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From car sickness to autonomous car sickness: A review

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ABSTRACT

Motion sickness comprises a set of symptoms, such as nausea, headaches, and disorientation, that affects healthy individuals when undergoing different types of motion, including virtual motion. The ways of mitigating motion sickness is a controversial issue as it strongly depends on variability among individuals due to anthropometric, physical as well as physiological traits, making it difficult to identify and derive a universal solution. With the introduction of autonomous vehicles, we are moving from car sickness, which is motion sickness induced when riding in cars, to autonomous car sickness, which arises from riding in autonomous vehicles. To ensure advancement of fully-autonomous vehicles, a comfortable experience must be provided to the passengers. An important factor that affects the acceptance of autonomous cars is the capability of passengers to perform non-driving tasks like reading, relaxing, and/or socialising in a comfortable style with no or limited motion sickness symptoms. Drivers, who never suffer from motion sickness while driving, might be, when riding as passengers in autonomous cars, susceptible to motion sickness due to the lack of controllability on the vehicle in addition to sensory conflicts. Therefore, in-depth investigations on the causes of autonomous car sickness are required. In this paper, we present different theories explaining the 'how' and 'why' of motion sickness and then discuss whether these factors are applicable to autonomous car sickness. The adaptation of different motion sickness predictors that can be used to limit autonomous car sickness are also discussed, with a proposal of a framework that provides a viable solution to mitigate autonomous carsickness.

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1. Introduction

Autonomous vehicles (AVs) are pushing their way into our lives and they will soon revolutionise the way our cities are built and managed. AVs are powered by the latest technology in sensing, computing, tracking and controlling (Elbanhawi, Simic, & Jazar, 2015) from the use of computer vision, LIDAR (Light Detection and Ranging), laser, and sonar technologies for obstacle detection and avoidance to the use of Inertial Measurement Units and Global Positioning Systems for localisation Van Brummelen, O'Brien, Gruyer, and Najjaran (2018). These technologies make the roads safer, greener and more fuel-efficient, contributing towards accident prevention in our roads, especially those due to human errors which makes up a large portion of road accidents (Bureau of Infrastructure, 2015). AVs also mean no more wasting time looking for parking, which is good news to urban drivers.

However, AVs face multiple challenges that need to be overcome before they become part of our daily life. Trust is a huge challenge. Trust from the road users either pedestrians or other drivers, in addition to the AV passengers (Saleh, Hossny, &

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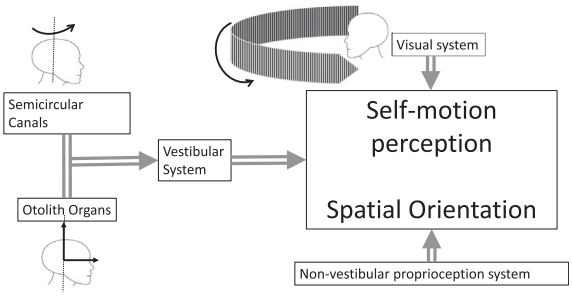

Fig. 1. An illustration of the interaction between different systems that provides the perception of self-motion. The vestibular system, represented by the semicircular canals and otolith organs, distinguishes neck rotational and translational motion. The eyes are stimulated by the movement of a large visual field. Non-vestibular proprioceptive inputs, besides motor control commands contributes to spatial orientation. The mismatch or misalignment between these coupled systems could cause motion sickness symptoms (Iskander et al., 2018; Bertolini & Straumann, 2016).

Nahavandi, 2017) is still under study by the research community. Another challenge is passenger comfort. How comfortable a once-a-driver can be when giving up control is still a major concern for many drivers. In this paper, we focus on motion sickness that can be induced in fully-autonomous vehicles, which we denote as autonomous car sickness.

Humans organise movements in relation to a spatial framework using three sources of spatial information (Donohew, 2006; Howard & Templeton, 1996; Mergner, Hlavacka, & Schweigart, 1993). Excluding auditory information, the sources are (1) proprioceptive inputs, which are derived from trunk and limbs, (2) vestibular inputs, which specify the position of the head, and (3) visual inputs, which establishes a visual framework. These three sensory systems can be viewed as producing three spatial reference systems, which depend upon continuous coordination and alignment with one another (Donohew, 2006; Howard & Templeton, 1996; Mergner et al., 1993), as illustrated in Fig. 1.

Perceptual adaptation (Howard & Templeton, 1996) represents the effect of the mechanisms by which the three systems are constantly aligned and calibrated against each other. Inconsistencies as well as failures of correlation between one type of input and another produce an immediate need to re-align the conflicting systems. Perturbation induced by motion to these coupled systems causes a set of symptoms coined by Irwin (1881) in 1881 as 'Motion Sickness'.

The question of why motion sickness occurs is still not conclusively answered, except that it is a natural response to unnatural environments (Diels, Bos, Hottelart, & Reilhac, 2016; Reason, 1978). There are multiple explanations to how motion sickness occurs; they include the theory of sensory conflict (Reason, 1978), evolutionary theory (Treisman, 1977) and posture instability theory (Stoffregen & Smart, 1998).

While research in motion sickness dates back to the 19th century, it still requires a re-examination, in view of the new development in AVs technologies. In this paper, we study different theories, methods, and strategies to mitigate motion sickness, and analyse how the findings can be integrated in modern AVs. The scope of this study focuses on fully-autonomous vehicles. This is classified as a level-4 autonomy (no steering wheel), according to the National Highway Traffic Safety Administration (NHTSA) autonomy index (Saleh et al., 2017). Therefore, we do not consider human-in-the-loop (HITL) or human-on-the-loop (HOTL) scenarios. We propose a motion sickness resilient framework that uses inputs from the passenger and the vehicle, and, accordingly, change the in-car environment to enhance the passenger's experience and mitigate motion sickness. The influence of car environment design in reducing motion sickness had been discussed in Diels and Bos (2016). However, our proposed framework does not rely solely on using in-car environment designs to mitigate motion sickness, but it also includes real-time adjustment of in-car environments. Our proposed framework contains an infotainment component that controls the type of media displayed to passengers, whether it is a game, an app or a movie clip. The infotainment component will be delivered by information technology companies and not car manufacturers.

The rest of this paper is organised as follows. Section 2 describes different types of motion sickness. Section 3 summarises the theories explaining motion sickness. Section 4 lists detection methods for motion sickness. Section 5 discusses the strategies used to mitigate motion sickness. Section 6 analyses the potential approaches to integrating different methods for mitigation of autonomous carsickness. Section 7 proposes a potential in-car motion sickness resilient framework with a discussion of the different components of the framework. Concluding remarks are presented in Section 8.

2. Types of motion sickness and autonomous cars

Motion sickness nowadays occurs only during travelling. With the advent of alternative types of real and simulated motion, humans experience different types of motion sickness induced by visually moving scenes or simulated motions in virtual environments, or when using different simulators such as flight or driving simulators. AVs constitute yet another source of motion sickness to drivers, who, in normal cars, can escape from motion sickness.

2.1. Visually Induced Motion Sickness (VIMS)

Vection is the sensation of self-motion, which is also known as circular vection, in absence of physical motion (Dichgans & Brandt, 1973). Vection is triggered by a rotating large visual field observed by an immobile observer. This is common, e.g.

when one observes a passing train from a stationary train. The self-motion illusion is always in the opposite direction to the moving scenes. Vection has been reported as a common prerequisite to visually induced motion sickness (VIMS) (Keshavarz, Hecht, & Lawson, 2014). However, vection can occur without VIMS, which is a type of motion sickness that is triggered by viewing a moving scene rather than by physical movements. In addition, VIMS occur in the absence of or with limited physical movements. Vection is useful in simulators and virtual environments to yield the desired illusion of motions. However, VIMS becomes a side-effect that must be mitigated to ensure a safe and comfortable immersive experience. In AVs, VIMS is not plausible since there are physical motions. However, if an immersive experience is used as a way of mitigating motion sickness or even for entertainment, a very accurate synchronisation between the moving scene presented in the virtual environment and the vehicle motion is required to avoid sensory conflicts (Hettinger & Riccio, 1992). Any fluctuation will increase the risk of discomfort and motion sickness. In fact, one of the main issues of AVs is the absence of vection, due to the absence of a visual input from the outside world.

2.2. Optokinetic Motion Sickness (OKMS)

The optokinetic eye movement system is concerned with holding the image steady on the retina during a sustained low-frequency head movement (Leigh & Zee, 2015). While nystagmus involves an involuntary, rapid and repeated eye movement; optokinetic nystagmus is a reflex triggered by motion of large visual scenes, which produce vection and VIMS. The OKMS is triggered when the head is tilted out of the axis of rotation with respect to the visual scene (Dichgans & Brandt, 1973) due to Psuedo-Coriolis effect (PCE). Coriolis effect (CE) is motion sickness triggered by head tilting during physical body rotations (Lackner et al., 1992), while Psuedo-Coriolis effect (PCE) is triggered by head tilting, without physical rotations, but only perceived self-rotation. The perceived self-rotation is caused by the rotation of the visual scene about a vertical axis (Dichgans & Brandt, 1973) when the subject is stationary. Therefore, the perceived self-motion and head tilting can cause PCE, which leads to motion sickness in virtual environments (Iskander, Hossny, & Nahavandi, 2018). In AVs, the OKMS is not plausible since no rotatory movement is present. However, downward head tilting when reading or using laptop computer can cause CE.

2.3. Seasickness, airsickness, and carsickness

Motion sickness can occur due to oscillating motions as well as varying accelerations (Money, 1970). Sea sickness and air sickness are mainly caused by slowly oscillating vertical motions, while carsickness is caused by varying horizontal accelerations due to braking and/or a rapid change of direction (Furman & Lempert, 2016; Money, 1970). Head movement relative to the body caused by vehicle (e.g. ship, aeroplane or car) motions has been found to be larger in subjects susceptible to motion sickness than in others. Consequently, fixation of the head to the vehicle can dramatically reduce motion sickness symptoms (Money, 1970). In autonomous cars, users are subjected to variation in accelerations. In addition, they tend to engage in different activities that may lead to increased head movements in different directions with respect to vehicle motions, which increase the occurrence rate of motion sickness.

2.4. Symptoms of different types of motion sickness

Motion sickness is commonly characterised by headache, pallor, sweating, nausea, vomiting, and disorientation (Reason, 1978). VIMS symptoms, especially simulation sickness symptoms, are similar to those of motion sickness, but less severe (Kennedy, Lane, Berbaum, & Lilienthal, 1993). In addition, simulation sickness affects fewer people (Kennedy et al., 1993). VIMS symptoms also include dizziness, fatigue, pallor, drowsiness, cold sweat, nausea, vomiting, in addition to oculomotor disturbances (Lawson, 2014). Oculo-motor disturbance is a symptom of VIMS, but it is not associated with motion sickness (Iskander et al., 2018; Stanney & Kennedy, 1997; Stanney, Kennedy, & Drexler, 1997). As reported in Stanney et al. (1997), simulation sickness causes more oculo-motor disturbances whereas cyber sickness causes more disorientation symptoms.

3. Why motion sickness occur?

There are three theories explaining why motion sickness occurs. They are the theory of sensory conflict (Reason, 1978), the evolutionary theory (Treisman, 1977), and the posture instability theory (Stoffregen & Smart, 1998). In the 19th century, Reason and Brand (1975), Reason (1978) attributed motion sickness to the conflict between sensory inputs, (aka sensory conflict theory), where the motion information sensed by the vestibular receptors, the eyes, and the non-vestibular proprioceptors deviates from the expected information based on past experiences. This explained motion sickness as triggered by sensory inputs that deviates from our expectations.

Treisman in 1977 (Treisman, 1977) gave a similar explanation. However, his hypothesis differed in attributing motion sickness to the continuous misalignment between the signals from the spatial frameworks defined by the visual, vestibular, or proprioceptive inputs. He took an evolutionary approach in answering the question of why this misalignment causes motion sickness symptoms. This misalignment is commonly caused by disturbances in motor control or sensory inputs pro-

duced by ingested toxins. Therefore, humans developed the symptoms as an early warning system that would aid in getting rid of ingested toxins. It also provides a mechanism to prevent future mistakes. Vomiting occurs to eliminate the ingested toxins, while nausea and fatigue occurs as a reminder to avoid future encounters with toxic materials (Treisman, 1977). However, when exposed to certain types of motion, similar perturbation and misalignment between the different spatial frameworks occurs, therefore causing the same symptoms (motion sickness). According to Treisman (1977), this is an accidental side effect of the early warning mechanism.

Riccio and Stoffregen (1991) contradicted the sensory conflict theory. They hypothesised that motion sickness could also be caused by prolonged posture control instability. Their theory, thus, attributes motion sickness to behavioural issues rather than sensory stimulation. In Stoffregen and Smart (1998), they studied posture instability induced in subjects by standing in "moving rooms". They found that there was an increase in posture sway preceding the onset of motion sickness symptoms. There was also a significant difference between the posture of susceptible and non-susceptible to motion sickness subjects, even without any motion or perturbation.

There is also a gender difference in tolerance to motion sickness. It has been reported in different studies that women are more susceptible to motion sickness than men (Flanagan, May, & Dobie, 2005). The relationship between postural control, motion sickness, and gender difference was studied in Koslucher, Haaland, and Stoffregen (2016). It was concluded that anthropometric differences between genders could be an explanation to why women are more susceptible to motion sickness. Their results were in agreement with the posture instability theory (Riccio & Stoffregen, 1991). On the other hand, personal traits are also correlated with motion sickness susceptibility (Bick, 1983). The study concluded that males with higher posture steadiness were less susceptible to motion sickness, while females did not show any significant correlations. This finding is aligned with the postural instability theory for males only; where as the same did not apply to females. On the other hand, they reported that neuroticism in females was significantly correlated to motion sickness susceptibility, while this was not found in males. However, the results are not conclusive due to the small sample size used, namely 15 males and 15 females. The gender difference was further studied with respect to the female menstrual cycle in Matchock, Levine, Gianaros, and Stern (2008) and Golding, Kadzere, and Gresty (2005). The studies suggested that hormonal fluctuations may mediate motion sickness symptoms. Consequently, the correlation between neuroticism and motion sickness in females can be tracked down to hormonal fluctuations due to the menstrual cycle.

It is important to note that vestibular stimulation is a necessary factor for motion sickness to occur (Cheung, Howard, & Money, 1991; Treisman, 1977). Motion sickness does not occur when the vestibular system is destroyed or the eighth nerve is cut. Moreover, the visual system alone cannot induce motion sickness when the vestibular system is defective; therefore a misalignment between visual and proprioceptive inputs is not enough to cause motion sickness. This leads to the assumption that they are only loosely coupled in the absence of the vestibular system. The importance of the vestibular system was further emphasised by the finding that during motions, i.e. when the susceptible subject had larger head movements relative to the body, the severity of motion sickness was decreased when the head was held immobile (Gordon, Spitzer, Doweck, Shupak, & Gadoth, 1996).

4. Detecting motion sickness

Motion sickness symptoms are commonly measured using the Pensacola Motion Sickness Questionnaire (MSQ) (Kellogg, Kennedy, & Graybiel, 1964). Simulator Sickness Questionnaire (SSQ) is a modified version of MSQ, which aims to better measure symptoms caused by VIMS (Kennedy et al., 1993). However, both are post-experience methods. The Fast Motion Sickness Scale (FMS) (Keshavarz & Hecht, 2011; Reinhard et al., 2017) is a fast and during-exposure scale for measuring motion sickness. The subjects give a 20-point verbal ratings of experienced motion sickness symptoms every minute.

Many advances have been made to predict the occurrence of motion sickness through objective measures. However, optimal methods are yet to be found. As stated in Shupak and Gordon (2006), an improved model can include human-related characteristics such as gender, age, and personality traits. The use of a single multivariate equation to represent the complex process that leads to motion sickness was proposed (Shupak & Gordon, 2006). Nevertheless, a single parameter model for predicting of motion sickness susceptibility is yet to be established (Shupak & Gordon, 2006). Different objective measures have been addressed in several studies as discussed in the following sub-sections.

4.1. Physiological signals

Increased salivation is a common reported sign of motion sickness. However, contradictory reports can also be found, i.e. a decreased salivary rate increases the severity of motion sickness (Shupak & Gordon, 2006). Heart rate variability (HRV) parameters provide an objective measure of autonomic response to motion sickness, as it significantly differentiates between subjects who are susceptible or insusceptible to motion sickness (Doweck et al., 1997; Yokota, Aoki, Mizuta, Ito, & Isu, 2005). Other objective measures, which include skin conductance, electrogastrogram (EGG), electroencephalography (EEG) (Hu et al., 1999), electrocardiography (ECG) (Shupak & Gordon, 2006; Warwick-Evans et al., 1987) have been used individually or collectively to determine the severity of motion sickness. However, more studies are required, especially in the case of autonomous car-sickness, to identify the main factors that can detect the onset of autonomous car sickness.

4.2. Vestibulo Ocular Reflex (VOR) parameters

The vestibulo-ocular-reflex (VOR) factors were studied (Nachum, Gordon, Shahal, Spitzer, & Shupak, 2002); and a significant difference was found in VOR phase lag between sea sickness-susceptible and sea sickness nonsusceptible subjects. In sea sickness susceptible subjects, a higher phase lag was found. This indicates that a lower vestibular response is a characteristic of sea sickness susceptible subjects. However, no defined value could be found to differentiate the susceptible and non-susceptible subjects due to a broad overlapping area (Nachum et al., 2002). On the other hand, recent advances in ocular biomechanics modelling and simulation (Iskander, Hossny, Nahavandi, & Del Porto, 2018) provide a test bed for simulating VOR and assessing the suitability of vehicle dynamics in reducing motion sickness. To evaluate VOR, the Sinusoidal Harmonic Acceleration (SHA) (Gordon et al., 1996) test at different frequencies was used, in addition to the vestibular autorotation test (VAT) (Nachum et al., 2002).

4.3. Posture stability

Smart, Stoffregen, and Bardy (2002) indicated that postural instability is associated with motion sickness, and measuring posture instability can be a predictor of motion sickness. In the absence of visual and sensory feedback, postural sway was strongly correlated to motion sickness (Owen, Leadbetter, & Yardley, 1998). It has been found that subjects with lower susceptibility to motion sickness are not affected by visual induced motions. This implies that they depend on proprioceptive, vestibular cues, and not visual cues for postural balance (Yokota et al., 2005). This emphasises the effect of personal differences and adaptation differences on susceptibility to motion sickness.

5. Mitigating motion sickness

There are several pharmacologically effective solutions available to mitigate motion sickness. Nevertheless, most of them have inevitable side effects, which often include drowsiness and decrease in psycho-motor performances (Shupak & Gordon, 2006). Some solutions even rely on the placebo effects of sugar pills or herbal recipes (Holtmann, Clarke, Scherer, & Höhn, 1989). In this paper, we focus on non-pharmacological methods to mitigate motion sickness by reducing the conflicting sensory inputs, enhancing sensory adaptation, or promoting psychological factors that induce coping mechanisms.

5.1. Visual cues

Anchors, also known as visual cues, have been used to relieve individuals experiencing motion sickness when riding a car. Anchors are static objects in the real world on which the individual can focus on, such as watching trees passing during a train ride, or a focusing on one point as a ballerina performs pirouette. Anchors help the brain to perceive the movement; therefore, reducing the conflict between the vestibular and perceptual systems.An artificial horizon projected in a closed cabin rooms of a ship simulators was found to reduce seasickness symptoms, but did not enhance performance (Tal et al., 2012). Visual cues are also useful to alleviate simulator sickness (Jeng-Weei Lin, Parker, Lahav, & Furness, 2005).

In 2014, Curtis (Curtis, 2014) explored various techniques to mitigate motion sickness within virtual reality. He found that the mitigation methods used in the physical world can be effectively used in virtual environments. He studied two methods, a hand-eye coordination activity and a natural decay task. In the hand-eye coordination activity, the subjects placed pegs on a board while in the natural decay task, the subjects were asked to sit still until the motion sickness faded. The natural decay method was effective, while the hand-eye coordination was less effective when it was performed in the virtual environment.

Turner and Griffin (1999) indicated that motion sickness increases with increased exposure to low frequency lateral accelerations, especially in situations with a poor frontal view of the external road. A significant reduction of motion sickness can be achieved by an improved forward view. However, providing a good forward view of the external road does not eliminate motion sickness entirely. This is in accordance with the sensory conflict theory of motion sickness, since with no forward view of the road, the visual cues are static while a dynamic motion is sensed by the vestibular system (Turner & Griffin, 1999). The susceptibility to motion sickness in this case depends on the frequency of travel (especially for first-timers or new users), seat location (rear seats are more affected by lateral accelerations,therefore a better forward view can reduce motion sickness).

Recently, it has been found that completely eliminating the visual input could delay the onset of motion sickness or reduce its severity (Ishak, Bubka, & Bonato, 2018). The findings are in accordance with the sensory conflict theory, since the visual occlusion weakens the effect of the visual input; therefore reducing the conflict, and reducing motion sickness. However, it is not a practical solution in AVs, since this means that passengers would have to keep their eyes close or wear dark goggles during the entire trip, which undermines any benefits of using AVs. However, this can be a temporary state to relieve motion sickness symptoms.

5.2. Posture and vehicle controllability

Fukuda (1976) pointed out that drivers and experienced passengers were less susceptible to motion sickness when they adopted what he called a 'centripetal posture'. This means that they rotate their head and upper body to face the direction of rotation of the vehicle. Active head tilt was further investigated and found to be able to reduce motion sickness (Wada, Konno, Fujisawa, & Doi, 2012) in passengers. Moreover, in traditional cars, where drivers have control on the vehicles speed and direction, drivers do not suffer from motion sickness. In Rolnick and Lubow (1991), the study found that controllability on the vehicle motion was correlated with an increased immunity to motion sickness.

5.3. Immersive experience

In March 2018, a patent filed earlier by *Apple Inc.*, aimed to address the use of virtual reality (VR) (Rober et al., 2018) in AVs, was published. The objective of the immersive virtual display (Rober et al., 2018) is to replace the real world with a virtual world that matches the visual cues with vestibular and sensory information; therefore, eliminating the conflict of sensory inputs. VR can be altered according to the user preferences and states, which indicates an alteration in the virtual scenes to accommodate signs of motion sickness. Investigating the usability of VR inside cars, the study in McGill, Ng, and Brewster (2017), found that there is no one-solution-fits-all in terms of virtual presentations that both mitigate car sickness and increase immersion, and, most importantly, fit all passengers (susceptible and non-susceptible to carsickness).

6. Autonomous carsickness

In this paper, we have discussed the different theories explaining why motion sickness occurs. We have also discussed different ways to detect, mitigate, and/or reduce the effects of motion sickness. It has been concluded (Shupak & Gordon, 2006) that a multi-variant equation including different physiological measures can be a good predictor of susceptibility to motion sickness and a predictor for the onset of motion sickness during exposure to sensory-conflict. This can be extended into the case of AVs, to provide a comfortable experience. In this section, we narrow down the discussion to AVs and autonomous car sickness.

AVs provide a solution to multiple problems in our lives, as they are predicted to make our roads greener, safer and less prone to accidents. In addition, they provide humans with a way to save time; and they also provide an independent transportation opportunity to children (Lee & Mirman, 2018) and people with disability (Ferati, Murano, & Giannoumis, 2017). Therefore, the spectrum of potential users of AVs is wide. One of the main challenges to the wide spread use of AVs is the increased susceptibility of passengers to motion sickness. Motion sickness may be induced in once-driver-now-passenger scenario, due to the lack of controllability besides the sensory conflict effects. This can be the most challenging barrier to the acceptability of AVs (Fukuda, 1976; Rolnick & Lubow, 1991).

Considering Treisman's evolutionary-based explanation of motion sickness (Treisman, 1977) and the sensory conflict theory (Reason & Brand, 1975), we anticipate that with the increased use of AVs a new generation would appear with less susceptibility to motion sickness. Riding, in AVs would become a habit, and immunity to motion sickness would be developed (Turner & Griffin, 1999). However, until then, how can we make riding in AVs as comfortable as possible, and to become a habit? Most importantly, if we are to introduce mitigation algorithms, would that deprive us or the future generations from developing the necessary skills to accommodate motion sickness in AVs?

Motion sickness is still a controversial issue as it strongly depends on variability between individuals, due to the underlying physical and physiological traits, making it difficult to find a universal solution. Therefore, investigations on different solutions are conducted to reach a satisfactory outcome. An integration of multiple simpler solutions need to be studied. Individual differences between humans make the causes and effects of motion sickness variable and dependent on personal differences. It is highly improbable to formulate a one-solution-fits-all answer. The results from the VR in-car study (McGill et al., 2017) shares the same finding. The best solution is a customised solution, whether it is a customisable virtual in-car environment or a modifiable in-car environment.

A personalised, highly-customisable solution has been recently provided by *Apple Inc.* (Rober et al., 2018). The solution provides an alternative VR that matches the sensed motion to mitigate motion sickness. The virtual environment is claimed to be customised according to individual preferences and it changes when signs of motion sickness are detected in passengers. However, as interesting as an alternative reality solution seems, it limits passengers to that virtual immersive experience only. No other forms of human communication might be possible, except through the VR realm. Passengers in AVs may be after different activities that VR may not be able to provide. In addition, whether VR can meet all the needed communication, entertainment and productivity aspects of passengers with high fidelity, is still unknown. Besides that, there is a possibility that passengers could suffer from cybersickness during immersion (Iskander et al., 2018). This solution might be very useful for scenarios with short travel times through a very controlled environment, such as the currently trending Hyper-Loop (Pierce, 2017) for accelerated personal mobility.

We can summarise the potential sources of autonomous carsickness into five categories, as shown in Table 1. They include (1) varying horizontal acceleration which is the major cause of carsickness (Furman & Lempert, 2016; Money, 1970); (2) posture instability or the loss of posture stability control as implied by the posture stability theory (Riccio &

Stoffregen, 1991; Stoffregen & Smart, 1998); (3) the loss of controllability, as introduced in Rolnick and Lubow (1991) and Fukuda (1976) and the loss of anticipation of motion direction which arises when a frontal view of the road is absent and no visual cues are given; (4) head downward inclination, as during reading, texting, or working on a laptop, which increase incidence of motion sickness especially with excessive vehicle rotation (cornering) due to CE (Lackner et al., 1992); and finally (5) the lack of synchronisation between virtual motion and the vehicle motion profile, when using very large screens or VR headsets;

Solutions can be categorised into two groups: prevention solutions and mitigation solutions. The prevention solutions includes human behaviour adaptation factors and vehicle control factors. The human behaviour adaptation factors include but are not limited to,

- posture steadiness by preventing sway (Stoffregen & Smart, 1998); and
- centripetal posture as proposed by Fukuda (1976).

The vehicle control factors include but are not limited to

- constant speed or smooth acceleration/deceleration profile (Le Vine, Zolfaghari, & Polak, 2015);
- elevated central display position; and
- seats with fixating head rests

The mitigation solutions are based on monitoring the state of passengers and then either performing an automatic adjustment to the in-car environment or recommending adjustments through audio or visual media. An example of the potential mitigation framework to autonomous carsickness is illustrated in Fig. 2.

7. Motion sickness resilient framework

Considering the rapidly growing involvement of information technology companies in car manufacturing, we believe the components of mitigating autonomous carsickness would most likely be based on new advancements in wearable computing, vehicle entertainment systems and a powerful as well as flexible framework for publishing third party health and well-being software applications (apps) that can, and should, mitigate motion sickness.

The components of the mitigation solution, as shown in Fig. 2, are passenger-centric physiological input; vehicle-centric input; vehicle-centric adaptation solution; and an interactive vehicle entertainment (infotainment) app-developing framework.

Table 1
Factors that might cause autonomous carsickness.

#	Factor	Description	Related Publications
(1)	Variation in horizontal acceleration	This factor is common in traditional carsickness when sudden braking and cornering occurs. It can also happen in autonomous cars. It can be avoided or reduced by maintaining a constant speed as long as possible	Money (1970), Furman and Lempert (2016), and Le Vine et al. (2015)
(2)	Posture instability	According to the posture instability theory, posture instability is the main driver of motion sickness, and a predictor of the onset of motion sickness symptoms. This can be solved by adding head rests to seats that fixates the head and neck to avoid/reduce lateral sway	Riccio and Stoffregen (1991), and Stoffregen and Smart (1998)
(3)	Loss of controllability and loss of anticipation of motion direction	Loss of controllability on the vehicle and engagement in other activities is linked to increased incidence of motion sickness occurrence in once-driver-now-passenger. This can be avoided/reduced through informing passengers on change of motion direction via audio/visual media. In addition, seat readjustment to face direction of motion when turning or cornering can also be useful	Fukuda (1976), Rolnick and Lubow (1991), and Turner and Griffin (1999)
(4)	Head downward inclination	Engagement in other activities other than driving, like reading and working on laptops might cause a head tilt downwards leading to Coriolis effect motion sickness. This can be avoided/reduced through designing book stands and displays at eye level. They must not completely block peripheral vision, since motion cues can be detected through peripheral vision to avoid sensory conflict	Lackner et al. (1992), Karjanto et al. (2018), and Diels and Bos (2016)
(5)	Lack of synchronisation between virtual motion and the vehicle motion profile	Virtual Reality or Augmented Reality have been introduced as a possible engagement solution in autonomous cars. However, they can pose a risk of increased motion sickness if the motion of objects and the visual scene produced in the virtual environment does not synchronise with the motion felt by the passenger due to the vehicle motion. The same applies when using very large screens that prevents the perception of any motion cues from the external environment	Rober et al. (2018)

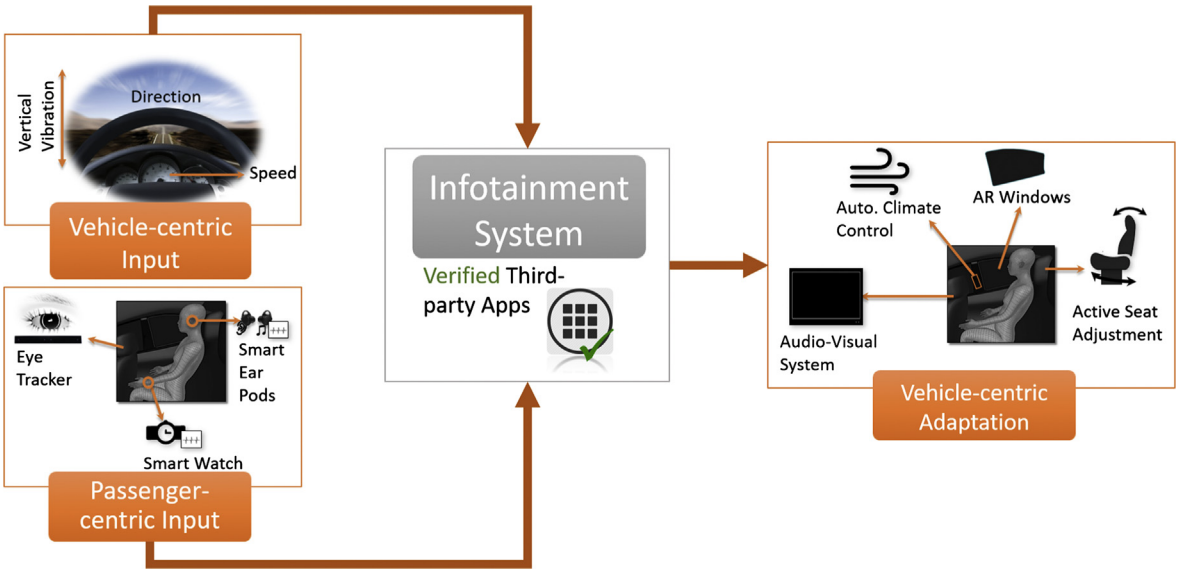

Fig. 2. A potential passenger-vehicle system to mitigate autonomous carsickness. The proposed system is based on an infotainment system comprising special third-party apps that use information gathered from the vehicle and passenger's vital signs, and produce car/environment adjustments to prevent/mitigate motion sickness symptoms.

7.1. Passenger-centric component

The data collected from the passengers are provided as the inputs to the infotainment system through measuring their physiological parameters. The collected data aid in detecting the onset of motion sickness. The physiological parameters, which include heart rate, heart rate variability, respiration and skin temperature, can be measured using wearable devices (Zheng et al., 2014) such as Apple Watch or Fit-bit or even more specialised sensors. Off-body sensors like marker-less or kinect-based motion capture systems can also be used to detect posture and head movements (Abobakr et al., 2017). Posture estimation incorporated with eye trackers, can be used to detect VOR parameters. In addition, thermal cameras can be used to measure skin temperature fluctuation, which can be a detector of sweating that accompanies motion sickness (Ioannou, Gallese, & Merla, 2014). Other measurements of physiological signals can also be integrated like EEG, among others. However, EEG and ECG might induce discomfort to passengers as they are more invasive and require wearing specific devices, mainly with skin-contact. Functional near infrared spectroscopy (fNIRS) (Irani, Platek, Bunce, Ruocco, & Chute, 2007; Soltanlou, Sitnikova, Nuerk, & Dresler, 2018) is a trending neuroimaging technique that is less invasive than EEG and yet is useful for detecting various cognitive and mental states (Strait & Scheutz, 2014) and also studying cognitive developments (Soltanlou et al., 2018) and brain disorders (Irani et al., 2007).

The main challenge with motion sickness, however, is still its subject specificity nature. Therefore, a customised solution using wearable devices is perhaps the best way to move forward. With the recent improvements in smart wearable devices, different personalised profiles can be derived for different passengers which allow implementing different mitigation approaches to different passengers in AVs.

Passenger physiological signals will be streamed continuously to the infotainment system that in turn provide appropriate data to the verified third-party apps used.

7.2. Vehicle-centric components

From a vehicle-centric perspective, the proposed system needs vehicle related inputs such as speed; direction; vertical vibration; along with information on in-car environment like temperature and seat position. Autonomous carsickness as well as the traditional carsickness can be largely reduced by maintaining a constant speed and by avoiding of acceleration in speed, as proposed by Diels (2014). Therefore, manufacturers should consider this as an essential factor for the successful acceptability of AVs. Diels and Bos (2016) presented design guidelines for in-car environment that included ensuring a clear view of the road (maximising windows and adequate seat heights), and visual cues for motion anticipation. On the other hand, when using displays, they recommended that the size and location of the displays be chosen such that the passenger's central vision is used for viewing while the peripheral vision is left to collect motion information (Diels & Bos, 2016; Karjanto et al., 2018).

In-car environment should be varied according to the passengers' states. Varying the passenger experience to mitigate motion sickness can include changing seat inclination to decrease the acceleration effects. On the other hand, it is useful to add visual cues for eliminating the sensory conflict by projecting the external view as an artificial horizon (Tal, Wiener,

& Shupak, 2014), presenting motion cues on the displays or using immersive technology to create a VR that compensates the difference between what is seen and what is felt (Rober et al., 2018).

Audio feedback can also be provided to help passengers anticipate changes in motion, like driving on rough terrains. Anticipation of changes in motion can help reduce motion sickness, especially when recommendations of a certain posture change (Fukuda, 1976), or an active head tilt can be given to accommodate the effects of the change. Koo et al. (2015) discussed the question of audio feedback efficiency in semi-autonomous cars. The study concluded that messages that contained 'why' information (why the car is acting that way, e.g. "Obstacle ahead.") gave better driver satisfaction and performance, whereas messages containing 'how' information (how the car is acting, e.g. "Car is braking.") gave decreased performance significantly. However, when combining 'why' and 'how' information, the safest performance was achieved, but drivers expressed increased anxiety and increased cognitive load. Although the study (Koo et al., 2015) discusses semi-autonomous cars, while we focus on fully-autonomous cars in this study, the findings in Koo et al. (2015) are useful when designing motion sickness resilient frameworks for AVs. The audio messages required to help passenger mitigate carsickness may need to carry concise but yet abbreviated messages (Reeves & Nass, 1996; Norman, 1990), in order to avoid overloading or frustrating the passengers with too much or too little information. The main challenge, here, hinges on providing the appropriate amount and type of information to the passengers (Koo et al., 2015; Norman, 1990). Therefore, in-depth studies investigating the effectiveness of audio messages to mitigate autonomous car sickness are required.

Finally, incorporating adaptive climate and environment control in AVs can regulate the breathing pattern of different passengers, in order to reduce the effects of motion sickness (Ziavra, Yen, Golding, Bronstein, & Gresty, 2003; Sang, Billar, Golding, & Gresty, 2003).

7.3. Infotainment software component

The main driver of the research in detecting and mitigating motion sickness would rely on facilitating an application development framework for AVs. This, however, is not likely to be driven by the automotive industry. Automotive manufacturers focus on the road safety aspects of AVs especially after the Tesla and Uber road fatality incidents. On the other hand, considering the recent patent published by *Apple*, there is evidence that the research momentum of information technology companies is more likely geared towards addressing the motion sickness issues. By providing a comprehensive framework for developing solutions, (aka. apps), that monitor and profile the physiological state of the subject, provide access to their music preferences, and operate the entertainment consoles in the vehicles, motion sickness can be predicted, detected and mitigated.

Apple's CarPlay and Google's Android-Auto are both competing for accommodating vehicle interior systems of different automotive makers. Supported by several business models, the software development of both frameworks could allow third party companies to develop more innovative solutions to mitigate motion sickness.

An important point in Diels and Bos (2016) was that media content presented to passengers should reflect the vehicles motion profile to mitigate or eliminate motion sickness. They also pointed out that this is out of the car designers' control. This is why in our proposed framework, we include an infotainment system that provides guidelines and restrictions on third-party contents presented to AV passengers.

The infotainment framework will resemble Apple's App Store or Google Play, but for apps that are played inside AVs. Therefore, verified AV apps need to comply with certain guidelines, which ensure security, privacy and safety. Verified AV apps should conform to guidelines pertaining to avoiding any stimulus that could initiate or aggravate motion sickness symptoms. In addition, AV apps should use different inputs provided by the infotainment system to continuously readjust their contents based on the state of the passengers.

As shown in Fig. 2, the third-party apps will use inputs provided by the infotainment system from the vehicle and the passenger, in order to provide suitable customised outputs to the passengers in the form of AV Apps that may include multimodal interactions (Ferati et al., 2017) (visual, auditory and even tactile interaction). The apps can decrease/increase the speed of contents, show motion cues relative to vehicle motion, or recommend shutting down for a short duration to reduce motion sickness symptoms and prevent aggravation. The outputs can also include adjustment to the in-car environment to better suit the passengers' states, e.g. seat adjustment and/or climate change, as illustrated in Fig. 2. In essence, the outputs should be modulated according to the passengers' states or preferences.

8. Conclusions

This paper re-opens the debate on whether motion sickness in AVs would fade away as more drivers become familiar with giving up control of their vehicles; or that it is a serious source of discomfort that needs to be addressed.

In fully-autonomous cars, where drivers lose their control over the motion of their vehicles, some drivers become susceptible to motion sickness which they never experience before. The discomfort of their experience can be a challenge that need to be mitigated.

While there are several motion sickness detection and mitigation strategies, the real challenge remains in integrating these solutions into AVs in a seamless design that guarantees comfort and privacy of the passengers. Although many predictors for motion sickness have been studied, a general equation that tackles all cases of motion sickness is yet to be estab-

lished. Motion sickness is still, after decades of studies, a controversial topic which creates a huge challenge for designers and manufacturers of AVs.

We have discussed different predictors of motion sickness, which include increased salivation, change in heart rate variability, change in skin temperature or sweating, in addition to vestibulo-ocular reflex parameters and posture sway or instability. Mitigation methods have also been analysed and discussed, which include the addition of visual cues or artificial horizons, adaptation of specific postural behaviour or the use of immersive experiences as proposed by *Apple*. We have initiated a discussion on the potentials of creating a complex framework that takes different inputs from the passengers and modifies the vehicle environment to reduce motion sickness symptoms while still giving passengers the ability to perform any preferable activity without limiting their options.

The information technology industry is more likely to be the main driver of the upcoming research in motion sickness, while automotive makers focus on the road safety related challenges. Additionally, incorporating audio, visual, and haptic cues into the vehicle cabin is most likely to be the adopted approach because of the involvement of different industries, which include wearable computing, entertainment, and social media industries.

Finally, the possibility of entirely eliminating motion sickness in AVs is still a subject for further investigation. More alternative solutions will be proposed in the future as AVs become an inevitable part of the future of human civilisation.

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