Motion Sickness in Automated Vehicles: The Elephant in the Room

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Abstract Automation disuse and associated loss of automation benefits may occur if users of automated vehicles experience motion sickness. Compared to conventional vehicles, motion sickness will be of greater concern due to the absence of vehicle control and the anticipated engagement in non-driving tasks. Furthermore, future users are expected to be less tolerant to the occurrence of motion sickness in automated vehicles compared to other means of transport. The risk of motion sickness may be manageable if we understand underlying causes and design our vehicles and driver-vehicle interactions appropriately. Guided by three fundamental principles, an initial set of design considerations are provided reflecting the incorporation of basic perceptual mechanisms.

Keywords Vehicle automation · Design · Displays · Motion sickness · Carsickness · Sensory conflict · Anticipation

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1 Introduction

During his campaign in Africa, Napoleon quickly became to realize the strengths of camels as a new mode of transport and subsequently instated his dromedary regiment. What he did not quite foresee, however, was that the gait of the camel made his soldiers suffer from motion sickness. Camels clearly weren't for everyone with some generals refusing to use them for their troops.

Motion sickness may also prove to be a hindrance to the successful introduction of vehicle automation. The fundamental feature of handing over vehicle control in combination with the anticipated engagement in non-driving tasks will increase the likelihood that occupants experience motion sickness [1, 2]. In turn, this may result in *automation disuse* and consequently limit the ultimate socioeconomic and environmental benefits this technology has to offer.

This is not to say that motion sickness is a showstopper. The risk of motion sickness can be managed if we understand its underlying causes and design our vehicles and driver-vehicle interactions appropriately. Whereas this may seem obvious, a review of the automated vehicle concepts recently being put forward by design consultancies, suppliers, and OEMs, suggests that the risk of motion sickness has not been considered in the design process, a notable exception being the Valeo Mobius™ system [3].

The crucial starting point is the realization that motion sickness is a natural response to an unnatural motion environment. Man was designed to travel by foot. For reasons not quite understood, we don't like being exposed to motion environments which violate our finely calibrated relationship between the motion sensed by our eyes, organs of balance, proprioception, and ultimately our brain. Whereas the final manifestation of motion sickness is vomiting, it is typically preceded by signs and symptoms such as (cold) sweating, pallor, flatulence, burping, salivation, and apathy, after which nausea and retching may occur [4]. To this date, the exact evolutionary advantages of these responses remain a mystery although they most certainly motivate the sufferer from seeking a less provocative environment in the hope of a speedy recovery. Nonetheless, whereas we may not quite understand the *why*, we know fairly well which conditions lead to motion sickness and seem to understand the *how*. As with many other human physiological regulatory systems, the control of body motion is at issue, and an assumed error signal correlates quite well with observed sickness. On this basis we are able to provide guidelines for the design of automated vehicles.

Before discussing these in detail, we would like to spell out why automated vehicles are a special case. One could argue that automated vehicles are not different from other modes of transport. After all, what is the difference between being a train or car passenger and driving in automated mode?

First, unlike most car journeys, a large proportion of journeys on public transport tend to consist of long distance and uninterrupted routes at largely constant speeds. With the exception of perhaps some remote, rural areas, the daily reality is that our traffic on the roads can perhaps best be characterized summarized as stop-start. As explained in more detail below, it is this varying velocity motion profile that is particularly conducive to motion sickness. It also goes some way in explaining why even today we see very few car passengers reading books and instead prefer to stare at the vehicles in front.

Secondly, and most importantly, the ability to free up our time to engage in more useful or enjoyable activities is more pertinent to vehicle automation. Whereas we may elect not to use public transport or accept that we won't be able to use our laptop sitting in the passenger seat as it makes us feel queasy, the proposition of vehicle automation differs. The benefits of automation may not be perceived significant unless we can actually engage in other activities. In fact, the inability to do so, and in the worst case, having to constantly monitor the system and environment, may well be perceived as less comfortable and acceptable than manual driving.

Finally, it can be predicted that even if people do not experience full blown symptoms of motion sickness, mild and subtle symptoms may already negatively affect the user experience. As a consequence, people may be unable or unwilling to take advantage of the new scenarios that vehicle automation affords.

It is for the above reasons that we believe that motion sickness in automated vehicles should be considered a special case. We propose that the development of measures to minimize the severity of motion sickness, or avoiding its occurrence altogether, ought to become an important line of automotive research. Moreover, there is a matter of urgency in that the issue will be especially relevant during the introductory period in which the general public may be hypercritical with the least publically known failure easily leading to unwanted delays.

2 Drivers of Motion Sickness

In the below, we set out the conditions that are conducive to motion sickness in order to then provide guidelines for the design of automated vehicles and driver-vehicle interactions.

2.1 Vehicle Dynamics

Motion sickness typically occurs when we are exposed to motion that, from an evolutionary perspective, we are not used to, such as low frequency oscillating motion [5]. Whereas sea and airsickness are mainly caused by slowly oscillating vertical motion, carsickness is largely associated with horizontal accelerations caused by accelerating, braking, and cornering [6]. An aggressive driving style involving plenty of accelerating and braking is therefore more likely to result in carsickness. The implication for automation is that the vehicle dynamics in terms of acceleration/deceleration may have to be restricted to ensure a sufficient level of occupant comfort. As a general rule, motion profiles in the region of 0.16 Hz should be avoided [7]. It is noteworthy that this may compromise the expected benefit of automation on network capacity. For example, LeVine et al. [8] have shown on the basis of microsimulations that limiting vehicle dynamics will reduce signalized intersections' vehicle-processing capacity and increase delays.

2.2 Anticipation of Vehicle Dynamics

The motion profile becomes even more critical in automated vehicles due to the fact that the driver hands over longitudinal and/or lateral control to the vehicle. This transfer, or loss of control, lies at the heart of vehicle automation per se and in effect renders the driver a passenger. Unfortunately, we already know that drivers of cars, pilots of aircraft, or Virtual Reality users in control of their own movements usually suffer much less from motion sickness despite the fact that they experience the same motion as their passengers [9]. Thus, the mere fact of not being in control of the vehicle dynamics increases the likelihood that people will experience motion sickness.

Anticipation plays a key role in explaining this phenomenon. The difference between a driver and passenger can be understood by assuming our central nervous system not only reckons sensed motion, but also makes a prediction about self-motion based on previous experiences [7]. A discrepancy or conflict between integrated sensory afferents, and a prediction thereof by a so called internal model or neural store, is assumed responsible for generating motion sickness [4, 7]. If the driver of a car is familiar with the transfer from pedals and steering wheel input to the actual motion of the car, he or she can make a more accurate prediction, i.e., anticipate motorically about future motion, thus minimizing the sickening conflict. Although a forward looking passenger can see a curve ahead, it is only the driver who knows whether this curve will be taken wide or sharp, thus having optimal information about self-motion, resulting in the smallest possible and typically sub threshold conflict. Braking and accelerating will likewise cause a difference in conflict and hence a difference in sickness.

What is of particular relevance for the avoidance of motion sickness in future automated vehicles is that this anticipatory mechanism is not only at play when individuals are able to motorically anticipate incoming sensory cues, but also on the basis of visual information alone. A clear view of the road ahead will allow for the prediction of the future motion path at least to some degree and is therefore beneficial in reducing sensory conflict.

The importance of anticipatory visual information in motion sickness is suggested by the anecdotal evidence that backward looking passengers suffer more from car sickness than forward looking passengers, the former only seeing the trajectory that has been followed, the latter seeing the trajectory that will be followed. In addition, we also know that rear seat passengers are particularly prone to car sickness under conditions where external visual views are limited [10].

Recently, the effectiveness of visual information in reducing motion sickness was strikingly demonstrated in a flight simulator study [11]. No less than a fourfold reduction in motion sickness was observed when a visual, roller coaster-like track to be travelled was presented. Although it has yet to be determined whether this approach could be successfully applied within an automotive context, in theory, we would predict a similar approach to reduce or prevent motion sickness in automated vehicles. Possible design solutions may include augmenting the natural scene with a future motion trajectory via contact-analogue Head-Up Displays (HUD) for example. Incidentally, such an approach was recently adopted by Weißgerber et al. [12] albeit with a different goal. In their study, providing the driver with an augmented view of the road ahead indicating, amongst other things, the vehicle's future trajectory improved driver's ability to create a correct mental model of the driving situation and automated vehicle system.

From the above, it becomes apparent that a person's ability to anticipate the future motion trajectory is a major factor in the development of motion sickness. When traveling in automated mode, the absence of vehicle control, facing away from the direction of travel or even traveling backwards, or not having a clear view of the road ahead due to it being obscured by displays or internal structures otherwise, will all increase the likelihood of occupants experiencing motion sickness and should therefore be avoided.

2.3 Conflicting Motion Cues

Vehicle automation will ultimately enable the driver to engage in non-driving activities. It is likely that popular activities will include reading, responding to emails, or engaging otherwise with nomadic or integrated infotainment systems such as in-vehicle displays, laptops, gaming consoles, or tablets [13]. From the perspective of the user, increased comfort and the ability to spend the driving time more productive or enjoyable are arguably the main advantages of automation.

As alluded to already, engagement in such activities can be expected to lead to an increase in carsickness. Similar to reading a map or book whilst driving, the (static or dynamic) motion shown on displays may not correspond to the motion of the vehicle which, in turn, will increase the likelihood of motion sickness. The essential point here is that our central nervous system integrates visual and vestibular signals (i.e., originating from the organs of balance within the inner ear) normally caused by congruent motion inputs as expected. Watching a scene showing different motion than that felt by our organs of balance is not what we expect and this inter-modality sensory conflict has long been known to lead to motion sickness [4].

With regard to non-driving tasks, Cowings et al. [14] reported a negative impact on crew performance and health when subjects attended to displays while the vehicle was moving. Similarly, in a study by Kato and Kitazaki [15] participants were driven around whilst sitting in the backseat either watching the road ahead, or a rear-seat

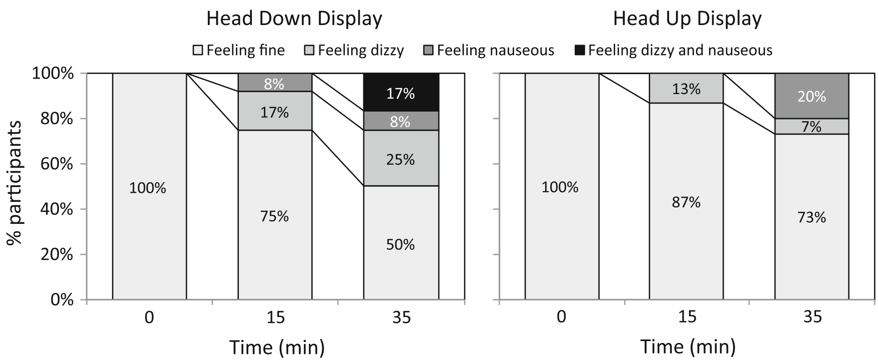

Fig. 1 Percentage of participants reporting motion sickness symptoms during a 35 min drive performing non-driving tasks using a head down display (*left*) and a head up display (*right*) [16]

display showing written text. As expected from a sensory conflict perspective, watching the in-car display led to significantly higher levels of carsickness.

Most recently, Diels et al. [16] reported on a study demonstrating the significance of display position on the occurrence of motion sickness in automated vehicles. Participants were asked to perform various reading and viewing tasks using a tablet located either in the users' lap (head down display) or mounted on top of the dashboard (head up display). The head up display resulted in considerably lower levels of motion sickness (see Fig. 1).

This finding is in line with what would be predicted on the basis of motion sickness theory. In comparison to the head down display, the head up condition enables the user to visually perceive the direction of travel to a larger extent therefore resulting in smaller sensory conflicts and associated motion sickness [17]. In the head down condition, one in four participants reported motion sickness symptoms after 15 min, rising to no less than one in two after 35 min. Positioning the display closer to the line of sight out of the window had a considerable beneficial effect and led to a 50 % reduction in the occurrence of motions sickness. These results clearly illustrate the potential scale of the problem of motion sickness in automated vehicles as well as the importance of designing the driver-vehicle interaction and HMI keeping in mind the causative factors of motion sickness.

Closely related to the above is the observation by Houben et al. [19], who studied the effect of an anti-seasickness display, comparable to that used by Feenstra et al. [11]. As with Diels et al. [16] they differentiated between display position which in this case however showed veridical Earth-fixed self-motion. Their observation was that motion sickness was reduced more when the display was centered on the line of sight than when positioned above it.

At this point, it is appropriate to note that the occurrence of motion sickness can be expected to be closely linked to the vehicle's motion profile. Our organs of balance are in essence biological accelerometers and are subsequently sensitive to accelerations only, i.e., to changes in velocity [18]. As a corollary, sensory conflict as a result of viewing a stationary visual scene is significantly reduced when traveling at constant speed. The organs of balance signal the body to be stationary and any stationary scene as sensed by our eyes will therefore be perceived as congruent. When driving at largely constant velocity, sickness is therefore less likely to occur as a result of reading or using in-vehicle displays. However, the moment dynamic media content is introduced, sensory conflict may of course occur under both constant and varying velocity motion scenarios [2].

3 Design Considerations for Automated Vehicles

From the above, it can be concluded that motion sickness will be of greater concern with automated vehicles compared to conventional vehicles in particular in the light of engagement in non-driving tasks. To minimize the likelihood of motion sickness, there are three fundamental principles that should be observed:

- Avoid vehicle motions around 0.16 Hz
- Allow occupants to anticipate the vehicle's motion trajectory
- Avoid incongruent visual-vestibular self-motion cues.

Although future research will be required to understand how these principles can be suitably applied in the development of future automated vehicles, the three fundamental principles allow us to propose the following initial design considerations [1, 2].

To enable anticipation, window surface areas (also known as Day Light Openings) should be maximized, whereas obstruction by A-pillars, belt or shoulder lines should be minimized. Similarly, seating should be at sufficient height to ensure passengers are able to look out of the window. Fully enclosed cabins and rearward facing seating arrangements can also be expected to exacerbate the problem. Future research may also explore the feasibility of artificial enhancement of the visual scene (e.g. Augmented Reality) possible also displaying the future motion path.

Conflicting motion cues can be minimized by locating displays showing content not related to the outside world near the line of sight out of the window, allowing for peripheral vision to gather information on the direction of travel. Likewise, display size should also be limited to allow for sufficient peripheral visual information and reduce the impact of the visual stimulus. Alternatively, see-through or Augmented Reality displays may avoid the problem of obscuration although issues related to visual comfort may be at stake. Finally, display content (i.e. dynamic vs. static) should be aligned to the vehicle dynamics where possible.

4 Conclusions

Vehicle automation has the potential to provide significant advantages to the driver and society. However, motion sickness may negatively affect the successful acceptance, especially at the critical introductory phase of this technology. Furthermore, it should be acknowledged that motion sickness may have additional consequences [2]. It can compromise task performance and therefore affect the drivers' ability to regain vehicle control. Aftereffects may negatively affect an individual's ability to engage in safety critical activities. Finally, it may prevent the anticipated increase in road capacity if automated vehicle control algorithms need to be tuned to avoid motion sickness. To avoid, or at least limit, the occurrence of motion sickness in automated vehicles and to tackle the problem systematically, it is imperative that we recognize and understand the basic underlying perceptual mechanisms. Future automated vehicles cannot be simply thought of as living rooms, offices, or entertainment venues on wheels.

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