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## Abstract
Self-driving cars have the potential to bring significant benefits to drivers and society at large. However, all envisaged scenarios are predicted to increase the risk of motion sickness. This will negatively affect user acceptance and uptake and hence negate the benefits of this technology. Here we discuss the impact of the user interface design in particular, focusing on display size, position, and content and the relationship with the degree of sensory conflict and ability to anticipate the future motion trajectory of the vehicle, two key determinants of motion sickness in general. Following initial design recommendations, we provide a research agenda to accelerate our understanding of self-driving cars in the context of the scenarios currently proposed. We conclude that basic perceptual mechanisms need to be considered in the design process whereby self-driving cars cannot simply be thought of as living rooms, offices, or entertainment venues on wheels.

## Author Keywords
Vehicle Automation; Design; Displays; Motion sickness; Carsickness; Sensory conflict; Anticipation.

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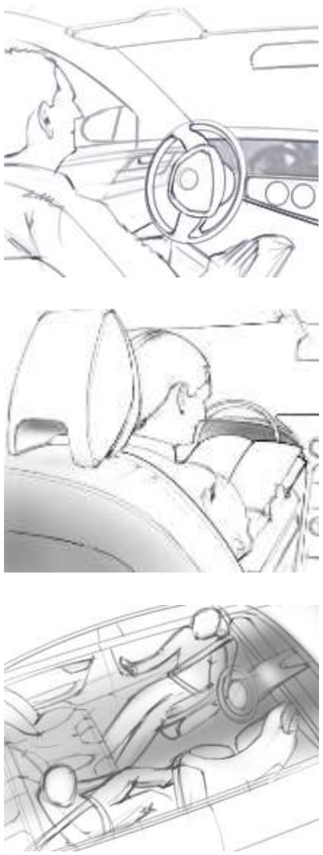

Figure 1: Illustration of the three main scenarios for automated vehicles: Transition from active driver to passive supervisor / passenger (top); Engagement in non-driving tasks (middle); Rearward-facing seating arrangements (bottom). Illustrations by Aamer Mahmud.

## Introduction

Self-driving cars have the potential to provide significant advantages to the driver but also society at large. Regarding the latter, self-driving cars are expected to lead to a reduction in vehicle crashes, congestion and associated energy consumption and air pollution, whilst improving traffic throughput, journey time reliability, and providing personal mobility for those unable or unwilling to drive. For these benefits to materialize, however, it is imperative that self-driving cars also bring clear benefits to the driver. Without this, automated vehicle technology may not generate the required interest and uptake and subsequent socioeconomic benefits. The benefits from the driver’s perspective largely constitute of an increase in comfort and/or productivity as the driver is able to engage in non-driving activities such as responding to emails, preparing a meeting, or simply sit back, relax, and listen to music.

However, on the basis of both existing data and theoretical underpinnings, we have argued that all scenarios currently envisaged for self-driving cars will significantly increase the likelihood that drivers/users will experience signs and symptoms of motion sickness such as sweating, burping, salivation, apathy, nausea and retching [1,2]. As such, the proposed increase in comfort and productivity may not materialize due to the occurrence of motion sickness, or better, “self-driving carsickness” [2].

The relevance of self-driving carsickness lies in the fact that its occurrence may hamper the successful introduction of vehicle automation. Most significantly, signs and symptoms of motion sickness may prevent the driver from activating the automation or engage in non-driving tasks. As such, the advantages of vehicle automation in terms of comfort and productivity may not be realized, reducing the perceived benefits and subsequent acceptance of this technology. In addition, self-driving carsickness may negatively impact an individual’s task performance [3] which, in turn, may compromise his or her ability to effectively and safely switch back from automated to manual vehicle control. Thirdly, following the use of self-driving cars, aftereffects may negatively affect an individual’s ability to engage in subsequent safety critical activities [3]. Finally, self-driving carsickness may prevent the anticipated increase in road capacity if automated vehicle control algorithms need to be tuned to avoid self-driving carsickness [4].

We have coined the term “self-driving carsickness” to reflect its multifaceted etiology in comparison to traditional carsickness. To appreciate the range of potential causes of self-driving carsickness it is instructive to consider the three scenarios currently considered to deliver comfort and productivity to the driver/user: 1) Transition from an active driver to a passive supervisor or passenger; 2) Engagement of the driver in non-driving tasks; 3) Rearward facing seating arrangements. As illustrated in Figure 1, it is these three fundamental scenarios that have led to the development of several concept vehicles and prototypes by both design consultancies [5] and Original Equipment Manufacturers (OEMs) [6]. As will be discussed in the following section, these fundamental scenarios will create conditions that are conducive to the occurrence of motion sickness. We will show that the design of the User Interface (UI) plays a particularly important role in the etiology of self-driving carsickness. We subsequently provide initial design considerations and propose areas for future research to better understand self-driving carsickness to ultimately facilitate the successful introduction of vehicle automation.

## User Interfaces and Self-Driving Carsickness

It is reasonable to expect that people's "spare time" will be used to work or consume media using integrated or nomadic devices such as tablets, laptops, or in-vehicle displays. The role of the UI in the context of self-driving carsickness can be two-sided. Whereas on the one hand it may exacerbate the situation, it also has the potential to mitigate the occurrence or severity of self-driving carsickness. In the following, both effects will be referred to in the context of respectively incongruent and anticipatory self-motion information (or ego-motion) provided by the UI.

*UIs Displaying Incongruent Self-Motion Information*

Self-driving carsickness occurs when self-motion information sensed by the visual system is incongruent with the self-motion information perceived by the vestibular system. At the extreme end of the scale, this situation may occur in self-driving vehicles in which windows have been replaced by displays, or alternatively, users wear Head Mounted Displays (HMD), which in both cases will enable them to be fully immersed in a Virtual Environment (VE). Sensory conflict will for example occur under conditions in which the UI displays static information (e.g. virtual vehicle interior, visual scene or pattern) with the vehicle driving at varying velocities (e.g. start stop traffic, winding roads): the visual system will signal the body to be stationary, whereas the vestibular system will signal the body to be in motion. Perceptually, this situation is identical to being below deck aboard a ship which we have known to lead to motion sickness for centuries [7].

Of more immediate concern is the situation where users are expected to consume media content via nomadic or integrated UIs that cover a smaller Field Of View (FOV) in otherwise standard interior vehicle layouts. Examples of this would include the use of tablets, laptops, or displays integrated in the dashboard when in autonomous mode. Similar to reading a book whilst driving, the static scene as perceived by the (central) visual system may be incongruent with the vehicle dynamics perceived by the vestibular system. From previous research into reading while driving [8] and the viewing of rear-seat entertainment displays [9], we already know that these conditions significantly increase motion sickness.

At this point, it is appropriate to note that the occurrence of self-driving carsickness is 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 [10]. 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. Under conditions of constant motion, sickness is therefore less likely to occur when reading or using UIs. However, the moment dynamic media content is introduced, sensory conflict may of course occur under both constant and varying velocity motion profiles.

*Anticipation of Future Motion Trajectory*

With vehicle control taken over by the automated vehicle, the driver effectively becomes a passenger. It is commonly known that drivers of cars, pilots of aircraft, or people immersed in Virtual Environments who are in control of their own movements are usually far less susceptible to motion sickness than passengers, or passive users are [11]. It logically follows that automation will increase the occurrence of motion sickness amongst drivers, now passengers. The moderating effect of control on motion sickness is related to the ability to anticipate the future motion path or trajectory. The difference between drivers and passengers 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 [12]. We refer to [2] for a more detailed explanation of the underlying mechanisms. However, for the purposes of this paper it is important that this anticipatory mechanism may not only be at play when individuals are able to motorically anticipate incoming sensory cues via pedals and steering wheel input, but also on the basis of visual information alone. Although with a reduced level of accuracy, a clear view of the road ahead will allow for the prediction of the future motion path and a subsequent reduction in sensory conflict. Recently, the effectiveness of anticipation on the basis of visual information was demonstrated by [13], in which no less than a fourfold reduction in motion sickness was demonstrated when a visual track to be travelled was presented in a motion simulator. The importance of anticipatory visual information is furthermore suggested by the anecdotal evidence that backward looking passengers suffer more from carsickness than forward looking passengers, the former only seeing the trajectory that has been followed, the latter seeing the trajectory that will be followed. The importance of visual information per se is also demonstrated by the fact that rear seat passengers are particularly prone to car sickness under conditions where external visual views are limited [14]. From the above, it becomes apparent that all the scenarios envisaged for self-driving cars have consequences for the occupants' ability to anticipate the future motion trajectory and, as such, the lack thereof may prove to be one of the most important factors in the development of self-driving carsickness. When traveling in autonomous 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, including that of a "passive" driver.

## Design Considerations

On the basis of existing research and our theoretical understanding of motion sickness, below we provide guidelines related to three key UI design considerations, namely size, positon, and content.

*Size*

Size matters for two reasons. Larger displays will provide stronger visual motion cues (static or dynamic) and therefore potentially lead to larger sensory conflict [10,15]. Secondly, larger displays may block out more of the view of the road ahead and thereby reduce the ability to anticipate the future motion path. The use of displays covering a relatively small FOV should therefore be preferred.

*Position*

Display position can be expected to have a significant impact whereby displays located near the out the window line of sight will be less likely to lead to sickness in comparison to displays located lower down in the vehicle. Displays located along the line of sight will better enable users to view the content of the display with their central vision, whilst still being able to use peripheral vision to gather information on the direction of travel and changes in velocity. Of course, the effects of display size and position are not independent.

*Content*

Ultimately, the content displayed will determine the degree of visual-vestibular congruence and associated sensory conflict. As a general rule, dynamic or static display content should be avoided in constant or varying velocity driving scenarios, respectively. The impact of content will furthermore be positively correlated to display size. Under conditions in which visibility is compromised, providing visual information that correctly indicates the direction of travel may prove to be effective in reducing motion sickness. As shown by [13], providing visual information via an Augmented Reality display significantly reduced the level of motion sickness. In a similar vein, the integration of displays in the interior (e.g. door cards) showing congruent motion information may be effective in avoiding sickness [16]. Finally, presenting content via see-through displays may avoid the aforementioned problems although the type of media displayed is likely to be limited.

## Future Research

The development of measures to minimize the severity of motion sickness, or avoiding its occurrence altogether, is expected to become an important line of automotive research to ensure the uptake and acceptance of self-driving cars. Moreover, this 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, as happened several times with the introduction of 3D-TV, for example. In order of importance, we have identified the following key research areas:

- Establish the scale of the problem, i.e. the incidence and severity of self-driving carsickness in the three fundamental scenarios identified.
- Understand the “forgiveness” provided by different motion profiles (i.e. constant vs. varying velocity vehicle motion) as a function of display content (i.e. static vs. dynamic).
- Understand the impact of display size and location related to the effectiveness of peripheral visual information in anticipating the future motion trajectory and limiting sensory conflict.
- Explore the feasibility of alternative display technologies that enable superposition of display content on the view of the outside world (e.g. see-through or Augmented Reality displays).
- Explore the use of additional visual information provided via artificial enhancement of the visual scene to allow for anticipation of the future motion trajectory.

## Conclusions

Self-driving cars have the potential to provide significant advantages to the driver and society. However, self-driving carsickness may severely jeopardize the successful introduction of this technology. It is therefore imperative to consider basic perceptual mechanisms in the design process since self-driving cars cannot simply be thought of as living rooms, offices, or entertainment venues on wheels.

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