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Motion Sickness and Concerns for Urban Air Mobility Vehicles: A Literature Review

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Acronyms and Definitions

ACTH	adrenocorticotropic hormone
AFTE	Autogenic Feedback Training Exercise
AQS	Additional Qualifying Symptoms
BVP	Blood Volume Pulse
C	central
DIZ	dizziness
DRZ	drowsiness
ED	epigastric discomfort
EEG	electrocardiography
EM	Electronic Module
FDA	Federal Drug Administration
g	grams
G	gastrointestinal
HAC	headache
HERA	Human Exploration Research Analog
HRV	heart rate variability
Hz	hertz (a unit of frequency equal to one cycle per second)
ISS	International Space Station
kph	kilometers per hour
min	minute(s)
mm	millimeters
mph	miles per hour
MSAQ	Motion Sickness Assessment Questionnaire
MSSQ	Motion Sickness Susceptibility Questionnaire
NASA	National Aviation and Space Administration
NSA	nausea
OVAR	off vertical axis rotation
P	peripheral
PAL	facial pallor
rpm	revolutions per minute
s	seconds
S	sopite-related drowsiness
SAL	increased salivation
SD	standard deviation
SEM	Sensor Electronics Module
SpO_2	oxygen partial pressure
SSQ	Simulator Sickness Questionnaire
SWT	sweating
TMP	body temperature

UAM	Urban Air Mobility
VMT	vomiting
VR	virtual reality
VTOL	vertical take-off and landing

Motion Sickness and Concerns for Urban Air Mobility Vehicles: A Literature Review

William B. Toscano[1]

Summary

Motion sickness is a general term for a constellation of signs and symptoms, generally due to exposure to abrupt, periodic, or unnatural accelerations, especially when traveling in a vehicle. Motion sickness results from a mismatch of the visual and nonvisual (vestibular and kinesthetic) information, the observed scene and the motion felt or lack of it. Motion sickness onset is associated with a pattern of physiological changes in heart rate, peripheral blood flow, respiration, and skin conductance and the pattern is repeatable for a particular subject but variable between subjects. Demographic factors such as gender and age that affect motion sickness are well known with children, women, and older adults more likely to be susceptible.

Often motion sickness is assessed and quantified using variations of the motion sickness susceptibility questionnaires including the Pensacola Diagnostic Rating Scale and the Simulator Sickness Questionnaire. Even though symptoms are easily identified by such questionnaires, they commonly are subjective. Tools such as these questionnaires for screening individuals susceptible to motion sickness are useful, however, they are only mildly predictive. Moreover, models for predicting motion sickness, which have largely been developed for sea sickness, do not consider task characteristics.

Predictions of motion sickness rates and prevalence for Urban Air Mobility (UAM) vehicles are not possible at present because data from actual flight or full-fidelity simulation are simply not yet available. Extrapolation from other modes of transportation (i.e., automobiles, buses, trains, boats, other types of aircraft) is difficult because of differences in the motion stimulus experienced, trip duration, and other factors. How UAM vehicles will change the social dynamics of passenger interaction and vehicle interior design changes (e.g., seat orientations) is unknown. Should motion sickness prove to be an issue, vehicle design modifications such as having passengers face forward, providing additional seat recline, giving each person their own climate control for airflow, perhaps ensuring the horizon is visible to all passengers (reducing visual occlusion by the headrest) and visually stabilizing displays on carry-on devices (smart phones, tablets, etc.) may benefit passengers. Several commercial companies provide wearable devices for physiological monitoring that have been validated and are suitable for use with passengers in UAM vehicles or high-fidelity simulators. Potential countermeasures for motion sickness include user-worn devices, anti-motion sickness medications, and non-pharmacological approaches such as biofeedback and Autogenic Feedback Training Exercise. Both simulator and in-vehicle UAM research is needed to evaluate the effectiveness of any potential countermeasure.

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1. Motion Sickness Background

Motion sickness is a general term for a constellation of signs and symptoms, generally due to exposure to abrupt, periodic, or unnatural accelerations, especially when traveling in a vehicle. This physiological condition is the consequence of exposure to an unfamiliar motion stimulus in land, sea, or air vehicles, and even space flight (Table 1). Devices designed to simulate these travel conditions—such as flight, car, and ship simulators, as well as 3D motion pictures and virtual reality—may have similar effects. Each sub-type of motion sickness is characterized by its own specific properties.

Overt signs and symptoms of motion sickness include pallor, cold sweating, increased salivation, headache, nausea, and vomiting (Kennedy & Graybiel, 1963; Wiker et al., 1979). The sequence of symptoms, their severity, and evolution depend on the properties of the motion stimulus, as well as the subject's personal susceptibility and ability to habituate. Motion sickness may also cause cognitive impairment, often referred to as "sopite syndrome." This is characterized by symptoms such drowsiness, mood swings (apathy, depression), sleep disturbances, and impaired performance. The syndrome is associated with poor execution of objective psychomotor and cognitive tasks, which is of particular importance in airsickness (Flaherty 1998). The sopite syndrome (severe drowsiness) may occur independently of other well-known motion sickness symptoms, without any accompanying nausea or vomiting.

1.1. Provocative Motion Sickness Stimuli

Table 1. Motion Sickness Situations and Stimuli
(modified from Golding, 2006)

Situations	*Examples of Stimuli*
Land	Cars, buses, trains, subways, carnival rides
Sea	Ships, boats, ferries, survival rafts
Air	Small and large aircraft, helicopters
Space	Shuttle, International Space Station
Optokinetic	Wide-screen cinemas, centrifuge, flight, driving and other simulators, virtual reality systems, head-mounted displays, rotating visual drums, reversing prism spectacles

1.2. Physiological Manifestations of Motion Sickness

Kennedy and Frank (1985) provide a comprehensive listing of the physiological manifestations of motion sickness as shown in Table 2.

Table 2. Physiological Manifestations of Motion Sickness
(modified from Kennedy & Frank, 1985)

Physiological System	*Signs/Symptoms*
Cardiovascular	Changes in pulse rate and/or blood pressure. ↑ blood volume to hands/sensations of warmth and tingling ↓ decrease retinal blood flow/headache, dizziness, nausea ↓ blood circulation to skin of head/facial pallor ↑ blood flow to respiratory and abdominal muscles/deeper breathing
Respiratory	Changes in respiration rate/sighing, yawning, air swallowing.
Gastrointestinal	↓ intestinal and stomach motility/stomach awareness, stomach discomfort, gas, belching, nausea. ↓ salivation/dryness in mouth.
Blood	↑ hemoglobin/constricts blood vessels increasing blood pressure. ↑ pH/lightheaded, nausea, muscle spasms. ↓ carbon dioxide/faster breathing. ↑ 17-hydroxycorticosteroids/stress hormone response. ↑ plasma proteins/nausea and vomiting. ↑ vasopressin/headache and nausea. ↓ blood sugar/severe drowsiness.
Urine	↑ 17-hydroxycorticosteroids/stress hormone response. ↑ catecholamines/stress hormone response.
Visual system	Ocular imbalance/dizziness and disorientation. Dilated pupils/specifically during vomiting. Small pupils/stress response to visually induced motion stimuli. Nystagmus/vestibular disturbance, dizziness, impaired vision.

1.3. Theories of Motion Sickness

Motion sickness symptoms are the result of a conflict between the senses responsible for spatial orientation. This hypothesis is known as the neural mismatch and sensory rearrangement theory (Reason, 1978). It is believed that neural mismatch occurs when there is a difference between current sensory input and expected motion experience. According to the theory, a spatial integration center in the brain compares information arriving simultaneously from the vestibular, visual, and proprioceptive receptor systems (Reason & Brand, 1975). A mismatch between this information leads to symptoms of motion sickness until the sensory input from each of the various systems is reweighted (Tal et al., 2013). n some forms of motion sickness visual input may lead to the conflict. One way of dealing with this is to focus one's gaze on the horizon, which will help ameliorate symptoms to some extent (Tal et al., 2012). Visual input seems to be less important but still important as the blind can get motion sickness. Motion sickness is more likely to occur when movements are slow and involve multiple simultaneous movements along or about different axes (Kraft, 2015). Other potential sources are intra-vestibular conflicts between rotational accelerations sensed by the semi-circular canals and linear-translational accelerations, including gravitational acceleration sensed by the otoliths (Golding, 2006).

Another explanation is the postural instability theory and the importance of the vestibular system in maintaining a stable posture and minimizing swaying (Riccio & Stoffregen, 1991). When the environment changes in ways unrelated to normal movement this leads to problems of maintaining a stable posture.

More complete summaries of the theories explaining motion sickness have been reviewed by many researchers (Reason & Brand, 1975; Kennedy & Frank, 1985; Lawson, 2014; Davis et al., 2014; Bertolini, 2016). Although understanding the etiology of motion sickness is helpful in understanding the broader view, these theories have limited predictive power and limited practical implications (Davis et al., 2014).

2. Motion Sickness Susceptibility

Motion sickness susceptibility is important for research related to motion sickness for two reasons. First, repeating and understanding research results depends on who the participants were. Therefore, having a means to identify the susceptibility of those serving as research subjects is important. Second, there is frequently a need to screen out subjects who are highly susceptible to avoid the consequences of exposing these individuals to provocative motion sickness stimuli.

The original standard questionnaire for this purpose is the Motion Sickness Susceptibility Questionnaire (MSSQ) (Reason & Brand, 1975). That questionnaire is lengthy, and as a consequence, takes some time to complete. It includes instructions and 4 basic questions, followed by 2 pages with 3 large tables each. The first set of questions concern sickness as a child while the second set concern motion sickness as an adult. There is also a page concerning scoring. Golding (2006) examined individual differences using a short version of the MSSQ (see Appendix A). This form was developed by removing items with low motion sickness prevalence such as wide screen movies and head-mounted virtual reality (VR) displays. Research by other colleagues (Lamb, 2015) found the short form a reliable and valid alternative to the long form. Over the past 10 years most researchers have adopted the short form and have used it for screening out susceptible subjects from car simulator studies where motion sickness is likely to occur.

2.1. Quantifying Motion Sickness Symptoms

Motion sickness is a multidimensional quality and although the number of ways in which motion sickness is quantified is limited there is some variety—which makes comparing studies difficult. Short of vomiting, determining the extent of motion sickness is not easy due to considerable variation as to which symptoms are exhibited in an individual and in what order.

The definitive document on quantifying motion sickness is Lawson’s chapter on motion sickness scales in the Handbook of Virtual Environments (Hale & Stanney, 2014), although the highly cited paper by Kennedy (1993) is also important. The focus of many of the earlier studies was not to develop a single motion sickness scale but to identify the attributes of motion sickness.

Most contemporary motion sickness scales trace their origins to research done at the Pensacola Naval Air Station in the 1960s by Graybiel, Kennedy, and others. They began with a checklist of items (nausea, vomiting, dizziness, etc.) that became a list of symptoms on a 0 to 3 scale (Graybiel & Johnson, 1963; Kennedy et al., 1993). Those symptoms are typically assessed every 5 minutes. One of the more commonly cited variations of these diagnostic criteria is discussed in a paper by Miller and Graybiel (1970). Interestingly, over time these diagnostic scales have been referred to by many names including the Pensacola Diagnostic Criteria, the Pensacola Diagnostic Index, the Pensacola Diagnostic Categorization, the Pensacola Diagnostic Rating Scale, the Graybiel Scale, and the Miller and Graybiel Diagnostic Criteria as shown in Table 3.

Table 3. Miller and Graybiel Diagnostic Criteria
(modified from Miller & Graybiel, 1970)

Malaise Category	*Point*	*VMT*	*TMP*	*DIZ*	*HAC*	*DRZ*	*SWT*	*PAL*	*SAL*	*NSA*	*ED*	*EA*
Pathognomonic	16											
Major	8					III	III	III	III	II, III		
Minor	4					II	II	II	II	I		
Minimal	2					I	I	I	I		I	
AQS	1		I, II	I, II	I							I

This scale is based on self-report and experimenter observations with respect to vomiting, subjective body temperature, dizziness, headache, drowsiness, sweating, pallor, salivation, and nausea. A single global motion sickness score can be derived using a complex scoring and weighting system. The symptom of vomiting (VMT) is pathognomonic of motion sickness under the conditions of the test and as such receives the maximum number of points (16). On the other end of the motion sickness spectrum, very minor symptoms of motion sickness are listed in this scale as Additional Qualifying Symptoms (AQS). Included in this symptom category are increased body temperature (TMP), dizziness (DIZ), and headache (HAC). The subject has the option of reporting two levels of increased temperature and dizziness (mild-moderate “I” or moderate-severe “II”). Level of headache is not differentiated with respect to point value. Remaining symptoms of motion sickness (not including nausea) are drowsiness (DRZ), sweating (SWT), facial pallor (PAL), and increased salivation (SAL). Each of these symptoms can be described as mild, moderate or severe, “I”, “II”, or “III” respectively. Symptoms of nausea or any sensations associated with the ‘gut’ can be reported as five separate levels: epigastric awareness (EA), described as increased sensations in the stomach but not considered uncomfortable, is rated as mild “I”; epigastric discomfort (ED), described as *not* nausea but becoming uncomfortable (e.g., lump in throat, knot in stomach), is rated as moderate “II”; and nausea (NSA) , reported as mild, moderate, or severe, “I”, “II”, or “III”, respectively.

As an example of how the total score is computed, if the subject reported a mild headache (1 point), moderate drowsiness (4 points), and severe sweating (8 points) then the total score would be 13 points. Total scores of 1 to 4 points represent minor malaise; scores of 5 to 7 represent major malaise; scores of 8 to 15 represent severe malaise. Scores greater than or equal to 16 points represent “frank” sickness.

Over time, motion sickness researchers tended to shift their test population from military personnel to civilians as well as a shift from physical systems to virtual systems (driving simulators, games, and using VR applications). That shift has led to an emphasis on less severe conditions and to the development of the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). The SSQ form is shown in Table 4 with an example (red ovals) where symptoms were scored on a 4-point scale (None = 0; Slight = 1; Moderate = 2; Severe = 3). Although the scale was intended to be specific to simulator sickness, it has been used more generally for all types of motion sickness and has been validated using simulators for a variety of U.S. Navy fixed-wing aircraft and helicopters.

Table 4. SSQ Form with Example Ratings (red ovals)
(modified from Kennedy et al., 1993)

SSQ Symptom	*Rating*			
1. General discomfort	None	[✓ Slight]	Moderate	Severe
2. Fatigue	[✓ None]	Slight	Moderate	Severe
3. Headache	[✓ None]	Slight	Moderate	Severe
4. Eye strain	None	Slight	[✓ Moderate]	Severe
5. Difficulty focusing	[✓ None]	Slight	Moderate	Severe
6. Salivation increasing	[✓ None]	Slight	Moderate	Severe
7. Sweating	None	[✓ Slight]	Moderate	Severe
8. Nausea	None	Slight	Moderate	[✓ Severe]
9. Difficulty concentrating	[✓ None]	Slight	Moderate	Severe
10. Fullness of the Head	[✓ None]	Slight	Moderate	Severe
11. Blurred vision	[✓ None]	Slight	Moderate	Severe
12. Dizziness with eyes open	None	[✓ Slight]	Moderate	Severe
13. Dizziness with eyes closed	[✓ None]	Slight	Moderate	Severe
14. Vertigo	None	Slight	[✓ Moderate]	Severe
15. Stomach awareness	None	Slight	Moderate	[✓ Severe]
16. Burping	[✓ None]	Slight	Moderate	Severe

This symptom scale was based on the Pensacola Motion Sickness Questionnaire which was partitioned into three subscales (clusters) using factor analysis. The subscales were: *Oculomotor (O)* – general discomfort, fatigue, headache, eyestrain, difficulty focusing, difficulty concentrating, blurred vision; *Disorientation (D*) – difficulty focusing, fullness of head, blurred vision, dizzy (eyes open), dizzy (eyes closed), vertigo; and *Nausea (N*) – general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, burping.

Scores were obtained by simple addition of the unweighted values of the symptoms in each cluster as defined by the correlation coefficients from the factor analysis. Thus, each entry in Table 5 in the weighting columns for N, O, and D was either a 1 (if the correlation coefficient was greater than .30) or a 0 (otherwise). To compute the scale scores, each symptom variable score (0, 1, 2, 3) was multiplied by the appropriate weight (1 or 0) and the weighted values were summed down the column to obtain the weighted total. The N, O, and D scores are then calculated from the weighted totals using the conversion formulas given at the bottom of the table. Summary weights for each subscale (i.e., 9.54 for N, 7.58 for O, 13.92 for D, and 3.74 for Total) are based on a sample calibration consisting of more than 1,100 observations as described by Kennedy (1993).

Table 5. SSQ Weights for Subscales and Example Rating
(modified from Kennedy, 1993)

SSQ Symptom[a]	*Example Rating*[b]	*Subscale Weight (Example Rating)*		
		N	*O*	*D*
General discomfort	Slight = 1	1 (1)	1 (1)	
Fatigue	None = 0		1 (0)	
Headache	None = 0		1 (0)	
Eyestrain	Moderate = 2		1 (2)	
Difficulty focusing	None = 0		1 (0)	1 (0)
Increased salivation	None = 0	1 (0)		
Sweating	Slight = 1	1 (1)		
Nausea	Severe = 3	1 (3)		
Difficulty concentrating	None = 0	1 (0)	1 (0)	
Fullness of head	None = 0			1 (0)
Blurred vision	None = 0		1 (0)	1 (0)
Dizzy (eyes open)	Slight = 1			1 (1)
Dizzy (eyes closed)	None = 0			1 (0)
Vertigo	Moderate = 2			1 (2)
Stomach awareness	Severe = 3	1 (3)		
Burping	None = 0	1 (0)		
Total score[c]		(a = 8)	(b = 3)	(c = 3)

[a] symptoms scored 0, 1, 2, 3.
[b] example rating from SSQ form (Table 4 – red ovals).
[c] sum obtained by adding symptom scores in each subscale. Omitted scores are zero.

Subscale Scores: N = (a) x 9.54, O = (b) x 7.58, D = (c) x 13.92
Example Subscale Scores: N = (8) x 9.54 = 76.32, O = (3) x 7.58 = 22.74, D = (3) x 13.92 = 41.76

Total Score = (a + b + c) x 3.74
Example Total Score = (8 + 3 + 3) x 3.74 = 52.36

Although research on this topic has been extensive, research continues with emphasis on improved diagnostics, applications to virtual environments, and reducing the number of data points so the data can be collected more quickly. As seen in Table 6, one example is the Motion Sickness Assessment Questionnaire (MSAQ) (Gianaros, 2001) that has 4 scales: gastrointestinal (G), central (C), peripheral (P), and sopite-related drowsiness (S).

Table 6. Motion Sickness Assessment Questionnaire
(Gianaros et al, 2001)

Not at all							*Severely*	
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*

1. I felt sick to my stomach. (G)	9. I felt disoriented. (C)
2. I felt faint-like. (C)	10. I felt tired/fatigued. (S)
3. I felt annoyed/irritated. (S)	11. I felt nauseated. (G)
4. I felt sweaty. (P)	12. I felt hot/warm. (P)
5. I felt queasy. (G)	13. I felt dizzy. (C)
6. I felt lightheaded. (C)	14. I felt like I was spinning. (C)
7. I felt drowsy. (S)	15. I felt as if I may vomit. (G)
8. I felt clammy/cold sweat. (P)	16. I felt uneasy. (S)

The overall motion sickness score is obtained by calculating the percentage of total points scored: (sum of points from all items/144) x 100. Subscale scores are obtained by calculating the percentage of points scored within each factor: (sum of gastrointestinal items/36) x 100; (sum of central items/45) x 100; (sum of peripheral items/27) x 100; (sum of sopite-related items/36) x 100.

Finally, in addition to using combinations of criteria to quantify motion sickness, there have been a number of recent efforts to develop single value estimates independent of the criteria, primarily for ease of application and speed of data collection. These scales are most useful when pinpointing the motion sickness at a specific time, often because the stimulus situation as well as the level of motion sickness are changing quickly. For example, if ratings are collected once per minute there is not enough time to ask about drowsiness, headache, nausea, etc. One complicating factor is that the time course of stimulus events matters. Stress accumulates and declines in response to the application and removal of stressful stimuli. Those changes can be gradual or rapid, may be nonlinear, and these effects may be specific to particular discomfort types or levels (Bock & Oman, 1982). An example of a simple and fast motion sickness rating scale was used in studies by Keshavarz and Hecht (2011). That scale is just a single rating with a range of 0 (no sickness at all) to 20 (frank sickness). In summary, if the motion sickness stimulus is severe, the Pensacola scale—based on its extensive literature—is appropriate. If the motion stimulus is less severe and it involves a simulator, then the Simulator Sickness Scale is appropriate.

2.2. Passenger Demographics Related to Motion Sickness Susceptibility

Some key factors of interest related to motion sickness susceptibility are age, gender, ethnicity, and physical condition. Age and gender differences were addressed in studies by Turner & Griffin (1999a, 1999b) who surveyed 3,256 bus riders, most being infrequent travelers. They reported a rating based on a 4-point scale: 0 = I felt all right; 1 = I felt slightly unwell; 2 = I felt quite ill; 3 = I felt absolutely dreadful. The most important result is shown in Figure 1 with mean Illness rating and mean symptom score calculated as:

$$\text{Mean illness rating} = (N_{\text{slightly unwell}} \text{ X } 1) + (N_{\text{quite ill}} \text{ X } 2) + (N_{\text{absolutely dreadful}} \text{ X } 3) / N_{\text{total}}$$

Mean symptom score was the weighted mean of eight symptoms (nausea, dizziness, vomiting, pallor, headache, increased salivation, feeling hot/sweating, drowsiness). The weights were based on the percentage of each age subgroup who vomited divided by 10. For example, vomiting had a score of 10 if 100% of the age group vomited. The same weighting method was applied to each symptom experienced and a mean of eight symptoms was calculated for each age group. As shown in the figure, the general trends of all three measures are similar: a steady decrease with increasing age for individuals 9 years old or more. These declines are inconsistent with the increases due to age reported by others. Details of the age by gender interaction are not provided.

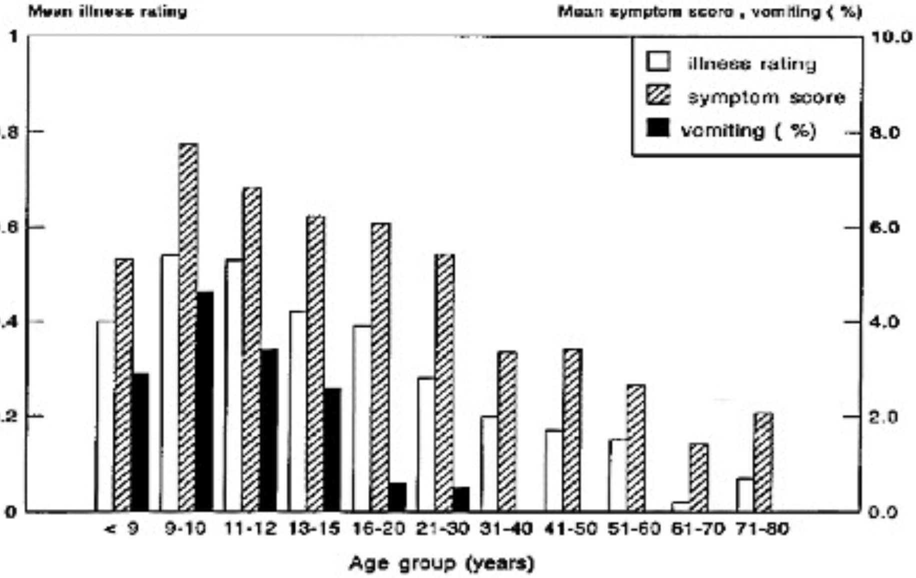

Figure 1. Mean illness ratings and mean symptom scores as a function of age (Turner & Griffin, 1999a).

Lawther and Griffin (1986, 1988a, 1988b) summarized results from a series of studies on motion sickness susceptibility and the effects of age. Motion sickness data were collected from 20,029 passengers on 114 voyages on 6 ships, 2 hovercraft, and 1 hydrofoil. The researchers also collected 370 hours of vessel motion recordings that included vertical (i.e., heave) acceleration. Table 7 shows the age and gender data which was adjusted for exposure as each age and gender subgroup was not equally represented on all types of vessels. This is relevant because there were differences in the size of the vessels, the destinations, and the duration of the trip. To compensate for the unequal numbers of passengers surveyed on each vessel the percentages were weighted with the overall sample size for each vessel before being averaged over all vessels. The weighted average percentages reveal a significant slight trend towards decreased sickness with increasing age. These data also show that women were significantly more likely to vomit than men but there was a decline with age. It should be noted that other factors such as what the passengers ate, whether they consumed motion sickness medications, number of previous trips, etc., may have influenced these results.

Table 7. Percentage of Subjects that Vomited by Age and Gender
(Lawther & Griffin, 1988a)

		Age			
		< 15	*15–39*	*40–60*	*> 60*
Males	n	634	3302	2648	1580
	Vomiting (%)	13.8	5.2	3.5	3.9
Females	n	744	3805	3399	1971
	Vomiting (%)	13.7	9.5	8.1	7.5

There have been a few studies concerning motion sickness and ethnicity. As an example, Klosterhalfen et al. (2005) induced motion sickness in 227 healthy Caucasian and 82 Chinese subjects in a rotating chair. The dependent measure was the time they could tolerate the rotation. The Chinese subjects had a statistically significantly greater mean tolerance (163 vs 111 seconds). The authors reported tolerance to rotation was predicted by the MSSQ, but they did not provide a predictive equation. It is uncertain whether the differences were social (e.g., did not report discomfort), genetic, or due to other factors.

In another study, Dobie et al. (2001) examined the experience of motion sickness of children (9–18) in 13 forms of transport. Unfortunately, they do not present any data on the year-by-year changes in motion susceptibility, possibly because the number of male and female subjects per age group ranged between 16 and 70. However, they do provide gender comparisons of various transport modes (devices) as shown in Figure 2.

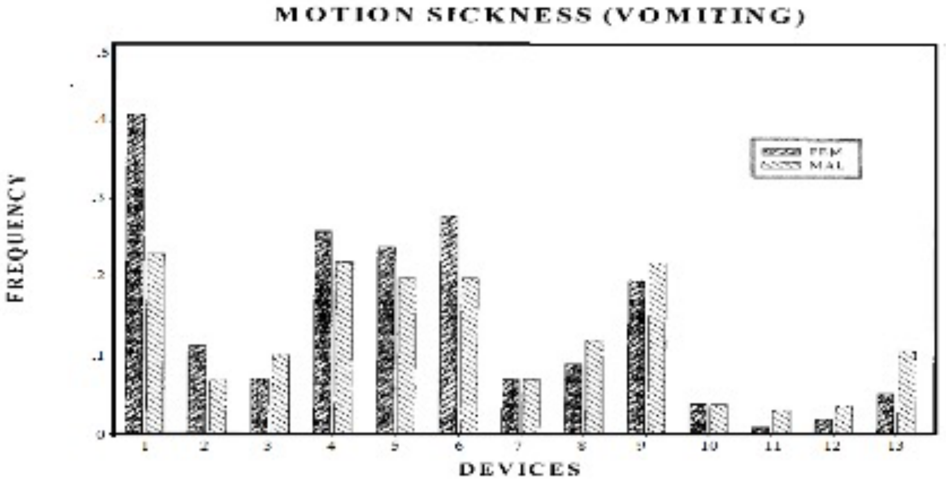

Figure 2. Number of males and females who vomited in each mode of transport. Devices: 1 = automobiles; 2 = buses; 3 = trains; 4 = airplanes in bumpy weather; 5 = small boats; 6 = cruise ships; 7 = swings; 8 = merry-go-rounds; 9 = roller coasters; 10 = elevators; 11 = escalators; 12 = bicycles; 13 = wide screen movies (Dobie et al, 2001).

3. Motion Sickness in Autonomous Vehicles

Diels and Bos (2016, 2015) attempted to predict the likely causes of motion sickness in autonomous road vehicles and, in some cases, the probability it will occur. They identify the key predictive characteristics as being the motion profile of the vehicle, the ability of passengers to anticipate/control the motion (which reduces sickness), the passengers' posture, and the support of non-driving tasks. Their review identified the relevant research involved and discuss only at a very general level some of the design solutions, such as maximizing window surface areas/increasing daylight openings (including using augmented reality as a supplement), and not having passengers face rearward. They also expressed concern about the possible effects of in-vehicle tasks, but they do not provide any estimates of the extent to which such factors may contribute to motion sickness in autonomous vehicles. A number of ways in which the magnitude of in-vehicle task effects can be determined are described in the sections below. These include: 1) asking passengers what they think may occur; 2) evidence from other self-driving car studies; and 3) vehicle characteristics (motion intensity in different axes, seat orientation, passenger external view) and rider activities in other forms of transportation. Some other characteristics influencing the probability of being motion sick are: 1) trip duration; 2) the likelihood that passengers will perform each task (napping, eating, talking on the phone, etc.); and 3) the extent to which each task induces motion sickness.

3.1. Asking Passengers What They Think May Occur

Schoettle and Sivak (2014) attempted to predict the probability that passengers riding in self-driving vehicles will experience motion sickness. Table 8 is a summary of factors involved.

Table 8. Self-driving Vehicle Characteristics that Influence Motion Sickness
(Schoettle & Sivak, 2014)

Contributing Characteristic	*Critical Factor*		
	Conflict between Vestibular and Visual Inputs	*Ability to Anticipate the Direction of Movement*	*Control over the Direction of Movement*
Extent of visual input	• narrow or small windows (-) • opaque or reduced-visibility windows (-) • no conflict when having the eyes closed or sleeping (+)	• narrow or small windows (-) • opaque or reduced-visibility windows (-)	• not relevant for passengers
Direction of gaze	• non-forward gaze (-)	• non-forward gaze (-)	• not relevant for passengers
Posture	• side or rear facing (-) • supine (+)	• side or rear facing (-)	• not relevant for passengers

+ = decreases motion sickness; - = increases motion sickness

Also included in Schoettle and Sivak's report are data from a survey of 3,255 adults, a significant sample, asking them what they would do in a self-driving vehicle if they were not the one driving. As shown in Table 9, the responses differed by country.

Table 9. Percentages of Activities That Subjects Would Perform in a Self-Driving Vehicle
(Schoettle & Sivak, 2014)

Response	*Country*					
	US	*China*	*India*	*Japan*	*UK*	*AUS*
I would not ride in a self-driving vehicle.	23.0	3.1	7.8	33.0	23.0	21.2
Watch the road even though I would not be driving.	35.5	36.1	30.7	33.2	44.0	43.4
Read.	10.8	10.5	10.2	5.6	7.6	6.5
Text or talk with friends/family.	9.8	20.8	15.0	7.4	5.5	7.9
Sleep.	6.8	10.8	4.7	12.6	7.2	7.1
Watch movies/TV.	6.0	11.3	12.3	6.2	4.2	5.7
Work.	4.8	5.4	16.3	0.7	4.9	5.1
Play games.	2.0	1.3	2.1	1.2	1.9	2.0
Other.	1.4	0.7	0.8	0.2	1.7	1.0

To estimate the likelihood passengers will become motion sick, Schoettle and Sivak (2009) used data from a prior study of 136 adults that examined in-vehicle video systems and reading. They asked respondents how frequently they experienced motion sickness from watching in-vehicle video (never, rarely, sometimes, often, usually, always) as well as for reading, and the severity of their symptoms (none, mild, moderate, severe). For the next step in their analysis they pooled the frequency data (often, usually, always) and severity data (moderate and severe) to estimate percentages of passengers expected to experience motion sickness as shown in Table 10.

Table 10. Percentages of Passengers Expected to Experience Motion Sickness
(Schoettle & Sivak, 2014)

Aspect	*Country*					
	US	*China*	*India*	*Japan*	*UK*	*AUS*
Expected to be involved in activities that increase the frequency and severity of motion sickness.	30.7	40.3	52/7	25.9	27.8	29.7
Would often, usually, or always experience some level of motion sickness.	6–10	6–10	8–14	4–7	4–7	4–8
Would experience moderate or severe motion sickness at some time.	6–12	6–13	8–17	4–8	4–9	4–10

A significant concern about these estimates is that no self-driving vehicles were in production when these studies were conducted with no evidence presented asking whether subjects had driven in them. Therefore, subjects' responses were beyond their experience. Based on this evidence it is uncertain what people will actually do in self-driving vehicles.

3.2. Evidence from Self-Driving Car Studies

To date, there have been few studies that examined passenger activities (reading a book, phone usage, watching movies, etc.) and how passengers are seated in highly automated vehicles. Ive et al, (2015) in a *simulated* self-driving car study had 17 students (14 males and 3 females, age M = 22.76, SD = 2.75 years) sit in the left front seat of a vehicle with right-hand drive. Subjects were asked to close their eyes and visualize three hypothetical trips of 1, 25, and 400 miles. The capabilities of automation were left to the subject to define. Subjects then engaged in varying combinations of visualization and think-aloud exercises or semi-structured situational interviews. To support immersion in all activities, the car engine was started and left running for entirety of the experiment. A brief summary of their results indicated that other than interacting with passengers the most common activity reported was phone usage, often for reading. Unlike reading a book, reading on a phone was reported by participants to not cause motion sickness. However, it is worth noting that while riding as a passenger during actual driving, half the participants in this group identified motion sickness as a problem while reading on a phone. Phone usage was popular because it enabled them to access the Internet. Subjects also commented on their ability and willingness to sleep as a passenger in a non-autonomous car, which varied due to physical comfort and trust of the driver. Interestingly, subjects demonstrated a wide variety of postures (supine and various fetal postures) other than the upright position. These results would be more compelling if a larger subject group spanning a greater age range had been recruited and the vehicle were actually driven rather than left idling.

A more recent study (Jones et al., 2019) was conducted during an actual in-vehicle road test that focused on the distribution and incidence of sensations associated with motion sickness experienced by passengers. Study participants included 26 men and 26 women between 18 and 78 years old (mean = 41 years). Testing was completed on a 20-minute scripted, continuous drive that consisted of a series of frequent 90-degree turns, braking, and lane changes at a road test facility. During the turns there were two acceleration levels: low acceleration with peak speeds of 24–26 kph and moderate acceleration with peak speeds at 32–40 kph. In addition, during the drive participants were asked to perform either a task (reading on a handheld iPad) or no-task (normal passenger behavior with unrestricted gaze). Each participant completed all aspects of the within-subject design. A study team driver drove the vehicle around the test track while a second investigator recorded the participant's self-reported motion sickness rating (every minute) and their comments on sensations and severity level experienced (every two minutes). Motion sickness was rated on a scale of 0–10, where '0' corresponded to *no* motion sickness and '10' corresponded to 'Need to stop the vehicle'. Sensations commonly experienced during motion sickness and their severity level (e.g., head sensations, dizziness, drowsiness, salivation, nausea, difficulty focusing, irritability, eyestrain, or difficulty concentrating) were also reported. Figure 3 lists cumulative probabilities of types of sensations reported for task versus no-task conditions. The most frequently reported sensation was nausea; with 30% observed for task versus 20% for no-task. Dizziness was reported approximately two times more frequently; 20% for no-task versus 11% for task. Participants reported "No Sensations" 14% for no-task in contrast to 4% for task. Sensations related to Device Use were constrained to the task condition at 11%. Drowsiness was reported two times more frequently for no-task at 12% compared to 5% for task.

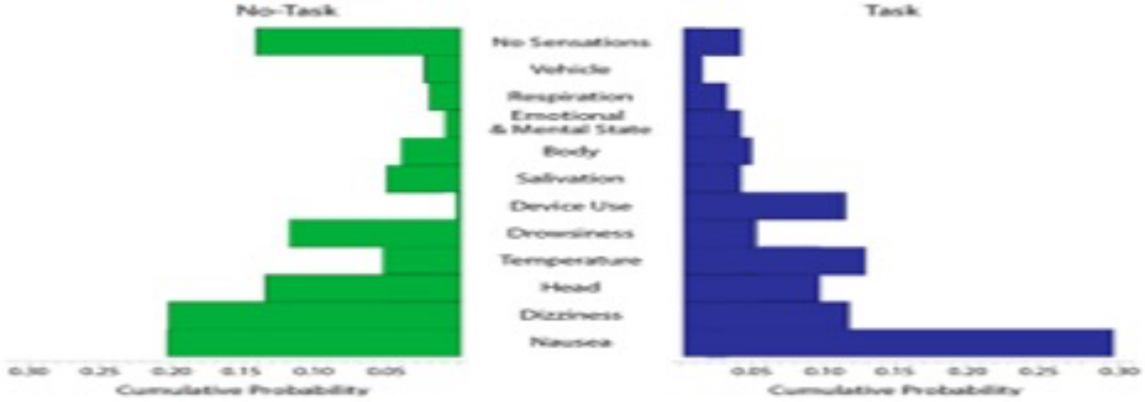

Figure 3. Frequency distribution of sensations reported (total of 2774) during No-Task and Task test conditions (Jones et al, 2019).

A further analysis demonstrated that the task and no-task conditions (Group-level) by types of sensation (total number of counts summed across each subject in each category) were associated with passengers' motion sickness susceptibility, defined by 4-levels: (Never, n = 4); Rarely, n = 17); Sometimes (n = 28); and Frequently (n = 3) as shown in Figure 4.

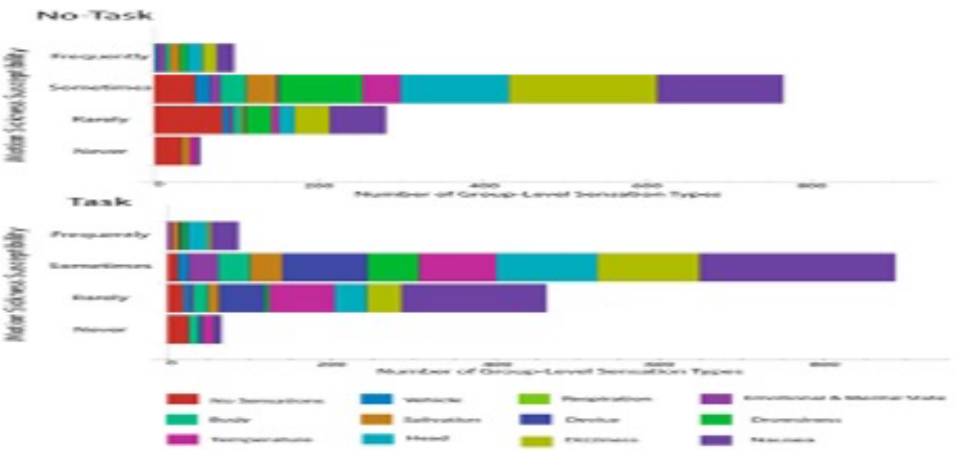

Figure 4. Stacked bar charts of task and no-task conditions (group-level) by sensation types across the levels of motion sickness susceptibility (Jones et al, 2019).

The most common finding was a positive association between some degree of motion sickness susceptibility (i.e., rarely, sometimes, frequently) and incidence of group-level sensation types. For example, during the task condition the number of nausea-related sensations (purple) relative to all sensations were 10% (4/40) to 38% (182/480), 26% (235/900), and 38% (29/75), respectively, for passengers who never, rarely, sometimes, and frequently experience motion sickness. For the no-task condition, a progression of increasing incidences of nausea-related sensations was also found for participants who self-reported increased motion sickness susceptibility. Participants who never experience motion sickness only reported 5% (4/80) of nausea related sensations, while those who identify as rarely, sometimes, and frequently susceptible to motion sickness on average reported nausea at 22%, i.e., (80/370 + 170/780 + 23/100)/3.

In summary, the researchers' selection of an open-ended and continuous self-report approach to quantifying sensations associated with motion sickness yielded a more comprehensive range of sensations and provided evidence of their temporal manifestation. A limitation of the study was the willingness of the individual participant to communicate or respond to verbal requests about sensations experienced throughout the in-vehicle drive. Given that communication behavior varies between individuals, the sensation dataset may have some response bias based on tendencies of participants who were more forthcoming in self-reporting. Observations derived from video also suggest that participants may not always be conscious of their responses to motion sickness. For example, some participants yawned, adjusted their seated posture, leaned against the armrest, supported their head against the head restraint, or altered the position of the handheld device throughout the road test. In many circumstances, participants did not verbalize these behaviors, which consequently were not included in the sensation dataset.

4. Vehicle Characteristics and Passenger Activities in other Types of Transportation

Another consideration is what passengers do in other vehicles, such as in airplanes, trains, subways, buses, and taxis. This includes boat and ships, but their motion is more extensive (particularly vertical pitching and heaving), which is dissimilar from flying in an airplane, at least from the task perspective. Cheung et al. (2006), in a comprehensive review of the effects of motion sickness on human behavior in all forms of transportation, summarized their findings as follows:

> *Ships:* A majority of information is obtained from ship-simulator or ship motion where vertical motion is the primary stimulus. Vertical motion does not correlate with the rate of carsickness and it is unknown if vertical motion will influence sickness in UAM vehicles. Vertical motion frequencies below 0.5 Hz are generally more likely to cause motion sickness. Whole body vibration at 2 Hz and above can cause discomfort or injury but will not provoke motion sickness.
>
> *Commercial airplane* trips include three phases (takeoff, flight, and landing). Passenger activities during takeoff and landing are restricted (turn off and stow laptop computers). Passengers are seated face-forward in the cabin. Amenities such as food and entertainment are provided and there are restrooms. The windows on aircraft are small and passenger external views are limited, especially during night flying and poor weather conditions. When the aircraft encounters air turbulence, the motion profile more closely resembles a ship. Passenger stress and motion discomfort can be considerable during air turbulence.
>
> *Trains and subways* have a significant amount of lateral motion and trips are of varying durations. Commuter rail and subway trips can vary from 5 to 30 minutes and may involve a significant amount of longitudinal acceleration. The windows for rail cars are large but external passenger views tend to be available only through the sides of the cars. During subway travel through tunnels, passengers cannot see very much outside due to darkness. Rail car seats may face forward or backward, although some commuter lines have bench seats whose seat backs can be flipped so everyone can face forward. On subways there are forward, rear, and side facing seats and some people stand.
>
> *Buses* on long-haul trips have passenger seats facing forward with individual armrests but those for local trips usually have some seats that face sideways. Bus motion profiles more closely resemble a passenger car but its longer wheelbase, greater suspension travel and adjustments result in a smoother ride. Also, buses have a lower horsepower-to-weight ratio resulting in less aggressive acceleration.
>
> *Taxis* are passenger cars driven by human operators and vehicle characteristics closely resemble self-driving cars. However, some taxi drivers attempt to maximize their income by minimizing driving time, which they do by driving aggressively. Also, with taxis the passengers generally sit in the back seat where motion sickness is more frequent.

Even though these other types of transportation are imperfect analogs for autonomous vertical take-off and landing (VTOL) aircraft or autonomous cars, studies of passenger activities can provide insight as to what may occur in such vehicles. Russell et al. (2011) summarized a number of earlier studies that included a wide variety of tasks as seen in Table 11. Unfortunately, not all the studies summarized used the same observation method.

Table 11. Passenger Activities on Buses and Trains
(Russell et al, 2011)

Activities	*Ohmori (2008)*	*Timmermans (2008)*	*Lyons (2007)*	*Gripsrud (2009)*	*Thomas (2009)*	*Russell (2011)*
Reading for leisure	*	*	*	*	*	*
Talking to passengers	*	*	*	*	*	*
Sleeping/snoozing	*	*	*	*	*	*
Listening to music	*	*	*	*	*	*
Window gazing	*		*	*		*
Working/studying			*	*		
Talking on phone	*	*	*	*	*	*
Text messaging	*	*	*	*	*	*
Nothing/staring ahead		*				
Personal care		*				
Work computer		*			*	*
Game (various)		*	*			
Romancing		*				
Eating/drinking	*		*			*
Smoking cigarettes	*					
Singing songs	*					
Thinking	*		*	*		
Play games on laptop	*		*	*		
Care of children			*	*		
Knitting					*	
Writing					*	*
Handling wallet						*
Being bored			*	*		
Being anxious about trip			*	*		
Planning return trip			*	*		
Other (describe)						*

Russell et al. (2011) focused on riders on a 2-hour train trip between cities in New Zealand and on city buses. As shown in Table 12, what is most interesting is that most people appeared to be doing nothing (i.e., looking ahead out window) with the percentage being lower for the train, which is a more stable ride and longer trip. The other major difference was that riders were much more likely to be reading on the train.

Table 12. Observed Activities on a Bus and Train
(Russell et al, 2011)

Activities	*Bus*		*Train*		*Total*	
	Number	*% of Total*	*Number*	*% of Total*	*Number*	*% of Total*
Looking out window	270	76.5	260	56.6	530	65.3
Reading	44	12.5	132	28.8	176	21.7
Headphones in	60	17	96	20.9	156	19.2
Talking	48	13.6	77	16.8	125	15.4
Texting	29	8.2	46	10	75	9.2
Sleeping	15	4.2	57	12.4	72	8.9
Handling wallet	16	4.5	42	9.2	58	7.1
Other	15	4.2	28	6.1	43	5.3
Eating/drinking	13	3.7	25	5.4	38	4.7
Using computer	1	0.3	34	7.4	35	4.3
Writing	4	1.1	22	4.8	26	3.2
On phone	6	1.7	6	1.3	12	1.5

5. Vehicle Design Countermeasures: Increase External Field of View

Griffin and Newman (2004) provide results of an experiment on motion sickness and the effects of visual field during 30-minute drives in a car. Participants sat in the center rear seat of the vehicle while they were driven around roads in a suburban city at variable speeds up to 30mph. The fixed route included turns and moving through crossroads with short delays for traffic. The same 30-minute car trip with the same driver was experienced by 100 male subjects assigned to 5 independent groups (visual conditions) of 20 subjects. The visual conditions were: 1) normal viewing for a passenger in the central rear seat; 2) similar to condition 1 but subjects wore a blindfold; 3) a solid panel between the front and rear portions of the car prevented any forward view and panels obscured the view outside the rear side windows; 4) similar to condition 3 except that the rear side windows were not obscured; and 5) similar to condition 3 except that a rectangular hole (100 mm wide by 200 mm high) directly in front of the subject allowed a narrow forward view. Illness ratings (collected at 1-minute intervals) were based on a 7 point scale: 0 = No symptoms; 1 = Any symptoms, however slight; 2 = Mild symptoms, e.g. stomach awareness but no nausea; 3 = Mild nausea; 4 = Mild to moderate nausea; 5 = Moderate nausea but can continue; and 6 = Moderate nausea and want to stop. Figure 5 shows increasing trends in the mean illness ratings with time for each of the five conditions. Conditions 1 and 5 produced the lowest mean illness ratings while conditions 2, 3, and 4 resulted in the highest ratings. The authors concluded that the absence of any visual field (blindfolded condition) resulted in similar sickness to conditions with no forward view (with or without a side view). The results provide no support to the suggestion that closing the eyes when in a vehicle with similar road conditions will reduce motion sickness in the average person. Providing a side view had no beneficial effect in reducing motion sickness when there was no forward view. However, providing even a very restricted forward view reduced the development of motion sickness when there was no side view.

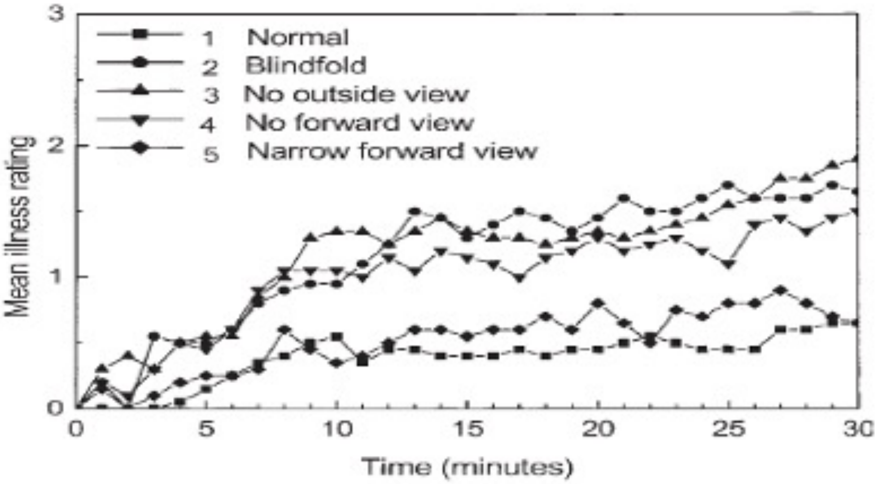

Figure 5. Experiment 1: Mean illness ratings over 30 minutes with five different viewing conditions (Griffin & Newman, 2004).

Studies comparing the effects of external and internal field of view may offer some insights into the situation where an artificial external display is provided such as in vehicle simulators. Bos et al. (2008) conducted an experiment varying the external field of view (defined as the field of view subtended by the display relative to the observer's eye) and the internal field of view (defined as what is shown on the display). They concluded that the size of the external field of view was by far the primary factor affecting motion sickness.

5.1. Stabilize In-vehicle Tasks

Another underlying issue is how the design of in-vehicle tasks such as reading, watching video, talking on the phone, etc. is affected by riding in an automated vehicle. One main source is the Schoettle and Sivak (2009) survey of motion sickness related to in-vehicle video. As noted above, that study involved 136 adults and 32 children who completed a survey. Tables 13 and 14 indicate some people never get motion sick from reading and video displays while riding in vehicles and some always do. Further research is needed that links the task the user performs, the exposure duration, the display size, the size of the external view, and the motion profile to the probability that motion sickness is likely to occur.

Table 13. Motion Sickness Experienced while Reading (%)
(Schoettle & Sivak, 2009)

Question		*Adults*	*Children*
Frequency of motion sickness	Never	43	69
	Rarely	15	9
	Sometimes	17	9
	Often	9	3
	Usually	8	6
	Always	9	3
Severity of motion sickness	None	43	69
	Mild	25	22
	Moderate	22	3
	Severe	10	6

Table 14. Motion Sickness Experienced while Watching Video (%)
(Schoettle & Sivak, 2009)

Question		*Adults*	*Children*
Frequency of motion sickness	Never	61	72
	Rarely	23	13
	Sometimes	12	6
	Often	2	6
	Usually	3	3
	Always	0	0
Severity of motion sickness	None	61	72
	Mild	29	22
	Moderate	7	6
	Severe	2	0

Precise prediction of how much various vehicle design changes are likely to change the likelihood that motion sickness will occur is not possible given the existing data. However, some considerations provided by these authors are listed in Table 15 in descending order from most to least likely.

Table 15. Design Factors that Influence the Likelihood of Motion Sickness (Schoettle & Sivak, 2009)

Factor	*Author Comments*
Vehicle control	People are more likely to get motion sick as a passenger in self-driving vehicles.
Outside view	Most important aspects are viewing the horizon and the size of the view. Sitting in the front row and viewing through a side window is more provocative.
In-vehicle task	It is very unclear what passengers in self-driving vehicles will actually do and how the task will vary with trip duration. Stabilizing the display and providing it closer to the horizon may help.
Seat orientation	The row in which passengers sit also has an effect in that it alters how much one can see. The effects of small angular changes (rotation in the z-plane) on motion sickness is unknown.
Seat posture	When people get motion sick, they prefer to lie down. Also, people may select more recumbent positions if they do not need to drive. However, implementing crash restraints becomes much more complex.
Climate control	Based on driving simulation studies, keeping the room cool and having cool air blow on the subjects seems to reduce the extent of motion sickness.

6. Physiological Measures and Sensors for UAM Research

Money et al., (1996) categorized a number of signs and symptoms associated with motion sickness, such as anxiety, release of stress hormones (e.g., adrenocorticotropic hormone [ACTH] and cortisol) into the bloodstream, pallor, and cold sweating as a “stress response.” This stress response is not a generalized autonomic nervous system response. Selective activation of components of the sympathetic and parasympathetic systems results in the autonomic responses that occur during motion sickness. The specificity of these autonomic responses is demonstrated by experiments of Cowings et al., (1986, 1990). These investigators showed that the pattern of changes in heart rate, peripheral blood flow, respiration, and skin conductance during motion sickness are repeatable for a particular subject but variable between subjects. Furthermore, the results show that individual physiological response patterns are stable across different types of motion sickness stimuli. The Cowings studies among research by others emphasize the importance of utilizing physiological monitoring in understanding motion sickness and its effects on passenger discomfort in various modes of transportation (airplanes, ships, trains, cars) as well as future UAM vehicles.

The commercial market for technologies to enable physiological monitoring and improve personal health and performance is ever expanding. A wide range of smart watches, bands, garments, and patches with embedded sensors, small portable devices, and mobile applications now exist to record and provide users with feedback on many different physical performance variables. These variables include cardiorespiratory function, movement patterns, sweat analysis, tissue oxygenation, sleep, emotional state, and changes in cognitive function. The following is a brief summary of the features of several technologies currently available for physiological monitoring according to what the technology is claimed to do, whether it has been validated against criterion methods, and if it is suitable for use with passengers in autonomous vehicles or high-fidelity simulators.

1. *Equivital EQ02* is a multiparameter body-worn device capable of monitoring a variety of physiological measurements, and it has been demonstrated to be reliable and valid during low and moderate physical activities against criterion lab equipment (Liu et al, 2013). The EQ02 has two components: The Sensor Electronics Module (SEM) and the Sensor Belt. The Sensor Belt is integrated with conductive fabric sensors available in a range of sizes and the belt is machine washable. The SEM connects to the sensor belt and is inserted in a pocket on the left side of the chest. The SEM weighs 38g and its dimensions are 78mm x 55mm x 11mm. The SEM has an internal rechargeable battery capable of 12–18 hours of data recording. Data can also be transmitted via Bluetooth to a mobile application residing on an Android phone/tablet or Equivital software residing on a laptop computer. Data internally stored on the SEM can be downloaded with the Equivital software to a computer. EQ02 has Federal Drug Administration (FDA) 510K clearance.

   EQ02 measures: 2 leads of electrocardiography (ECG), heart rate, breathing rate, skin temperature, and activity (tri-axial accelerometer).

2. *Astroskin:* The Astroskin system is a garment-based physiological monitor that has been previously validated with crew in the NASA Human Exploration Research Analog (HERA), a space habitat analog at Johnson Space Center (Toscano et al, 2017) and was recently commissioned for use by crew aboard the International Space Station (ISS). The Astroskin system consists of a garment with integrated smart fabric sensors, a headband with an oxygen partial pressure (SpO_2) optical sensor, and a small Electronic Module (EM) that contains signal conditioning circuitry, a Bluetooth LT radio transmitter, and four AA alkaline batteries. Data are recorded internally on the EM for a maximum of 24-hours and is downloaded from the EM to a laptop computer with Astroskin software. Data can also be live streamed via Bluetooth to a mobile application residing on an iOS phone or tablet for viewing.

   Astroskin measures: Two-lead ECG, heart rate, respiration waveforms (chest and abdomen), SpO_2, systolic blood pressure (derived from pulse transit time), skin temperature, and activity (tri-axial accelerometer).

3. *Empatica E4* is a wristband device capable of measuring electrodermal activity often referred to as galvanic skin response or skin conductance. In a stress protocol study the E4 yielded higher discrimination power than when the signal was measured at the fingers with standard lab equipment (Ollander et al, 2016). The E4 is a wrist-worn, battery-operated, biosensor device that can store data for up to 24 hours. Data acquired with the E4 are stored locally on the device and subsequently transferred to a computer through the Empatica software for offline processing and analyses. Data can also be live streamed (Bluetooth) to a phone or tablet application for viewing.

   E4 measures: Photoplethysmography measures Blood Volume Pulse (BVP) from which heart rate, heart rate variability (HRV), and other cardiovascular features may be derived; *Triaxial Accelerometry* captures motion-based activity; *Event Mark Button* tags events and correlates them with physiological signals; *Electrodermal Activity* is used to measure sympathetic nervous system arousal and to derive features related to stress, engagement, and excitement; and *Skin Temperature* reads peripheral skin temperature at wrist.

7. Countermeasures for Mitigating Motion Sickness in UAM Vehicles

Potential countermeasures for mitigating motion sickness in passengers seated in UAM vehicles and high-fidelity simulators include a visual fixation device, relief bands, motion sickness medications, and non-pharmacological methods such as biofeedback and Autogenic Feedback Training.

Visual Fixation Device: Bonato et al, 2015) tested the effectiveness of a user-worn device that provides a visual fixation point that moves with the user. Fourteen subjects viewed the interior of a rotating optokinetic drum (60°/s) through a visor that displayed either a clear view of the scene (control group) or the scene with a fixation point (experimental group). After 5 minutes of viewing, symptoms were assessed using the SSQ that yields four scores (total, nausea, oculomotor, and disorientation) and a 0 to 10 motion-sickness overall scale. The results showed that viewing the fixation point resulted in significantly lower scores for all measures. Control condition scores were as much as 400% higher than when the fixation point was viewed. A wearable device presenting a visual fixation point that moves with the user may reduce motion sickness in other motion environments that include UAM vehicles and flight simulators.

Relief Band: Miller et al, (2004) examined whether acupressure (Acuband) and acustimulation (Relief Band) prevent motion sickness. The study included 80 subjects (19 men and 61 women) who were randomly assigned to 1 of 5 conditions: Acuband (trained or untrained); Relief Band (trained or untrained); or placebo. Subjects were exposed to a 20-minute baseline and a maximum of 20 minutes of optokinetic drum rotation. Untrained subjects read the device operating instructions and used it as they considered appropriate. Trained subjects read the device operating instructions and were trained to use the device appropriately prior to drum exposure. Symptoms were monitored during baseline and rotation using a modified version of the MSAQ with a scale range of 0–10, with 0 being no symptoms, 1 being “not very,” and 10 being “severely.” Results showed that in all conditions symptoms of motion sickness increased during drum exposure. The only difference found between conditions was a potential delay in symptom onset for the Relief Band compared with the Acuband. Neither band nor placebo prevented the development of motion sickness regardless of whether the bands were used correctly or incorrectly.

Pharmacological: Numerous medications have been evaluated as a countermeasure for motion sickness in both lab research and various operational environments (Dobie (2019). According to Dobie, there are a number of anti-motion sickness medications that are quite effective although most have some unwanted side effects (i.e., drowsiness) and some adversely affect performance. Scopolamine and promethazine are still considered to be the most effective anti-motion sickness medications. Both medications are used by NASA for treating astronauts who experience space motion

> sickness which is most frequently reported during early mission days. Other research (Gates, 1999) has shown that drugs such as droperidol in combination with fentanyl that were effective for treating vertigo in Meniere's patients have not been found to be effective in a motion environment. When treating passengers in various modes of transport, the best choice of medication should be based according to circumstances such as duration and severity of exposure and individual idiosyncrasies (e.g., high susceptibility to motion sickness).
>
> *Non-pharmaceutical:* Psychophysiological methods such as biofeedback and Cognitive Behavioral Therapy vary in effectiveness and can require time to be beneficial (e.g., especially desensitization of high susceptible individuals). In a study by Jones et al. (1985), military aircrew were provided biofeedback-moderated behavioral treatment. The study included 53 fliers grounded for chronic, severe motion sickness and followed each flier for two years after treatment completion. Each subject had approximately 20 sessions in a rotating chair, each lasting 30–45 minutes, twice a day for two workweeks, with one session in the morning and one in the afternoon. Chair rotation was initially counterclockwise but if the subject appeared to habituate during later sessions the direction of rotation was changed to clockwise. The chair speed was controlled by the subject, with rotational rates up to 20 rpm. In some sessions the chair was tilted 40 degrees to the left during counterclockwise rotation or to the right during clockwise rotation. The biofeedback instruments which measured skin temperature, skin conductance, and muscle activity were mounted on a shelf approximately 18 inches in front of the subject with remote readouts to the subject and to recording devices. Success was defined as returning to and maintaining satisfactory operational flying status. Of these, 42 fliers (79%) met this criterion; 3 (6%) were partially successful; and 8 (15%) were subsequently grounded for recurrent airsickness.

In a recent study by Cowings et al. (2018), a modified rotating chair test was used to simulate the cross-coupled angular accelerations limits for astronauts on NASA's Orion capsule during re-entry from space. During this phase of flight there is potentially a very high risk of spatial disorientation, motion sickness, and degraded performance to astronauts. The primary objective of the study was to determine whether a physiological training method—Autogenic Feedback Training Exercise (AFTE)—can mitigate these adverse effects. Fourteen men and six women were assigned to two groups (AFTE; no-treatment Control) balanced for gender and motion sickness susceptibility (number of chair rotations tolerated during a baseline test). In addition, all subjects received three training sessions on a manual performance task (mental arithmetic using a keypad while blindfolded) and four exposures in the rotating chair. AFTE subjects were given 2 hours of training before Test 2, 4 hours of training before Test 3, and 6 hours of training before Test 4. Motion sickness symptom ratings, task performance metrics, and physiological measures were collected during all tests. Results showed that the AFTE group had significantly lower symptom scores when compared to Controls on Tests 2, 3, and 4. No significant effects were found on task performance. These findings suggest that AFTE may be an effective countermeasure for mitigating spatial disorientation and motion sickness in astronauts during re-entry from space. In earlier flight studies on the Space Shuttle, Cowings et al. (1988) and Toscano et al. (1994) demonstrated that 6 hours of pre-flight AFTE was sufficient for preventing and/or controlling motion sickness symptoms during the mission. Three astronauts who were given pre-flight AFTE reported significantly fewer symptoms or were asymptomatic than the three control subjects who reported severe malaise and took anti-motion sickness medications. The results suggest AFTE may provide an effective alternative countermeasure to medications for mitigating space sickness, however, it will require obtaining additional flight subjects for statistical inference testing. An important benefit of AFTE is there are no adverse side effects as is often observed with motion sickness medications.

8. Conclusions

Motion sickness leads to nausea when people are exposed to motion stimuli, particularly while traveling in a vehicle. Other symptoms include vomiting, headaches, sweating, increased salivation, drowsiness, dizziness, warmth/flushing, and pallor. Motion sickness may be experienced in cars, trains, buses, ships, planes, driving simulators, and amusement rides such as a roller coaster.

8.1. Theories of Motion Sickness

Motion sickness is caused by a mismatch between visual and nonvisual (vestibular and kinesthetic) information, the observed scene and the motion felt or lack of it. For example, in a fixed-base driving simulator, the scene moves but the person does not, leading to a sensory conflict. In the case of seasickness, the visual representation is of a stable world whereas other signals indicate movement. A second theory is that the conflicting information leads to problems in maintaining a stable posture.

8.2. Quantifying Motion Sickness

Motion sickness can be quantified by identifying the symptoms presented, weighting them based on their impact on motion sickness to compute a total score, or just using a single number to quantify the experience, usually on an interval scale. A commonly used scale is the SSQ, which consists of 3 subscales (nausea, oculomotor, disorientation) and each symptom is scored 0 to 3 (0 = none; 1 = slight; 2 = moderate; 3 = severe). The total score is a weighted total of the 3 subscales.

8.3. Susceptibility to Motion Sickness

The most common method for assessing motion susceptibility is the MSSQ, in particular the short version. Tools such as MSSQ for screening individuals susceptible to motion sickness are useful, however, they are only mildly predictive of sickness to different motion stimuli including cross-coupled Coriolis acceleration, 0.2 Hz frequency translational oscillation, off vertical axis rotation (OVAR), or visual-motion simulator (Golding, 2006). Moreover, models for predicting motion sickness, which have largely been developed for sea sickness, do not consider task characteristics.

8.4. Factors Related to Susceptibility

Factors like age and gender are related to susceptibility such that children from 5 to 12 years old, women, and older adults get motion sickness more than others do. Other data cited in this report suggests that motion sickness declines with age, though most of that data concern seasickness, and it could be that grouping all types of motion sickness together may not be appropriate.

8.5. Motion Sickness in Autonomous Vehicles

Evidence from UAM vehicles and simulator research is not yet available, and to date there are only a few studies on passenger discomfort in autonomous road vehicles. Schoettle and Sivak (2014) asked subjects if they would ride in a self-driving vehicle and if they did, what they would do. Using data from prior studies concerning the relationship between motion sickness and tasks that people do (in particular, watching videos and reading), estimates of the percentage of riders that would experience motion sickness are offered. Their approach is an interesting attempt to use available data to make predictions. Unfortunately, there was no evidence these subjects had ever driven in a self-driving car, and people are not very good in making projections beyond their experience. Jones et. al (2019) recent study examined the incidence of motion sickness symptoms in passengers during an actual in-vehicle road test that included a series of frequent 90-degree turns, braking, and lane changes. In addition, during the drive participants were asked to perform either a task (reading on a handheld iPad) or no-task (normal passenger behavior with unrestricted gaze). The most important finding was that during the task condition the incidence of symptoms were 10%, 38%, 26%, and 38%, respectively, for passengers who never, rarely, sometimes, and frequently experience motion sickness. For the no-task condition, a progression of increasing incidences of symptoms was also found for participants who reported increased motion sickness susceptibility. A limitation of the study was the willingness of the individual participant to communicate or respond to verbal requests about symptoms experienced throughout the in-vehicle drive. It is currently unknown if task conditions and type of activity will influence motion sickness in passengers of UAM aircraft.

Some inferences about motion sickness could be made based on other forms of transportation, namely ship, air, rail, and bus. There are a number of differences between those situations and UAM vehicles that may affect motion sickness. They include: 1) trip duration and time (longer trips, night trips, and subdued lighting are more likely to lead to sleeping), the amount of personal space available; 2) the support for phone and computer tasks; 3) amenities provided (food, water, bathroom); and 4) the vehicle motion profile experienced. Other important variables that should also be considered are types of tasks that will be supported; the direction seats will face; and the external view provided to passengers. These questions each will have an impact on motion sickness and the answers will all depend on how these services and their technologies develop.

8.6. Vehicle Design Countermeasures

Some potential design countermeasures from most to least effective are as follows: 1) controllability (UAM passengers will be passive riders); 2) external view (seeing the horizon, although large windows with increased field of view may elicit vertigo in air passengers, especially in vehicle withs aggressive or novel flight profiles); 3) in-vehicle task (passenger in-flight activities cannot be fully specified; image stabilization may help passengers use personal display devices); 4) seat orientation (reclining seats may help but would complicates passenger protection); and 5) climate control (providing temperature and air flow control).

8.7. Physiological Measures and Sensors for UAM Research

Studies have shown that the pattern of changes in heart rate, peripheral blood flow, respiration, and skin conductance during motion sickness are repeatable for a particular subject but variable between subjects. Further, these “individual unique” physiological response patterns are stable across different types of motion sickness provocative stimuli. There are a number of wearable devices for physiological monitoring that are commercially available. Device selection should be based on usability in the test environment (any size and weight limitations), passenger acceptance and comfort, and if the device has been previously validated against a gold standard.

8.8. Countermeasures for Mitigating Motion Sickness in UAM Vehicles

A passenger worn visual fixation device may be an effective means for mitigating sickness in UAM vehicles and high-fidelity simulators, and it may be more cost effective than vehicle design modifications (e.g., smaller windows for external view). Relief bands have not been effective for reducing motion sickness symptoms provoked by optokinetic stimuli, and evidence is lacking for passengers in various types of transport (ships, commercial aircraft, trains). Anti-motion sickness medications are somewhat effective, but frequently result in adverse side effects (drowsiness, blurred vision, performance impairment). Non-pharmacological approaches, biofeedback and Autogenic Feedback Training Exercise, have been effective for mitigating sickness in military aircrew and in astronauts during spaceflight, but they require time to administer.

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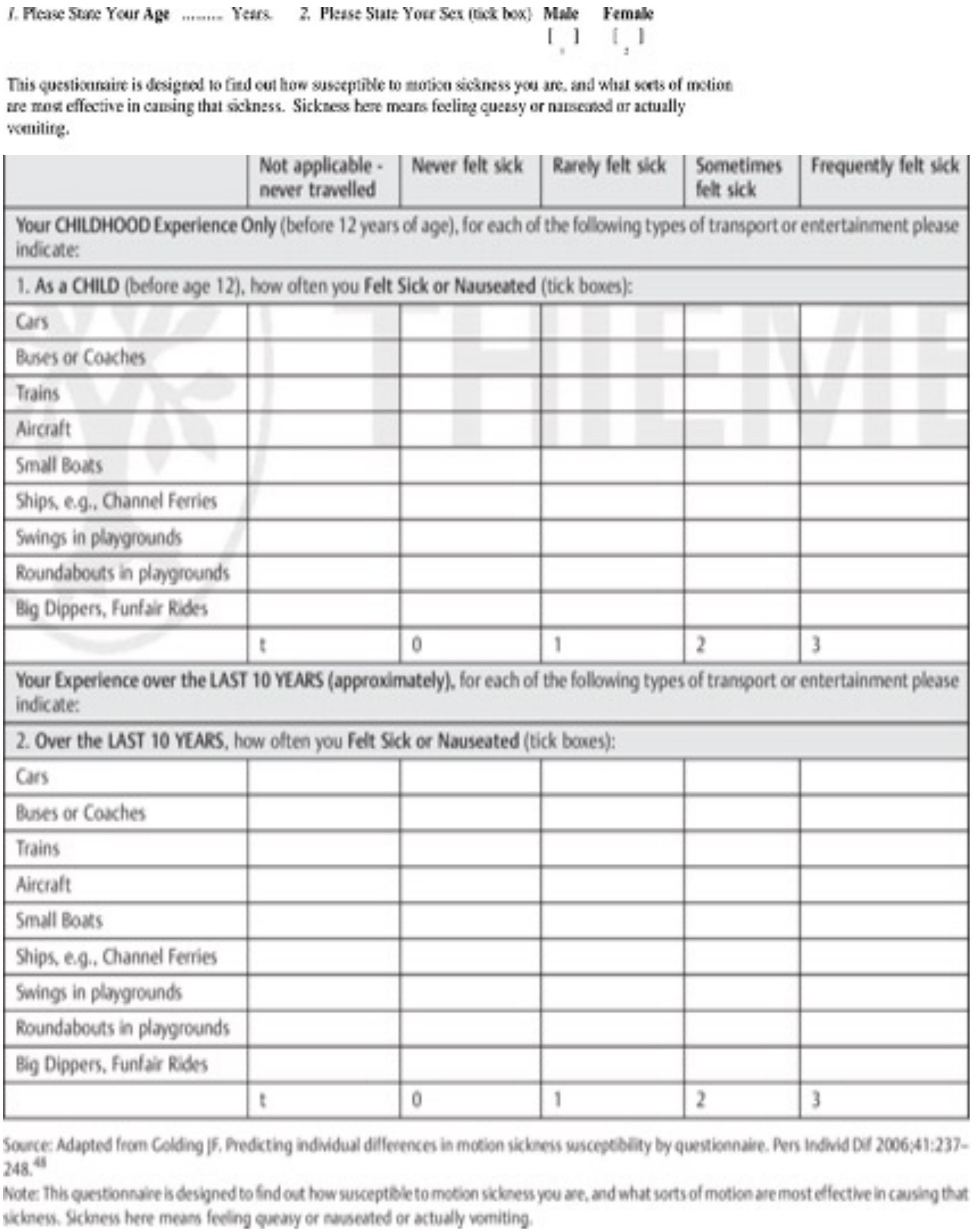
Appendix A. Short Version of Motion Sickness Susceptibility Questionnaire



1. Please State Your Age .... Years. 2. Please State Your Sex (tick box) **Male** [$_1$] **Female** [$_2$]

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

	Not applicable - never travelled	Never felt sick	Rarely felt sick	Sometimes felt sick	Frequently felt sick
Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:					
1. **As a CHILD** (before age 12), how often you **Felt Sick or Nauseated** (tick boxes):					
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g., Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3
Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:					
2. **Over the LAST 10 YEARS**, how often you **Felt Sick or Nauseated** (tick boxes):					
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g., Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					
	t	0	1	2	3

Source: Adapted from Golding JF. Predicting individual differences in motion sickness susceptibility by questionnaire. Pers Individ Dif 2006;41:237–248.[48]

Note: This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.