [1]. It may also make our individual journeys more enjoyable and productive by virtue of us becoming passengers no longer responsible for controlling the vehicle, a benefit that can already be enjoyed by those choosing to use ride sharing services. However, the possibility of freeing up time spent driving for a more meaningful or joyful journey experience may be compromised by passengers feeling slightly uncomfortable. The passenger comfort experience in future vehicles may be affected by a wide range of psychological, physical and physiological factors [e.g. 2,3]. Here we focus on one aspect in particular, namely the experience of signs and symptoms of motion sickness [4,5].

These signs and symptoms of motion sickness include (cold) sweating, pallor, flatulence, burping, salivation, and apathy, which symptoms may vary considerably between people regarding their (order of) occurrence and severity and tend to be followed by nausea, retching, and ultimately emesis [6-8]. The root cause of motion sickness is widely thought to be a mismatch between sensed and expected motion [6,9]. Such mismatches occur under conditions in which the actual sensory information following motion is sufficiently at odds with the expected bodily sensory state as based on prior experiences, also explaining that passengers suffer considerably more than drivers do [10-15].

Given the estimates that passengers currently comprise 1/3 of all car occupants and 2/3 of them suffer from carsickness, a game changer in the field of automated driving concerns the change of a minority of 2/9 of all car occupants suffering from carsickness nowadays, to a majority of 2/3 in automated vehicles in which all occupants will be passenger [16]. Although not trivial, it seems pertinent that of all factors affecting discomfort when motion is at issue, motion sickness is generally considered most detrimental [17].

Motion sickness is experienced when we are exposed to motion that, from an evolutionary perspective, we are not accustomed to, such as low frequency oscillating motion [18]. Whereas sea and airsickness are mainly caused by slowly oscillating vertical motion, carsickness, on the other hand, is mainly caused by horizontal accelerations due to accelerating, braking, and cornering [19-21]. Hence, an aggressive driving style involving plenty of these actions is therefore more likely to result in carsickness.

In addition to the motion of the vehicle per se, there are several modulating factors that have the potential to aggravate carsickness [22]. These modulating factors are becoming increasingly important in the design of automated vehicles in which we are witnessing a transition from a driver-centric to a passenger-centric design philosophy (see figure 1 for an illustration). Indeed, it has previously been argued that the mere fact of being a passive passenger, engagement in so-called Non-Driving Related Activities (NDRA), new vehicle designs challenging our spatial orientation, and any combinations therefore, will further increase the likelihood of passengers experiencing motion sickness [4,5].

Fig 1. Example of passenger-centric design approach towards future automated vehicles ("Prospect & Refuge" concept; © 2020 Oliver Winter, all rights reserved)

These predictions have since been substantiated in several (Wizard of Oz) studies with passengers exposed to future use cases envisioned for an automated future [e.g. 23-27]. It becomes increasingly apparent that motion sickness is not just a luxury problem affecting the hypersusceptible amongst us. In fact, the above studies show that almost everyone being exposed to what may initially may appear to be benign conditions, such as reading a tablet, will feel uncomfortable within a matter of minutes, given the right, or rather, wrong, conditions.

Here we briefly want to reiterate the point that, in comparison to other modes of transport, vehicle automation presents a special case in which the ability to use our travel time more constructively is pertinent [22,28,29]. Whereas we have come to accept that we may feel queasy when trying to read or write in public transport or a taxi, the proposition of vehicle automation differs and the benefits of automation may not be perceived significant unless we can actually engage in such activities. Critically, we argue that mild symptoms, or a general sense of unease caused by symptoms that may not even be consciously perceived, are perhaps more insidious than blatant manifestations of motion sickness. In worst case, passengers may not appreciate the link between their sense of discomfort, their behaviour and that of the vehicle, and may develop a general dislike to automation negatively affecting public acceptance. Indeed, the link between motion sickness and the comfort experience more widely on the acceptance of automated vehicles has already been demonstrated [e.g. 30].

It is now clear that the mitigation of motion sickness needs to be a strategic goal for any vehicle manufacturer or mobility service provider. In this article we provide a systematic overview of the existing literature and propose principal research questions that need to be addressed as part of a concerted effort to understand the causative factors of motion sickness, the relative effectiveness and people's acceptance of different mitigation strategies, and the need to develop and apply common, standardised, protocols to accelerate knowledge and subsequent innovation in this field.

1.1 ISO 2631-1 (1997)

We here take as a starting point that the physical motion of the vehicle is at the basis of motion sickness and the most basic way to reduce motion sickness should hence concern the motion of the vehicle. The good news regarding automated vehicles is that these motions are controlled by algorithms that allow to be optimised for comfort, in this case by minimising carsickness. This does however require that we know the dose-effect relationship as numeric estimates. To this end, we here consider the International Standard ISO 2631-1 (1997) [31], that followed on from the British Standard BS 6841 (1987) [32]. The Standard already provides guidelines for the measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock, and includes an empirical approximation describing a method of evaluating motion sickness. It considers the likelihood of motion sickness as a function of the motion input as defined by the accelerations passengers are exposed to over time. In its simplest form ISO predicts the Motion Sickness Incidence (MSI) by

$$MSI = K_m \times MSDV \quad (1)$$

where K_m is a constant which may vary according to the exposed population. As per ISO2631-1 (1997), for a mixed population of unadapted male and female adults, K_m = l/3. MSDV is the Motion Sickness Dose Value as explained further below.

ISO 2631-1 (1997) assumes that the motion sickness dose value of a complex motion can be described by the linear addition of the separate responses to each of the single frequency sines of which the complex motion is composed of. For the evaluation of whole-body vibration, the vibration is measured at all frequencies within the human sensitivity range. Subsequently, the frequency weightings are used to reflect this sensitivity, where the most sensitive range is given a heavier weighting range than those with a less sensitive range [33]. ISO 2631-1 (1997) uses the frequency weighting (w_f) to predict the MSDV for any motion according

$$\mathrm{MSDV} = a_w \times \sqrt{t} \quad (2)$$

in which a_w is the frequency weighted acceleration (m/s^2) and t the time (s) and the *MSDV* is hence given in m/s$^{1.5}$. According to the model, motion sickness shows a positive linear relationship with acceleration, increases with frequency up to around 0.2 Hz and decreases for higher frequencies, showing virtually no sickness, i.e. emesis, above 1 Hz.

However, as will be discussed in more detail below, the applicability of the Standard to automated vehicles may be limited. In general terms, such limitations are already acknowledged within the existing Standard which is expected to be expanded when sufficient data becomes available (e.g. see section 9, BSI (1987)). We argue that future research and development efforts, and subsequent standardisation efforts, should concentrate on key strategic areas identified here. Future revisions or supplements to the Standard ISO 2631-1 (1997) should provide Original Equipment Manufacturers (OEM), Tier suppliers, mobility service providers and other stakeholders with guidelines and Standards to avoid or minimise the incidence and severity of motion sickness in future vehicles.

It should be noted that the development of the ISO 2631-1 approach is not the only approach or even necessarily the best approach tackling the challenge of motion sickness in automated vehicles. Alternative observer-theory model approaches based on underlying perceptual mechanisms have been proposed including Oman’s Observer-theory model [11], Bles et al’s Subjective Vertical model [34], and Wada’s subsequent expansion of Subjective

Vertical model [35]. Although these models do add functionality, they also do rely on a number of basic assumptions (and parameters) and have only been validated for a limited number of conditions. The advantage of the ISO approach is its mere focus on the dose-effect relationship with a minimum of underlying assumptions (and parameters), its widespread use and proven success so far. For these reasons, we suggest the ISO 2631-1 as an appropriate and pragmatic approach.

In the following sections we briefly summarise the current state of the art and identify gaps in knowledge. Section 2 discusses the impact of the physical motion experienced by passengers, multi-axis motion, and their mutual weighting regarding amplitude and frequency dependence. In section 3 we take a closer look at modulating factors, in particular those that are pertinent to the design of future vehicles and Non-Driving Related Activities such as vision, anticipation, passenger orientation and reclination. Section 4 addresses questions around the assessment and evaluation of motion sickness and the (lack of) methodological consistencies across studies to further our understanding. In section 5 we discuss our findings and present principal research questions for future research. Finally, section 6 provides some concluding remarks.

2. Motion

The Standard was originally developed to be applicable to motion in ships and other vessels. As such, it considers vertical (*z*) motion only, which, at that time, was the dominant stimulus for seasickness. The model has not been validated for horizontal motion (fore-aft *x*, and lateral *y*) which is of particular concern in road vehicles (see figure 2). In addition, rotational motions are currently not considered, nor are any potential interactions between axes of linear and / or rotational motion.

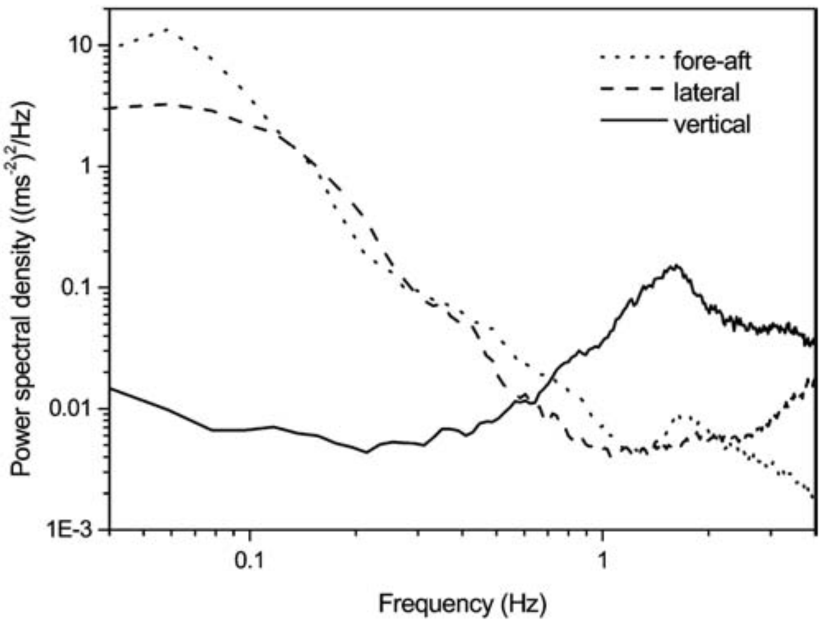

Fig 2. Median acceleration power spectral densities spectra in the fore-and-aft (x), lateral (y), and vertical (z) axes for a passenger car on a suburban route (From [36])

2.1 Horizontal motion

Dating back in the 90s, a series of lab experiments were conducted to explore the sickening effect of fore-aft and lateral sinusoidal motion. Studies compared the effect of fore-aft and vertical sinusoidal motion at a frequency of 0.205 to 1 Hz with a peak acceleration of 3.6 m/s^2, showing that fore-aft motion causes more sickness than vertical motion [37-39]. These studies concluded that horizontal motion was more nauseating than would be predicted based on vertical motion. Furthermore, the frequency dependence for fore-aft motion was significantly less steep than previously reported for vertical motion below 0.5 Hz and rapidly declined for frequencies above 0.5 Hz. Further research have shown that there is a decrease of sickness with frequency in the range of 0.25 - 0.8 Hz [40-42]. [43] studied frequencies below the 0.2Hz, and concluded that down to 0.0315 Hz, sickness severity did not vary with frequencies (see Figure 3). These results suggested that sickness decreased roughly inversely proportional to frequency, but a more complex dependency would be required over the full frequency range and there are no differences in motion sickness severity reported between fore-aft and lateral motions.

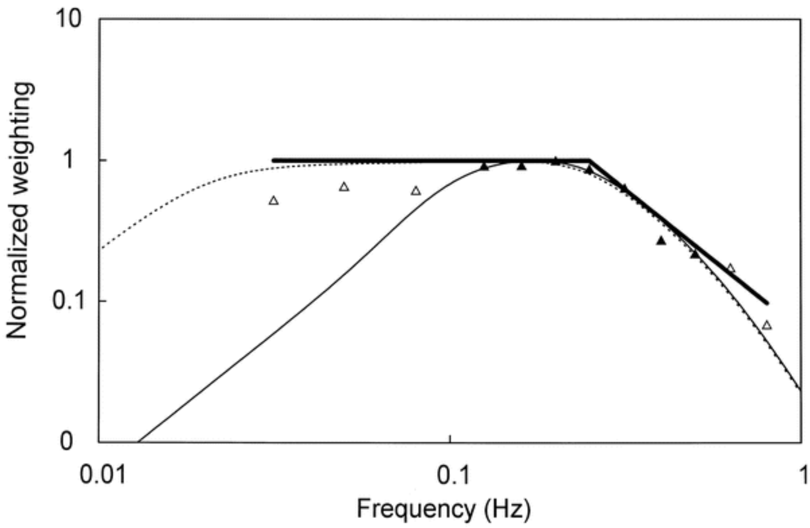

Fig 3. Asymptotic and realizable frequency weightings for lateral acceleration compared with the weighting for vertical acceleration, w_f. Asymptotic weighting=solid thick line; realizable weighting=dotted line; w_f =solid thin line black; triangles points at which values differ significantly from static condition, open triangles points at which values not significantly different from static condition (from [43]).

The above studies provide useful data comparing motion sickness levels during horizontal motion. However, these data are neither complete nor conclusive. Part of the reason is that comparisons across studies are problematic due to the different measures of motion sickness used as well as differences in experimental protocols (see section 4). Nevertheless, the ISO2631-1 (1997), though validated for vertical motion only, is still applied occasionally to analyse the sickening effect of horizontal motion [e.g. 43]. [43] pointed out that based on other studies, the constant K_m in the formula can be replaced with 1.41 K_m (or √2 K_m) when the formula is to be used for horizontal acceleration. However, the authors also stated the limitation of this approach noting that the formula was derived on the basis of only a few laboratory studies and would require further validation. Since, several efforts have been made to further explore Donohew & Griffin's approach [e.g. 44,45] but further research will be required to validate the approach. Furthermore, the frequency-dependence for lateral oscillation found in the study may not be applicable when motion sickness is caused by combined lateral and roll motion.

2.2 Rotational motion

Studies have been designed to investigate the effect of rotational motion on motion sickness severity. [34] and [46], for example, concluded that angular motion about an (Earth-vertical or horizontal) axis through the head (thus generating minimal linear accelerations) is not provocative. [47] furthermore exposed participants to roll rotational vibration at 5 frequencies from 0.025 – 0.4 Hz with ±8° magnitude, and showed that there is no significant difference in the motion sickness of these five frequencies and only provoked mild motion sickness with a mean illness rating below 2 (i.e. mild symptoms but no nausea) [47]. It indicated that mechanisms that mediate the motion sickness under pure roll oscillation may be different from horizontal oscillation. [48] studied the effect of magnitude in roll or pitch oscillation on motion sickness, the results suggested motion sickness severity increased with rotational angle. Moreover, there was no significant difference in motion sickness between roll and pitch oscillation. This finding is consistent with the results from [49] where exposure to pitch oscillation through ± 3.69°at 0.2 and 0.4 Hz was found to cause similar motion sickness. Further research is required to establish the suitable frequency weighting that could be applied to evaluate the motion sickness for rotational motion.

2.3 Interactions

Laboratory studies have been conducted to investigate the effect of combined horizontal and rotational motion. [46], for example, found a significant interaction effect of combined vertical and angular motion, while each of these motions studied separately were hardly provocative. Similarly, studies into the effect of lateral and roll oscillation have shown that low levels of sickness were reported with pure roll or lateral oscillation [43,50]. However, when combined, significant higher levels of sickness were reported [51].

The phase between the horizontal and rotational motion is a further important factor for motion sickness. [48] found that motion sickness was reduced with an increased phase delay from 0° to 29° between lateral and roll oscillation. A follow up study used a phase difference of 180° between pitch and fore-aft motions. The results suggested that the mean illness ratings of in-phase were less than out-of-phase (pitch motion was 180° out of phase with fore-aft motion), suggesting phase to be dependent on the magnitude of phase [49]. In similar experiments, [52] included active versus passive head tilt and concluded that active control may overrule the effect of tilting per se.

Despite the above hints, to date, there is still a significant dearth of knowledge regarding multi-axis motion and its effects on motion sickness in general and carsickness in particular. Furthermore, it should be noted that vehicle motion in the field is more complicated than in the laboratory as it combines different motion axes while the frequencies and magnitudes of motion are more irregular. At the same time, centripetal and tangential linear accelerations caused by angular motions do result in a high correlation between angular vehicle motion and its linear accelerations. It remains to be seen to what extent these correlations are that strong to make incorporating rotations separately superfluous or not. In case of 4-wheel steering, these correlations will be different, and the need to reckon these interactions regarding carsickness will then have to be (re)considered.

2.4 Accumulation over time

As indicated by Eq. 2, the MSDV increases with the square root of time. According Eq. 1 this implies an unlimited increase of the MSI over time, while MSI, by definition, is limited to 100%. For that reason, ISO just limits exposure duration for valid predictions to periods in the range of 20 min to about 6 h, with the prevalence of emesis varying up to about 70 % [53]. Although the 70% and the upper time limit seems appropriate for reckoning carsickness, the lower time limit may not. Besides accumulation, habituation is yet another issue to be elaborated on in case of motion exposures lasting several hours.

3. Modulating factors

While motion *per se* is considered the primary cause of motion sickness, we use the term modulating factors to refer to those factors that are able to regulate, adjust or adapt motion sickness that would not cause sickness in the absence of motion. A recent large scale international survey on motion sickness prevalence and causative factors identified culture (i.e. highest and lowest incidence was reported in China and Germany, respectively), age (i.e. decreased susceptibility over time), gender (i.e. females more susceptible), low air quality (i.e. cigarette or exhaust smell, warm air), visual activities (i.e. reading, using a device, writing, watching a video) as important modulating factors [22].

In the following sections, we will focus on those factors that are pertinent to the design of future automated vehicles and refer to [5] for factors that fall outside the design domain such as culture, gender, age, and temporal characteristics of motion sickness including accumulation, habituation, and retention.

3.1 Vision

ISO2631-1 (1997) [31] was derived from data obtained in studies using participants having no view of the outside world. However, vision is known to be an important modulating factor, causing grief as well as relief. Incongruencies between visual and vestibular motion cues with regards to body motion, motion anticipation, and visually-induced motion, are of particular relevance in the current context. Key scenarios include passengers of automated vehicles engaging in non-driving related activities such as reading, watching a display (possibly presenting potentially conflicting motion cues itself), or not having a view of the road ahead due to occluded windows or traveling facing rearwards.

Indeed, various studies have demonstrated the importance of vision. Early work by Probst et al. [54] demonstrated motion sickness in rear seat passengers to be worst while reading a map, followed by keeping their eyes closed, and looking at the direction travel. In a large-scale public transport survey, [21] found that sickness occurrence was greatest for passengers for which visibility ratings were lowest, e.g., those located towards the rear of the vehicle. In one of the most extensive studies into the effect of vision to date, [36] also found that sickness was reduced when the external view ahead was more accessible, as also observed in the context of ship motion [7].

More recently, [28] and [23] evaluated the impact on motion sickness with passengers using head-down versus head-up displays and found that the presence of peripheral vision afforded by head-up display configurations resulted in significantly lower levels of sickness. Similarly, [55] reported motion sickness levels twice as high when watching a movie using a head-down display compared to looking out of the vehicle. [25] showed that rearward facing seating arrangements that prevent the passenger from seeing the road ahead led to significantly elevated levels of motion sickness compared to conventional forward facing seating arrangements. Alternatively, like having a view on the real world, artificial imageries showing an Earth-fixed frame of reference have been shown to offer relief as well [56].

Whilst these studies demonstrate a clear link between vision out of the window and motion sickness, the exact nature of the relationship between vision and motion sickness is yet to be determined. Outstanding questions concern the relative importance of instantaneous visual information available to estimate body motion (direct visual-vestibular conflict) and the ability to anticipate future motion on the basis of the visual information [57]. In both instances, the optimum quality and the quantity of the visual information is yet to be determined. Besides optic flow characteristics, *frame* information, i.e. visual information to indicate horizontality and verticality [58,59], derived from the vehicle interior may also play a role in particular in the absence of an outside view.

An additional consideration is the role of visually induced self-motion (i.e. vection) when using in-vehicle displays and its potential to both alleviate or aggravate motion sickness depending on the congruence with the perceived car motion [5,28,60]. Vection becomes particular relevant when incorporating Virtual Reality or similar technologies into the vehicle environment [e.g. 61].

3.2 Anticipation

The beneficial effect of vision has been attributed, at least partly, to the ability to anticipate the future motion trajectory [12,21,36,54,57,62]. The role of anticipation in the development of motion sickness can be understood by considering that our Central Nervous System (CNS) not only reckons sensed motion, but also makes a prediction about self-motion based on previous experiences. A discrepancy or conflict between integrated sensory afferents indicative for specifically attitude, and a prediction thereof by a so-called internal model or neural store, is assumed responsible for generating motion sickness [6,11,34].

In the context of carsickness, it becomes apparent that unlike passengers, drivers are able to anticipate the future motion due to the tight coupling between the control of pedals and steering wheel and subsequent known (learnt) vehicle motion, and thus minimising the likelihood of motion sickness (see figure 4 for a simplified representation of the proposed underlying principle). Further, whereas forward-looking passengers will be able to see a curve ahead, only the driver knows when the vehicle will decelerate and whether this curve will be taken wide or sharp, thus having optimal information about upcoming self-motion, resulting in the smallest possible conflict. Likewise, braking and accelerating will cause a difference in conflict and hence a difference in sickness between drivers and passengers.

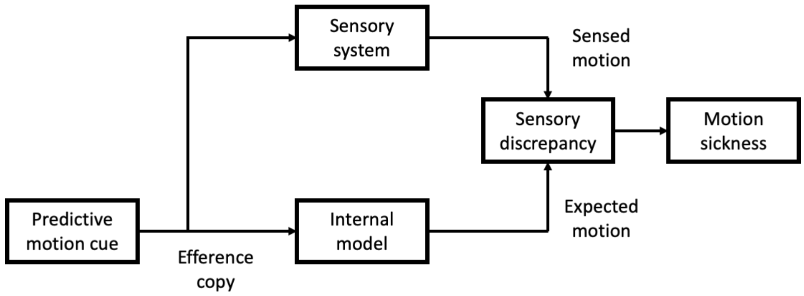

Fig 4. Simplified motion sickness model illustrating the principle of the impact of predictive motion cues (anticipation), activation of an internal model and subsequent impact on sensory discrepancies and associated motion sickness [63].

Several recent studies suggest that the feedforward mechanism can be initiated by a range of predictive motion cues and may be exploited within the context of automated vehicles. [24] informed rear seat passengers of upcoming left or right turns 3 seconds ahead of the actual manoeuvre via an ambient light (i.e. vertical LED array) display located at either side of an in-vehicle display. The visual cues led to a significant reduction in sickness as measured by the Motion Sickness Assessment Questionnaire (MSAQ) [64].

Similarly, [65] showed that auditory cues (e.g. left hand corner ahead, slowing down to a stop, turning right) provided to front seat passengers engaged in a head-down visual search task significantly reduced sickness levels as assessed using the MIsery SCale (MISC) [7]. While the cues were shown to be effective, at the same time, they were reported to be perceived as rather annoying with some participant ignoring the cues indicating that not only effectiveness but also the acceptance and experience of such cues need to be considered.

Rather than exploring the effectiveness of predictive motion cues, [66] evaluated the impact of the predictability of the motion per se. To this end, participants were exposed to repeated fore-aft motion on a sled while sitting in an enclosed cabin positioned on top of the sled which did not allow for an external view. They were exposed to the repeated fore-aft motion at 1) constant intervals and consistent motion direction (i.e. predictable: condition P); 2) at constant intervals but varied motion direction (i.e. directionally unpredictable: condition dU); and 3) varied intervals but consistent motion direction (i.e. temporally unpredictable: condition tU). As hypothesised, both the directionally and temporally unpredictable conditions led to 52% higher illness ratings (MISC) compared to the predictable condition.

Finally, in a follow up study using the same experimental setup, [57] compared motion sickness during fore-aft displacements with a semi-random timings of pauses and directions. In the anticipatory condition, the auditory cues informed both of timing and of direction (i.e. a sound clip communicating either “forward” or “backward”), by occurring consistently 1 s before the motion started and with the actual direction of upcoming motion. In the control condition, the auditory cues were presented at semi-random timings, 2–6 s after a motion was already initiated and were therefore non-informative, not aiding in the participants ability to anticipate the upcoming motion. The auditory cues in the control condition were included to ensure that the level of stimulation (i.e. hearing an auditory cue) was identical in both conditions. It was found that the informative auditory cues led to significantly lower sickness ratings (MISC).

The above proof-of-concept studies indicate that motion anticipation is a significant factor that needs to be taken into account. To date, however, its true potential in reducing carsickness is yet to be determined and requires further research into the relative effectiveness as a function of sensory modality, timing, and information detailing while also taking into account acceptance of different cues and the wider passenger experience in particular in relation to non-driving related activities [63].

3.2 Passenger orientation and reclination

Vehicle automation and associated Non-Driving Related Activities open up and require the reconsideration of occupants' seating orientation, posture and reclination which, to date, has remained largely unchallenged. In particular, the idea of enhancing social interaction has led to the idea of rotated seats, rearward and sideways-facing seating configurations. Similarly, relaxation and sleeping implies the reclination of seats. Few studies have thus far explored the effects of seating orientation and reclination but the available data suggests that these factors need to be taken into consideration.

[25] compared motion sickness levels with forward and rearward facing seats and observed a significant increase in motion sickness when traveling rearwards, and, as expected, this was particularly pronounced under urban driving conditions. Similar observations were reported by [21] in the context of public transport. While the differences observed by [25] may be attributed to the inability to anticipate future motion, and hence overlaps with the impact of vision, the available visual information for forward facing passengers in this study was severely limited and raises the question whether these differences can be ascribed to vision alone. Future studies would benefit from the systematic investigation of orientation (rearward, forward, and intermediate angles) while controlling for vision and anticipation.

In the context of motion sickness in ambulances, [67] compared motion sickness levels during braking manoeuvres with participants sitting upright facing forward, lying supine with the head forward or backward. More sickness was reported when seated facing the direction of motion than when lying along the axis of acceleration and deceleration and suggests that reclined positions may have an alleviating effect. In fact, more recently, [26] demonstrated that increasing the backrest angle from 23 (upright) to 38 degrees (reclined) significantly reduced motion sickness and this effect was found to be larger than that observed for seat direction, i.e. forward versus rearward facing.

With alternative seating arrangements widely anticipated to become an integral aspect of future automated vehicles, the limited but available studies suggest the need to better understand the role of passenger orientation and motion sickness in particular in the light of possible interactions with vision and anticipation. In case of dynamic seating, additional motions and interactions will be at play, and it remains to be seen if the interactions as discussed above suffice to predict carsickness in these challenging conditions as well.

4. Research protocols: measurement, assessment and evaluation

While the developments in automated driving have significantly raised the interest in carsickness, there is still a relative paucity of studies. Importantly, deriving meaningful comparisons and conclusions across these studies is severely hampered by the lack of consistency and standardisation in the study protocols employed. In particular, this refers to motion sickness assessment methods and evaluation criteria and vibration measurements.

4.1 Measurement of vibration

Current vibration measurement methods (location and axis) defined in the ISO2631-1 (1997) for seated occupants take into account the vibration from three input locations (back, seat and foot) with 12 vibration axes (3 translational directions at back, 3 translational and 3 rotational directions at seat, 3 translational directions at foot). This measurement method was developed to assist the evaluation of vibration discomfort. However, the underlying mechanisms involved in the development of motion sickness are different from vibration discomfort, and the relative importance of vibration from the feet, seat, back and head should be known.

Though not decisive, two studies may, however, already be indicative. [68] applied above 1 Hz vibration to the head of subjects simultaneously exposed to nauseating off-vertical axis rotation (OVAR), finding a decrease of sickness as compared to OVAR only. Elaborating on that, [69] applied a comparable vibration to the seat of subjects simultaneously exposed to a nauseating visual stimulus, and did not find an effect. Moreover, there is substantial evidence that the organs of balance within our inner ears (sensitive to linear and angular motion as well as to gravity), are crucial in the genesis of motion sickness, making the head the primary location of interest in this respect, as was also the basis for the experiment by [68].

Following a similar approach to that provided in the ISO2631-1 (1997), motion sickness studies have used vehicle-based systems to assess motion sickness with accelerometers located near on the floor close to the position of a rear-seat passenger [e.g. 36], seat pad of the front passenger seat [e.g. 70,71], as well as the centre of gravity and the passengers' feet [e.g. 72,73].

To provide better prediction and evaluation of motion sickness, previous studies have also tried to measure the head tilting angles and found that the driver's active head movement could increase the visibility and decrease of effect of the inertial force to the body, and reduce the severity of motion sickness [49,74-76]. However, none of these studies have proposed a suitable measurement method on how to measure the head rotation and how to interpret the additional information on head rotation angle together with the existing measurement methods defined in ISO 2631-1 (1997).

For future AV development, it is therefore essential to establish appropriate measurement points to represent the vehicle and passengers' six degrees of freedom motion to facilitate comparisons across studies and motion sickness prediction.

4.2 Motion sickness assessment and evaluation

Emesis is the ultimate and unequivocal manifestation of motion sickness. The frequency weighting curve as per ISO2631-1 (1997) was derived on the basis of the percentage of passengers reaching the point of emesis, referred to as the Motion Sickness Incidence (MSI). However, besides emesis, there are many more symptoms associated with motion sickness, generally clustering in pre-nausea symptoms and nausea [7,77].

As most drives are stopped before passengers would reach the point of emesis, these pre-emesis symptoms are relevant to consider in rating and predicting carsickness in particular. Importantly, and illustrated in section 2 above, it seems probable that the frequency weightings at issue are dependent on the type of rating used to describe motion sickness severity. This may, for example result in pre-emesis symptoms ~~sickness~~ also occurring at frequencies above 1 Hz, which does have serious consequences, in particular when considering vertical motion as affected by ~~(active)~~ suspension, Figure 2 being informative in this respect. Future research would therefore benefit from the systematic evaluation of the frequency dependency of motion sickness for milder levels of motion sickness.

For reasons of measurement objectivity and associated benefits, significant efforts have been made to identify objective, physiological measures to quantify motion sickness signs and symptoms such as heart rate, skin conductance, and gastric activity [e.g. 78]. However, to date, this has proven to be relatively unsuccessful largely due to intra- and inter-individual variability and individual differences in physiological responses and subjectively reported motion sickness levels [79, 80]. Moreover, to our knowledge, current research has merely focussed on sensitivity (i.e., the chance of concluding someone is sick if she or he is), while knowing specificity (i.e. the chance of concluding someone is not sick when she or he is not), is as important. As a consequence, subjective sickness or illness ratings are still the primary measures of motion sickness.

Subjective measures of motion sickness can be categorised into i) multiple symptom checklists and ii) single answer scales. Multiple symptom checklists, originally derived from the Pensacola Diagnostic Criteria (PDC) [81], typically include the cardinal signs and symptoms of motion sickness, i.e. increased salivation, pallor, cold sweating, drowsiness and nausea. In addition, they include signs and symptoms of presumed less importance such as epigastric awareness, epigastric discomfort, flushing/subjective warmth, headache, and dizziness.

Over the years, several multiple symptom checklists have been developed and adopted that differ with respect to the signs and symptoms included, the manner in which these signs and symptoms are rated (i.e. different Likert scale points and descriptors), the way scores are calculated (i.e. post exposure scores, difference scores (post-pre exposure)), how results are analysed and presented (i.e. sickness presented as an overall score or as a multidimensional construct with several symptom components or factors), and what participants are instructed to rate (e.g. symptoms as experienced now, at the end of the drive, or at their worst during the drive). Examples of frequently used symptom checklists include the Simulator Sickness Questionnaire [82] and the Motion Sickness Assessment Questionnaire (MSAQ) [64].

Since multiple symptom checklists are relatively time consuming and cannot be administered unobtrusively or repeatedly during a session, single answer scales are used in addition or instead. They allow for assessing the time course of motion sickness by asking participants to successively provide a single overall motion sickness rating of increasing severity (e.g. 1 = no symptoms; 4 = moderate nausea), typically rated at 1-, 2-, 5- or 10-minute intervals. Examples of widely used single answer scales include the Malaise scale [83], illness rating scale [84], and the MIsery SCale (MISC) [7]. Comparisons between conditions are made using a variety of different metrics, e.g. maximum, average, accumulative, and final sickness scores, as well as time to reach certain sickness ratings. Alternatively, unpleasantness has been rated as a measure of motion sickness severity, without explicitly reckoning its symptomatology (Fast Motion sickness Scale or FMS) [85]. Although symptomatology and unpleasantness generally do show a certain correlation, there seems to be an anomaly for which reason unpleasantness can uniquely be derived from symptomatology, while symptomatology cannot uniquely be derived from unpleasantness [8].

The above section illustrates the wide range of assessment and evaluation methods that are employed. In addition, there is a proliferation of self-styled questionnaires and rating scales to, for example, accommodate cultural and language factors [e.g. 71,55]. While acknowledging the desire to innovate assessment methods and respond to study- or population-specific needs, at this stage, this variability in assessment and evaluation methods is hampering comparisons across studies and our understanding of motion sickness. Hence, future research should focus on establishing the most appropriate methods on the basis of set criteria (including validity, reliability, sensitivity, specificity, and practical feasibility) and promote the use of a minimum set of standardised assessment and evaluation methods that may be supplemented by other methods to allow for individual needs or circumstances.

5. Principal research questions

In this paper we addressed the concern of motion sickness in future automated vehicles and identified research findings relevant to sickness mitigation. In this section, we briefly discuss our findings and identify the research questions that concern the root cause of the problem to facilitate our understanding of motion sickness in this field. The proposed directions are intended to expand the existing International Standard ISO 2631-1 (1997) and provide Original Equipment Manufacturers (OEM), Tier suppliers, mobility service providers and other stakeholders with guidelines and Standards to minimise the incidence and severity of motion sickness.

5.1 Motion

While physical motion of the vehicle is at the basis of motion sickness it also points to the most basic way to reduce motion sickness. To be of practical value it requires an understanding of the dose-effect relationship as numeric estimates in order to be implemented in future motion algorithms. ISO 2631-1 (1997) already provides an empirical approximation of the likelihood of motion sickness as a function of the motion input as defined by the accelerations passengers are exposed to over time. However, the Standard was developed and validated on the basis of vertical motion which is of limited concern for motion sickness in (automated) road vehicles as discussed in section 2. Future research would therefore benefit from the systematic investigation of:

- *The frequency and acceleration dependency of lateral and longitudinal motion.*
- *The frequency and acceleration dependency of rotational motion.*
- *Mutual weightings and potential interactions between axes of linear and / or rotational motion.*
- *Predictability of motion per se.*

5.2 Modulating factors

Modulating factors are factors that are able to regulate (i.e., increase or decrease), adjust or adapt motion sickness that would not cause sickness in the absence of motion. There is a large number of modulating factors including personal factors such as age, gender, ethnicity, diet, as well as temporal factors such as adaptation, habituation, and retention. Whilst we acknowledge their importance and necessity to ultimately be included in the development of future guidelines and Standards, we here focussed on those factors that are under direct control and have an impact on the design strategy of future automated vehicles.

As discussed in section 3, vision is arguably the most important modulating factor and closely associated with the ability to anticipate future motion. Obscuration due to internal vehicle structures and elements such as headrests, displays, occluded windows as well as seating orientation and gaze orientation directly impact the out-the-window view potentially exacerbating motion sickness. Likewise, the provision of artificial motion cues may alleviate some of these concerns.

ISO 2631-1 (1997) was derived from data obtained from studies using participants who had no out-the-window and currently does not take vision or anticipation into account. Vision and anticipation represent natural extensions of the Standard but the exact nature of the role of vision and anticipation, and hence design implications, are yet to be fully understood. In particular, we identify the following key research questions:

- *The quality and quantity of visual information in terms of field of view, optic flow characteristics, and frame information.*
- *The role of visually induced self-motion (i.e. vection) and its potential to both alleviate or aggravate sickness.*
- *The relative effectiveness of anticipation as a function of sensory modality, timing, and information detail.*

Passenger orientation and reclination are further modulating factors shown to affect motion sickness and widely regarded as a key design feature of future automated vehicles. The exact relationship is yet to be explored in particular given the fact that vision and anticipation tend to be confounded with orientation and requires further research, in particular:

- *The impact of rearward, forward, and intermediate angles of passenger orientation*
- *The impact of range of reclination angles from upright to supine*

- *The impact of changes in orientation and reclination in dynamic conditions*
- *Interaction effects between vision, anticipation, orientation and reclination*

5.3 Research protocols: measurement, assessment and evaluation
ISO 2631-1 (1997) was derived on the basis of the percentage of passengers reaching the point of emesis (i.e. Motion Sickness Incidence) while less severe levels of motion sickness, characterised by a variety of symptoms typically preceding emesis, are of greater interest and may show a different relationship between the motion frequency and acceleration characteristics. As such, the Standard does not provide any guidance with regards to the assessment and evaluation of less severe motion sickness levels which compromises comparisons across studies as also described in section 4.

Within the field of motion sickness there is an absence of well-defined, agreed-on, or even standardised research protocols that include guidance and best practice on how to measure and characterise vehicle motion and how to assess, analyse and evaluate less severe motion sickness levels. In light of the above research questions, it is paramount to address the following questions:

- *What are the most appropriate vehicle motion measures for motion sickness prediction and evaluation, considering the precision, repeatability, accessibility, and their mutual (cor)relations*
- *What are the most appropriate subjective motion sickness measures on the basis of criteria including validity, reliability, sensitivity, specificity, practical feasibility, and their mutual (cor)relations*

6. Conclusions

The principal research questions presented above are considered essential building blocks to develop our understanding of motion sickness in automated vehicles. We argue that future research and development efforts, and subsequent standardisation efforts, should concentrate on these key strategic areas. Future revisions or supplements to the Standard ISO 2631-1 (1997) including the extension and validation of the mathematical model should provide Original Equipment Manufacturers (OEM), Tier suppliers, mobility service providers and other stakeholders with guidelines and Standards to avoid or minimise the incidence and severity of motion sickness in future vehicles. Importantly, this should include the identification and implementation of common research protocols and motion sickness measures and metrics to accelerate our understanding of motion sickness in the rapidly evolving field of vehicle automation. The research to date has shown that motion sickness is not merely a luxury problem but a hygiene factor. Minimising if not avoiding motion sickness in future automated vehicles is essential to achieve the personal, socio-economic and environmental benefits vehicle automation may be able to provide. The research questions identified here are largely pre-competitive in nature and require elaborate research resources. This research would therefore benefit from joint efforts by a multitude of the industries mentioned above in collaboration with universities and research institutes, not only for economic reasons but also to obtain objectivity and consensus from an early stage onwards.

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