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A Knowledge Discovery in Motion Sickness: A Comprehensive Literature Review

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ABSTRACT Motion sickness is a common perturbation experienced by humans in response to motion stimuli. The motion can happen in either real or virtual environments perceived by the vestibular system and visual illusion. The extensive varieties of research studies have been conducted in order to determine and evaluate aspects of motion sickness and its symptoms. To provide insights upon physiological changes in regards to motion sickness, researchers have used subjects from different ages, gender in addition to electrode positions and environmental conditions. The main purpose of this study is to provide a comprehensive review and comparison of the existing research studies regarding aspects of interference of the existence and augmentation of motion sickness. In this paper, we discuss the appearance of symptoms after motion sickness and summarize the physiological behaviors and emotions via a range of scenarios. In addition, the existing methods for measuring motion sickness levels are compared and discussed in detail. This study considers a number of important factors such as age, gender, health condition, participants (non/fatigue or non/drowsiness), road conditions, and different experimental set-ups impacting the results of motion sickness. Finally, this paper presents a range of practical methods to minimize and prevent the unpleasant side effects of motion sickness. This includes air ventilation, homogenized road/virtual environment features, and providing comfortable set-up and pre-movement before visual acceleration. A deeper understanding of changes in physiological signals during vection helps us to confirm the traditional subjective report and also improves our knowledge in the concept the vection.

INDEX TERMS Motion sickness, vestibular and visual conflict, vection, eye movement, postural instability, physiological signals.

I. INTRODUCTION

Motion sickness (MS) is defined as any unwell feeling that happens due to a provocative motion such as travelling over sea, sky, and land [1]–[3].

Experience of MS in virtual environments is called Visually Induced Motion Sickness (VIMS). It can be divided in to different categories such as (a) Cybersickness generated by Oculus Rift due to lack of physical activity [4], (b) Simulator sickness generated in motion simulators [5], and Game sickness generated by playing games [6]. Symptoms of VIMS can happen in virtual environments comparable as in the real world [4], [7] such as vomiting, nausea, and light-headedness. However, there are differences between the two types of sickness:

1) Traditional MS is induced by vestibular stimulation; however, the exact source of VIMS is not clear [8].
2) VIMS does not happen if people close their eyes, while MS can happen with closed eyes [8].
3) Fewer sickness symptoms in VIMS are more highlighted than traditional ones such as oculomotor, disturbances and disorientation [9].
4) People exposed into the virtual environment usually experience MS in the earlier stages of scenarios in comparison to real world environments [10], [11].

Although newly developed technologies have many advantages in various fields such as medical, military and entertainment [12],limitations including discomfort while utilising these devices is a common disadvantage. To reduce the negative side effects of MS, the first step is to determine how motion in real and virtual environments cause an individual to experience symptoms of feeling sick. There are several

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factors that contribute to the inducing of MS in real and virtual environments. First, the conflict in visual, vestibular (semicircular canal and otolith organs) and somatosensory inputs are the primary reasons for causing this sickness. When one sensory input was inconsistent with other inputs, or was absent, the probability of experiencing MS increased [13]. Secondly, eye movement evokes the optokinetic nystagmus (OKN). It innervates the vagal nerve leading to MS [14]. Thirdly, the body posture reduces its ability when exposed to virtual environments and leads to MS [15]. Lastly, subjective vertical conflict called vection frequently precedes to MS [16].

In the normal driving situation, The motion sickness does not happen to the driver as drivers can control the behaviour of their vehicles; however passengers can not predict the acceleration of the vehicle. Therefore, they are exposed to the motion sickness more than the driver due to unpredictable acceleration. This reduces the road safety and the benefits of autonomous vehicle [17]. It is shown that reaction time increases when cybersickness is induced.

The next step is to understand the probability of an individual experiencing motion sickness. Symptoms including malaise, pallor, cold sweating, nausea, and vomiting are exhibited when individuals feel motion sickness. Therefore, these symptoms and physiological changes can help researchers to find a reliable way to detect and predict this sickness. Extensive amounts of research have considered several subjective and objective measurements regarding MS. However, their findings are not consistent with each other due to sickness and physiological variability in individuals.

Some factors are more prominent for increasing the intensity of sickness; however, they have not received enough attention in previous studies which has had influences on their results. For example, electroencephalography (EEG) or heart rate (HR) changes can be dependent on the individual, resulting in subjective differences in the same environment. Also, the size of display, time and gender influence the existence and severity of MS. Therefore, the probable effect of stimuli characteristics on estimation of MS should be considered to increase the accuracy of results.

The aim of this study is to review and compare the existing research studies on MS. The symptoms and measurement methods that have been developed will also be analyzed and techniques for future research discussed. Therefore, the significant contribution of this study will be the comparison and detailed analysis of a broad range of MS data. In addition, possible causes of discrepancies in the results will also be discussed. Finally, the proposed practical methods for minimizing MS will be defined.

The rest of the paper is as follows. The main resources stimulating MS are presented in Section 2. Section 3 compares various MS measurement methods. Section 4 discusses the primary reasoning for differences in results within studies. Also, discussion of probable methods are introduced to reduce the severity of MS. Section 5 presents the conclusion of this review.

A. VESTIBULAR SYSTEM

Vestibular-visual conflict is the fastest stimulation which is perceived by humans [18]. Researchers have used a rotating chair [19], a parallel swing [20], an off-vertical axis [21], driving simulator [8], and a flow field video [22] to stimulate the vestibular system.

Fig. 1a shows how MS is induced when there is a mismatch in the semicircular canal and otolith organ [23]. The vestibular system, which is known as the sixth sense of humans, has three main functions:

- Detection of motion in different directions is responsible for the feeling of motion and spatial orientation of the head [24]–[26].
- Stabilization of the postural body and contributor to sense of balance [27].
- Maintaining the gaze on a fixed point when rotating the head [28].

The semicircular canals detect angular velocity and otolith organs detect linear acceleration inside the inner ear. If the head rotation perceived by the semicircular canal does not align with the gravity direction perceived by otolith organs, MS is provoked [29]. As a result, disorientation and nausea will happen to individuals [30], [31].Head rotation more than a single time is defined as cross-coupling. The origin of cross coupling lays on the false estimation of direction between angular velocity and head rotation through the semicircular canals. In other words, direction and magnitude play a key role in increasing the cross-coupling stimulation [30], [32].

MS is also evoked by vertical and horizontal linear oscillation at low frequency (0.1-0.5) Hz [2] in road transport. Therefore, research evidence suggests that the combination of acceleration and frequency of angular and linear oscillation increases nausea [33], [34]; however, some have failed to obtain similar results [35].

Similarly, the link between head rotation and lateral acceleration have been found to correlate with the severity of MS. If the head is pitched, strong nausea is reported in lateral acceleration, while if the head is rolled, no MS is experienced [36]. The angular movement around the Y axis (pitch) provoked more sickness than angular movement around the Z axis (yaw) [37]. The provocative frequency for Off-Vertical Axis Rotation (OVAR) is around 0.3 Hz and for Vertical Linear Oscillation (VLO) is 0.2 Hz. Differences in time constant variables would not provide a conflict but sustain it [38].

Some research studies used twist factors (angular motion) and stretch factors (linear motion) to quantify the conflict during vestibular cross coupling stimulation [38].

B. EYE MOVEMENT

Eye movement is a fundamental contributor to VIMS. Fig. 1d shows some eye responses such as saccades, smooth pursuit, or eye blinks and eye movement in different directions are identified in VIMS [39]. Vestibular ocular reflex stabilizes the images on the retina when the head is moved [40].

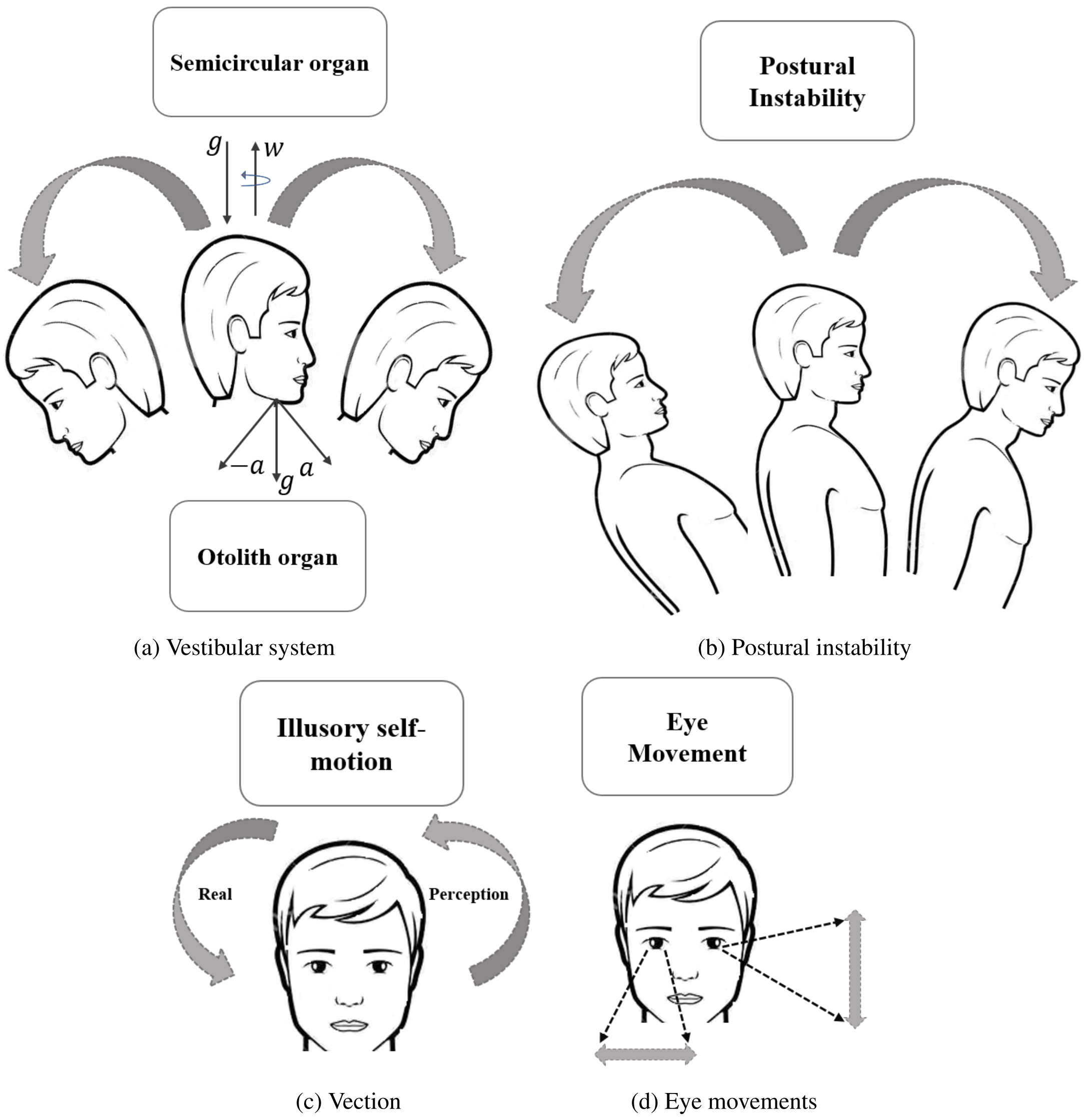


FIGURE 1. Sources of motion sickness a) conflict among otolith organ (linear acceleration) and semicircular canal (angular velocity), b) postural instability due to loss of body control c) illusory self-motion when there is a mismatch between real motion and what is perceived, D) eye-movement as direction of eyes proceed the VIMS.

According to Ebenholtz hypothesis, exposing individuals to various visual movements causes VIMS [41]. Therefore, some research studies stated that fixation point [16] and low velocity of the drum rotation reduce VIMS [42]. Audiokinetic nystagmus (AKN) shows that variation in white noise intensity causes saccades [43].

C. POSTURAL INSTABILITY

MS will occur since the body loses its ability to control postural stability during swaying in both real and virtual environments [15]. Fig. 1b shows if the visual scene is moved, the body postural stability may be changed. In other words, postural instability is the response in reaction to visual or vestibular cues. Both central and peripheral vision control the bodies ability to maintain stability. As a result, this issue precedes MS [44].Recent studies have claimed the findings of a link between the postural swing and vection.The result showed that participants reporting vection had experienced postural sway [45]. As the vection frequently leads the MS, postural sway can be related to MS as well [46].

D. VECTION

Vection is referred to as self-motion perceived by individuals. However, this perception is not consistent with real feelings. For example, when a person is seated inside a drum rotation (circular vection) and vehicle (linear vection), this person experiences motion which is not distinguishable whether the chair is moving or if the person themselves is moving. Based on Fig. 1c, it is shown that our perception is the opposite of the real motion. This means that vection is the unusual error due

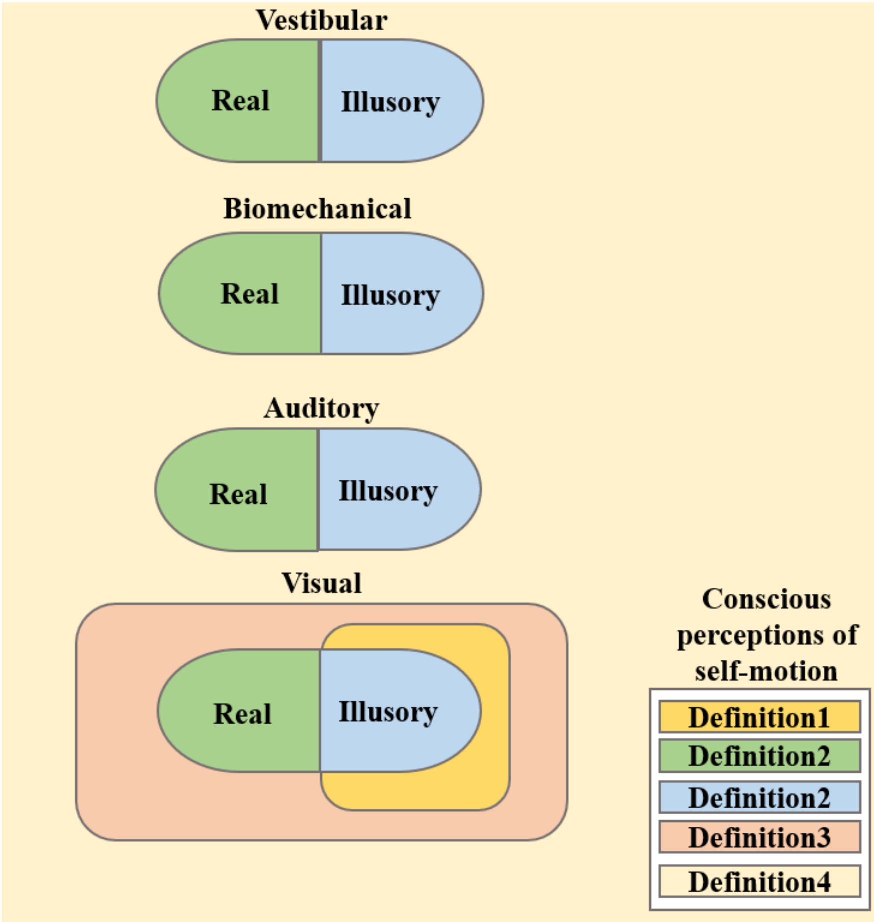


FIGURE 2. Various definition of vection: Visually illusory (first definition), illusory self-motion with other non-visual stimulation (second definition), visually self-motion induced by passive and active physical motion (third definition), self-motion in real and illusory condition based on the body movement (fourth definition).

to the disability of our body to estimate the correct direction of motion. Vection is challenging due to its varying definitions, measurement techniques, and significance of vection and its neural basis [47]. Vection can be broadly defined in the following popular ways. Fig. 2 summarizes the various definitions for vection.

1) FIRST DEFINITION

Visual Illusory Self-motion is the first definition of vection which is stationary observer generated by sitting in a drum rotation with black and white stripes. Circular vection or self-rotation is induced when the drum starts to rotate. Linear vection or self-translation is induced when motion is horizontal. Vertical vection is created when auditory sounds/ visual observers are perceived in the vertical direction (up/downwards).

2) SECOND DEFINITION

- Illusory self-motion is induced with other non-visual stimulation. The auditory illusory self-motion is generated when a subject perceives acoustic sound [48]. Even though the level of self-motion provoked by acoustic cues is weaker than visual ones, it is a great modality for posture prosthesis, navigation in non-visual, and unusual gravitoinertial environment such as air, space, under-water and multisensory integration [49]. The Auditory-Induced Vection (AIV) is very sensitive and can be destroyed by other noise [50].
- Haptokinetic Vection is induced by applying tactile motion on the subjects body [51], [52].
- Arthrokinetic Vection is produced when a subject's limb stimulates passively [53].
- Biomedical vection is induced when subjects sit or stand on the treadmill [54], [55].

3) THIRD DEFINITION

Visual self-motion is induced with passive and active physical motion. This can happen in real environments such as on a treadmill [56] and illusory conditions such as a computer display [57].

4) FOURTH DEFINITION

The fourth definition of vection is based on body parts and two types of activities (passive and active) in real and illusory conditions. Thus, it is important to know which part of the body perceives self-motion and based on the body part, vection is categorized. Most subjects experiencing VIMS reported vection; however VIMS can occur in the absence of Vection. Therefore, vection can proceed the VIMS. Vection has the following roles:

- Making Judgements:It is more likely to get lost when subjects are immersed in the virtual environment compared to the real world because the vection is usually absent in the virtual environment [58]. Subjects can also distinguish the right and left heading when they experience vection.
- Controlling of Self-motion: Vection increases the accuracy of heading and steering. Also, vection allows the free gaze activation compared to static gaze [59].
- Navigation and Spatial Orientation: Subjective experience can help to navigate our position in the real world [60]. Due to the lack of illusory self-motion, most errors were observed when observers saw simple simulated points in spatial orientation. If vection is induced, observers can better find their position [61]. Larger view displays compared to smaller ones induce greater vection. Therefore, this vection can navigate observers to find their position and orientation if they are immersed in a larger displayed virtual environment [60].

E. VECTION MEASUREMENT METHODS

Measuring vection through subjective measurement has been discussed in different research studies. Observers reported self-motion by pressing a joystick button to measure the onset/offset and rate vection strength [62]. Latency on the report of vection may be inflated during the onset of experiment [63]. Objective measurement can be more effective compared to the subjective measurement since it can be validated and analysed precisely [47].

Eye movement is a great objective indicator of illusory self-motion. Vection strength increases in four gaze conditions (up/down, right /left eye position in a 3D cloud objects) when eye velocity is slow [59]. Tokumaru *et al.* reported that alpha power band was high in spatial disorientation such as vection and they observed that the changes of this band were not similar among subjects [64]. Other methods of physiological parameters such as HR, BP, skin conductance, and eye movement were applied to measure vection in another study [39]. The results were varied among individuals due to somatosensory and vestibular control of autonomic regulation [65] Magnetoencephalography (MEG) [66], positron emission tomography(PET) [67] and functional magnetic resonance [68] showed the correlation among neural network and illusory self-motion.

F. IMPORTANT PARAMETERS IN VECTION

Flow and apparent depth of the objects are factors generating the vection [24]. Exposure time is another factor to induce vection. For example, Warren concluded that subject's perceived self-motion after being exposed to optic flow for 300 ms [69]. Dichgans and Brandt showed $(1-10)$s is enough to induce illusory self-motion [51].

II. MS SYMPTOMS AND MEASUREMENT METHODS

A. MS SYMPTOMS

There are some main symptoms during or after feeling MS and the level of MS can be determined by observing these symptoms. The symptoms consist of eye strain, disorientation, headache, sweating, pallor, dryness of mouth, dullness of stomach, vertigo (swirling dizzily), ataxia (postural disequilibrium), nausea and vomiting [24]. The nausea symptoms are affiliated to gastrointestinal distress and include stomach awareness, sweating, salivation, and burping. Eye-strain, difficulty focusing, blurred vision, and headaches are symptoms of the oculomotor. Disorientation is affiliated to vestibular disarrangement like dizziness and vertigo [70].

Naqvi et al. observed some uncomfortable feelings such as dizziness, visual fatigue, eye-strain, blurred vision, and headaches when watching 3D movies. Some symptoms are similar between MS and cybersickness. It should be noted that cybersickness happens during or after experiencing the virtual environment and it occurs because of conflicts between sensory systems such as: visual, vestibular and proprioceptive [71]. When participants are immersed into the full vision, researchers observed that malaise is experienced for more than one hour [72] or one day [73]. Other studies claimed that the speed of thought and response time decreased when experiencing the MS compared to the normal condition [24].

1) NUMERICAL RESULTS FOR MS SYMPTOMS

Generally, participants feel increasing levels of nausea and disorientation 10 min after starting their experiments. They feel discomfort in oculomotor 15 min after staring their experiments. The maximum score (simulator sickness questionnaire) for nausea level is around 50 from 200 during 60 min. The oculomotor level is around 60 from 200 during 60 min. The disorientation level is around 70 from 200 during 60 min. Total simulator sickness level is around 100 from 200 [74]

B. SUBJECTIVE METHOD

Many researchers used a MS questionnaire to measure the level of MS. The original standard sickness questionnaire called MS Susceptibility Questionnaire (MSSQ) was introduced by Reason and Brand [13]. Kennedy et al. introduced famous theory for assessment of the MS level. MSSQ includes 2 parts. Before immersing into the virtual environment, subjects were given a questionnaire called Before MS Susceptibility Questionnaire (BMSSQ) to measure their susceptibility [8].

After immersion, subjects were given a different questionnaire called AMSSQ. They share their experience after using transport systems [5], [70]. It includes 5 scales:

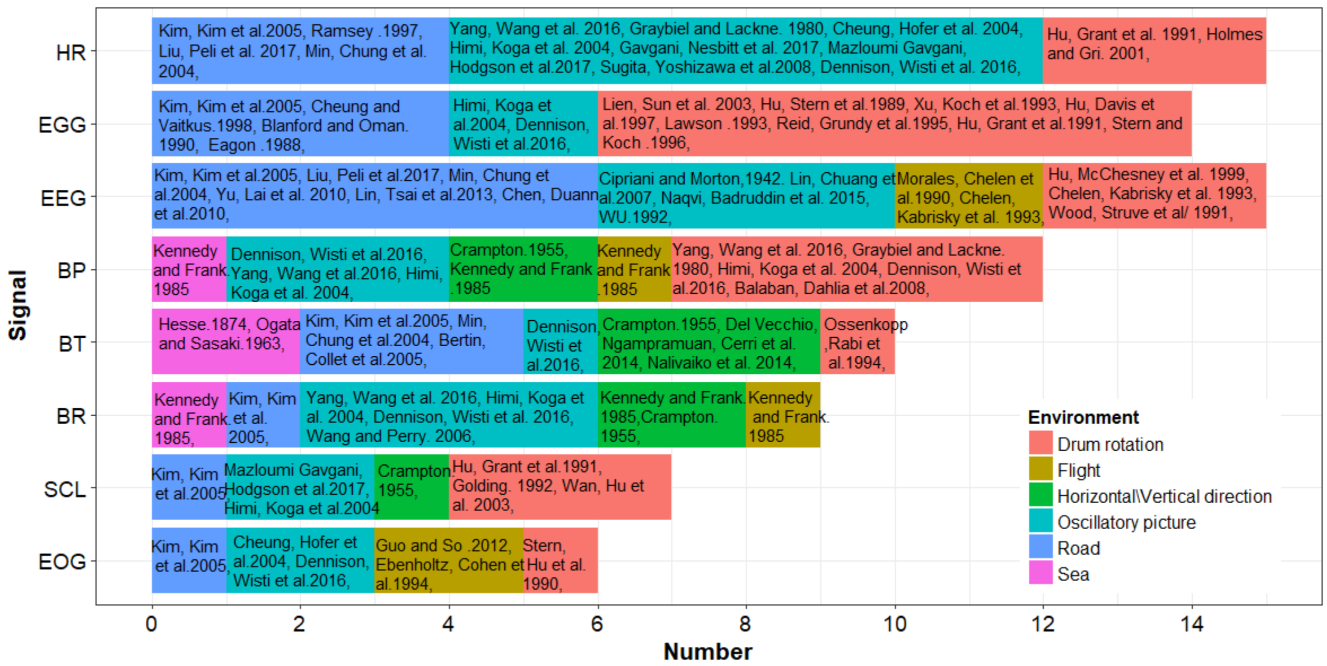


FIGURE 3. Physiological aspects of subjects recorded before and after exposure them into various environments such as drum rotation, flight, horizontal or vertical direction, road and sea are considered with the number of papers. Generally, road, oscillatory pictures and drum rotation are extensively studied.

Scale 0 indicates no symptoms, scale 1 for some symptoms but no nausea, scale 2 for mild nausea and scale 3 for moderate nausea. In a virtual environment, these scales can be determined with three symptoms: Nausea, Oculomotor, and Disorientation. The Simulator Sickness Questionnaire (SSQ) was used along with t-test to distinguish symptoms [71]. Some questions in the MSSQ and SSQ show similarity in statements. The scales could be rated based on four symptoms: gastrointestinal, central, peripheral, and drowsiness [75], [76].

Hale and Stanney redeveloped the MS questionnaire based on 4 symptoms including: 1. Un-easiness (no symptoms), 2. Dizziness, warmth, headache, stomach awareness, sweating, 3. Nausea, 4. Vomiting and scored on Slight, Fairly, Severe and Retching [9]. The Hamilton Anxiety (HAM-A) is a reliable and validated test to evaluate the severity of neurosis disorders, anxiety syndromes and anxious mood [77].

C. OBJECTIVE MEASUREMENT METHODS

Physiological parameters were used as objective measurements. Participants did not have any disorder in their history to give a precise report [8], [78]. Any correlation between the MS questionnaire or simulator sickness questionnaire with physiological changes were evaluated by metrics such as pearsons correlation coefficient [8], bonferroni corrections [79] and pairwise t-test [78]. Fig. 3 shows physiological of subjects recorded before and after exposing into various environments such as drum rotation, flight, horizontal or vertical direction, road and sea are considered with the number of papers. Generally, road, oscillatory pictures and drum rotation are extensively studied. These papers used various physiological signals to evaluate physiological changes of subjects after feeling motion sickness. Nearly, all physiological changes are considered in various environment in different years. Therefore, their studies and findings give great direction for future research in this field.

D. OBJECTIVE MEASUREMENT

1) STUDIES ON MEASURING MS USING ELECTROENCEPHALOGRAPHY (EEG)

The delta, theta, and alpha powers of certain areas in the brain demonstrated the level of MS [21], [80], [81]. Delta and theta band power increased while alpha power changed slightly in cross coupling stimulation [21]. $8-10$ Hz power in parietal and motor areas is highly correlated with sickness-level; this power increased to $18-20$ Hz in these areas for some subjects [82]. The EEG signals of parietal, motor and occipital areas are highly related to MS level [83]. The parietal and right motor components showed less significant change in alpha power and also theta and delta power increased due to vestibular stimulation whereas beta power was greater in the right than the parietal components. The left motor area showed a positive correlation between all frequency bands and the MS level [83]. The occipital components demonstrated significant increase in the delta and theta bands [84]. A rise in MS leads to higher delta powers at Fz and Cz, meanwhile theta power decreases [74]. There is a similarity between gamma-band and broadband curve;

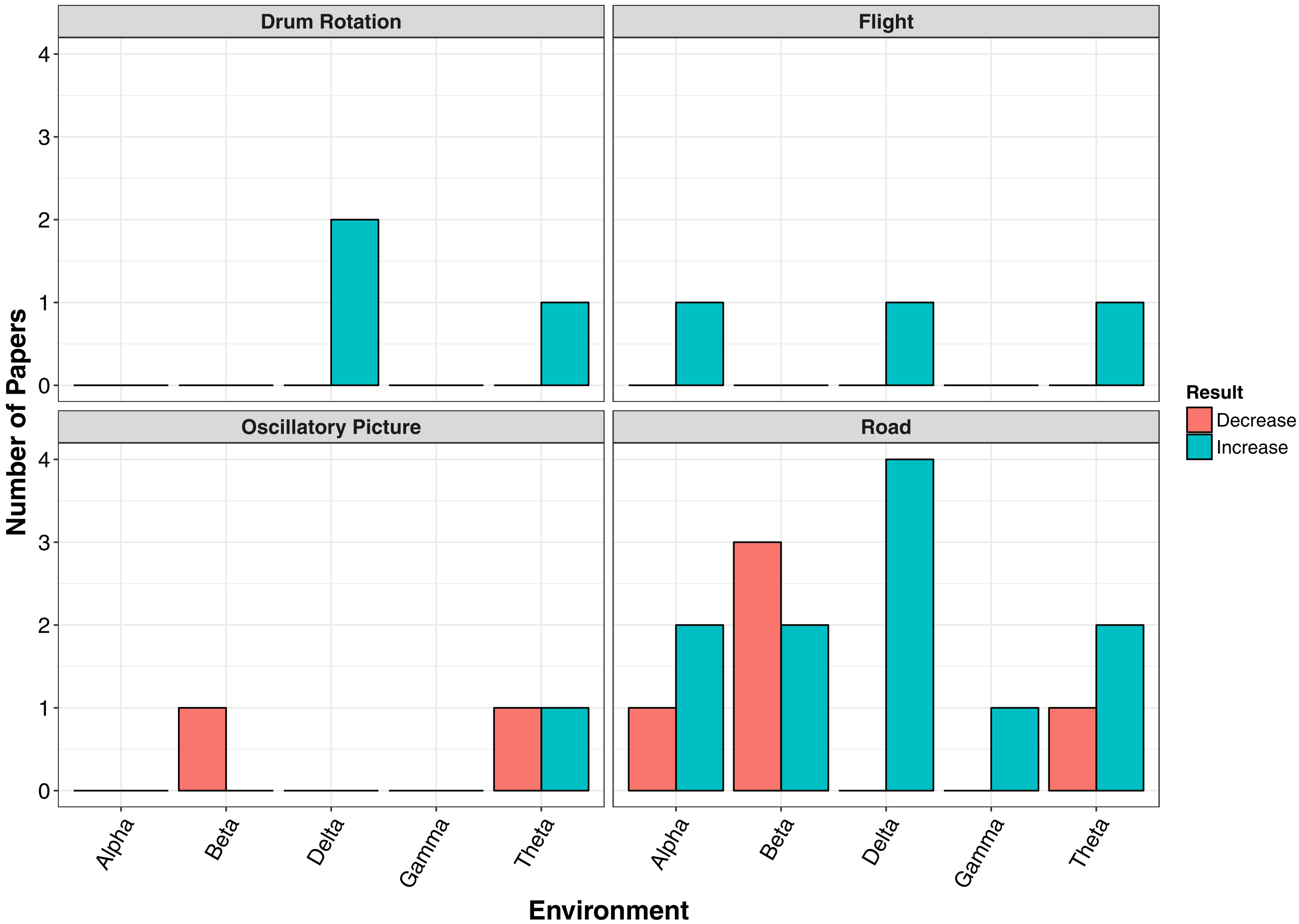


FIGURE 4. EEG activation based on different environments.

alpha band power is highly correlated with the midline occipital brain area; the midline occipital brain area also has the highest correlation with the actual MSL curve [85]. There is a low correlation among delta and theta band powers with increasing sickness level in driving simulators [85].

Many studies exhibited augmentation of theta power in parallel swing [20], rotating chair [86]. Theta band was more in the right motor than the left one [87]. Delta band increased at C3 and C4 when using drum rotation [88] and [21], and also when using cross coupling stimulation to induce MS in curve-road conditions. The gamma and alpha powers are correlated with the level of MS. The gamma strength in the right and the left motor components is greater in comparison with other areas of the brain in winding road conditions [89]. The delta power at F3 and T3 and beta power at F3 and P3 ($13 - 20$ Hz) gradually increased and decreased respectively [8]. In 3D movies, beta activation in the temporal lobe and theta activation in the frontal lobe reduced, while theta power in 2D increased [71].

After comparing VIMS and non-VIMS, significant changes were only obtained in delta at TP9, theta at FP1, and beta at TP10, and alpha at TP9 and TP10 in a driving simulator [78]. Alpha, beta, and theta had negative correlation by simulator sickness questionnaire (SSQ), where delta had a positive relationship with it at both Fz and Cz in driving scenario [74]. To the best of our knowledge, no studies compare the EEG signal in the virtual environment in comparison to real world in MS condition [89]. Generally, Fig. 4 shows the EEG activation in different environments. Delta increased in flight, drum rotation and road [8], [21], [78], [80]. Also, gamma increased only in road [85]. Theta increased in flight and drum rotation [80], [86]. [78], [84]reported it increased while [74] reported it decreased in the road conditions.

Also, Researchers in [71] and [90] evaluated theta power band in oscillatory picture scenarios. In [90], it increased while [71] reported, it decreased. Three studies assessed the beta power band in the road condition. In [8] and [74] it decreased and in [78], it increased. Beta decreased in oscillatory picture scenarios [71]. Alpha power band increased in flight and road [78], [80]; however, [74] reported it decreased. Generally, this figure shows that some EEG power bands were not very similar in the same environments. For example, the result of alpha, beta and theta in road and theta in oscillatory picture are varied based on recorded papers or they have not studied in all environments. For example, beta and gamma only considered in oscillatory picture and road condition. No papers assessed these power band changes in the other environments. To the best of our knowledge, no paper studied all EEG power bands and reported whether they have changed or not in different environments. To provide a reliable conclusion, we need to evaluate the activation of other power bands in all possible environments

2) STUDIES ON MEASURING MS USING ELECTROGASTROGRAM (EGG)

Exposing into the virtual environment through optokinetic drum caused more stomach contraction activity [91], [92]. Some studies claimed that gastric myoelectric activities were successful indicators of MS when using drum rotation [42], [93], [94]. Although other researchers failed to obtain similar results [95], [96]. For example, researchers in [95] found that the total EGG changes minute by minute with the severity of MS while the total power did not change. Reference [97] found the adipose tissue, shape and topography of the stomach cause variations in EGG amplitude among different individuals. The direction of gravity vection and gravity axes determines the severity of MS and nausea feeling. If they are orthogonal to each other, the severity and frequency of sickness is more when they are coincident [98].

Different research studies scored the same participants' symptoms differently [99]. In other words, no standard symptoms that can be used for all experiences [100]. Oscillatory picture plays an important role to augment the EGG [101]. Gastric tachyarrhythmia activation is positively correlated to parasympathetic variables, but negatively correlated to sympathetic. As a result, these nervous systems play an important role in inducing sickness in the virtual environment [91], [102].

3) STUDIES ON MEASURING MS USING ELECTROOCULOGRAM (EOG)

Eye blink and eye movement are some factors showing the level of MS. In this regards, Eye blink was observed to fluctuate during the MS experiment. The mean eye-blink rate (number/min) was lower in the initial minutes of navigation as compared to the baseline rate and it was considerably greater during the middle of the trial in the driving simulator (Kim, Kim et al. 2005). The number of eye blinks per epoch were found more in HMD than monitor displays [103].

Eye tracking monitors can record the total number of saccadic eye movements, pupil diameter, number of eye blinks, horizontal and vertical eye positions according to the report in 3D/2 D virtual environment experiment [39]. In a pilot study, Foveal retinal slip velocity plays an important role in increasing the level of visually induced MS [104]. Some studies in drum rotation and pilot studies claimed that unnatural eye motion can irritate VIMS and eye fixation can abolish the effect of it [16], [19], [41], [105], [106].

4) STUDIES ON MEASURING MS USING SKIN CONDUCTANCE LEVEL (SCL)

Skin conductivity of all subjects was high during the final minutes of experiencing the virtual environment compared to the baseline in the driving simulator as well as drum rotation [8], [91]. It is concluded that there is less conductivity when a HMD is used rather than a monitor display [103]. In cross coupling stimulations, Galvanic Skin Response (GSR) of the forehead and palm were compared. Results showed that the forehead was more sensitive than the palm in both phasic and tonic [107]. The amplitude and frequency of a measurement on the forehead in forward riding condition was higher than reverse side. Greater nausea ratings were reported during the final minutes of forwarding riding than backward [107]. Rats' sweating reduced the resistance of skin response when stimulated in virtual environments [108].

Another research studied the correlation between sweating symptoms and nausea ratings after navigating into a drum rotation [104]. Even though the GSR was higher in driving than resting conditions, there was no considerable change between values. SCL increased after subjects were immersed in different visual stimulation such as watching a visual oscillatory and optokinetic drum [91], [101], [109]. Sweating was high for people who feel nausea or vomiting after using elevator [110].

5) STUDIES ON MEASURING MS USING HEART RATE (HR)

HR was studied by many researchers. HR was shorter during driving as compared to the baseline [8], [91]. HR increased when subjects were immersed in the driving simulator [111]. Other researchers found similar increases in HR during optokinetic stimulation for their test [112]. HR has been found a great indicator of MS in the virtual environment and non-virtual environment [113]. It is reported that HR is higher in the 3D virtual environments than in 2D virtual environments as a result of visual fatigue [39], [114], [115].

Even though HR declined during the initial period when driving was started, it increased during the final minutes of driving [78]. It is found that there was no correlation between HR and nausea when riding a roller coaster [107], [116], [117]. Root Mean Square and Standard Deviation of HR dropped during forward ride while it did not change during backward ride [107]. Oscillatory picture plays an important role in increasing HR [101]. HR was lower when using HMD as compared to monitor display [103] whereas other studies found changes due to lack of arterial pressure [118].

6) STUDIES ON MEASURING MS USING BLOOD PRESSURE (BP)

BP was observed to have an upward trend when subjects were exposed to virtual environments in the driving simulators [111]. Other researchers found a similar result in optokinetic stimulation for their test [112]. Reference [114] reported that BP is greater in 3D than 2D virtual environment. In driving simulators, diastolic remained stable whereas systolic increased. Also, both decreased during last the minutes of driving [78]. In review of visual and vestibular stimulation, diameter of retinal vessels and peripheral circulation decreased when MS level was increased [119]. Some parameters in blood change such as PH and paCO2 levels, plasma proteins and ADH [119].

Mean arterial BP dropped remarkably during the initial duration of head roll in the flight simulator. After changing the altitude of flight, no changes were witnessed between the trail and recovery conditions [39]. Epinephrine and vasopressin of the blood increased significantly during rotation in the experiment as compared to the baseline [93]. Oscillatory picture plays an important role in augmenting the BP [101]. One area of research was conducted in a cab elevator and it was observed that BP increased [110]. It demonstrated that the maximum amplitude of Photoplethysmogram diminished during stimulation [8]. No significant effects were found for changes in pulse amplitude for both HMD and monitor display [103].

7) STUDIES ON MEASURING MS USING BR

Compared to the baseline or the initial minutes of driving in simulators, BR significantly increased in the middle and final stages [8]. In a review of Kennedy and Frank, changes in respiration rate, yawning and air swallowing are the side effects of MS [119]. Playing video games through monitor display raises BR [120]. In addition, oscillatory picture plays an important role in augmenting the respiratory rate [101]. Many individuals feel nausea or vomiting while using an elevator and they were observed to have an increase in respiration [110]. The respiration rate decreased as compared to baseline in the driving simulator [8]. The average breath was varying for both HMD and monitor condition, and it was high when subjects played the game than initial and final minutes of playing [103].

8) STUDIES ON MEASURING MS USING BODY TEMPERATURE (BT)

Fingertip skin temperature decreased during the MS [8]. One of the indicators of sickness which is mentioned in most studies is coldness in BT [119]. To the best of our knowledge, no study illustrates the effect of ventilation on MS while cool air circulation is more likely to reduce the extent of MS. Many subjects experienced feeling clammy after using the HMD [103]. Other researchers observed decrease in temperature on fingertips [121]. Some studies measured rectal [122] or abdominal temperature of rats [123], [124] and it fell when they navigated into a back-and-forth motion. Even though skin temperature decreased from driving to rest conditions, this change was not significant after 5 minutes [74]. During a sea voyage, the BT was lower than normal days [125], [126].

9) STUDIES ON MEASURING MS USING FUNCTIONAL MAGNETIC RESONANCE IMAGING (FMRI)

The medial prefrontal cortex (MPFC) and ventromedial Prefrontal Cortex (vmPFC) was measured by fMRI. The positive relationship between specific parts of the brain and parasympathetic system was observed when MS was reported by subjects [127]. Some asymmetries like eye movement, vection and postural instability may occur as a consequence of desynchronization of the left and right medial temporal lobe [128].

In summary, Fig. 5 shows the changes of physiological signals when subjects incur the feeling of motion sickness based on the number of papers. All papers published in this field showed BT decreased. Most papers reported HR, BP, EGG (bradygastric), SCL and EOG activations were increased [8], [91], [103]. In this research [108] was reported HR and SCL and BP decreased, respectively. Some papers concluded that EGG, SCL, BR and EOG were changing compared to the normal condition while BP [103], [115] and EGG [92], [103] were not changed.

III. NUMERICAL RESULTS FOR OBJECTIVE MEASUREMENT

According to the latest research article, the R-value for EEG signal in frontal lobe (Fz) is $\alpha = -0.524, \beta = -0.695, \theta = -0.842$ and $\gamma = 0.694$ and EEG signal in partial lobe (Cz) is $\alpha = -0.544, \beta = -0.680, \theta = -0.930$ and $\gamma = 0.713$. The ECG average is -0.483 and galvanic skin response is -0.493 [74]. The p-value is calculated for physiological changes. The saccade amplitude is 0.01, heart rate (number/min) is 0.154, respiratory rate is 0.365, skin conductance is 0.01 and skin temperature is 0.459 [118].

IV. DISCUSSION

The relationship between MS and physiological parameters are not necessarily correlated. For example, in the same scenario of driving, HR levels were lower at the final stage of the experiment compared to the initial minutes of driving [8] while this result was not reported by [111]. BP was higher in various experiments only [115] showed there was no correlation between BP and MS. There is a direct relationship between the SCL and MS. In most of the studies, the skin conductivity response is increased when subjects experience MS except in the seasickness studies [108]. The results of BT and BR were similar among all studies.

All research confirmed the correlation between eye movement and MS. Only a few studies focus on FMRI because it is high in cost and also, it is not always possible to record on-line. According to the recording of different parts of the brain, EEG showed different results. The differences among these results are not confined to the condition of the tests including room temperature, humidity, light, seat comfort; however other factors play an important role to obtain various results. In the following section, we will discuss some other contributing factors such as individuals, device and task factors which impact on results.

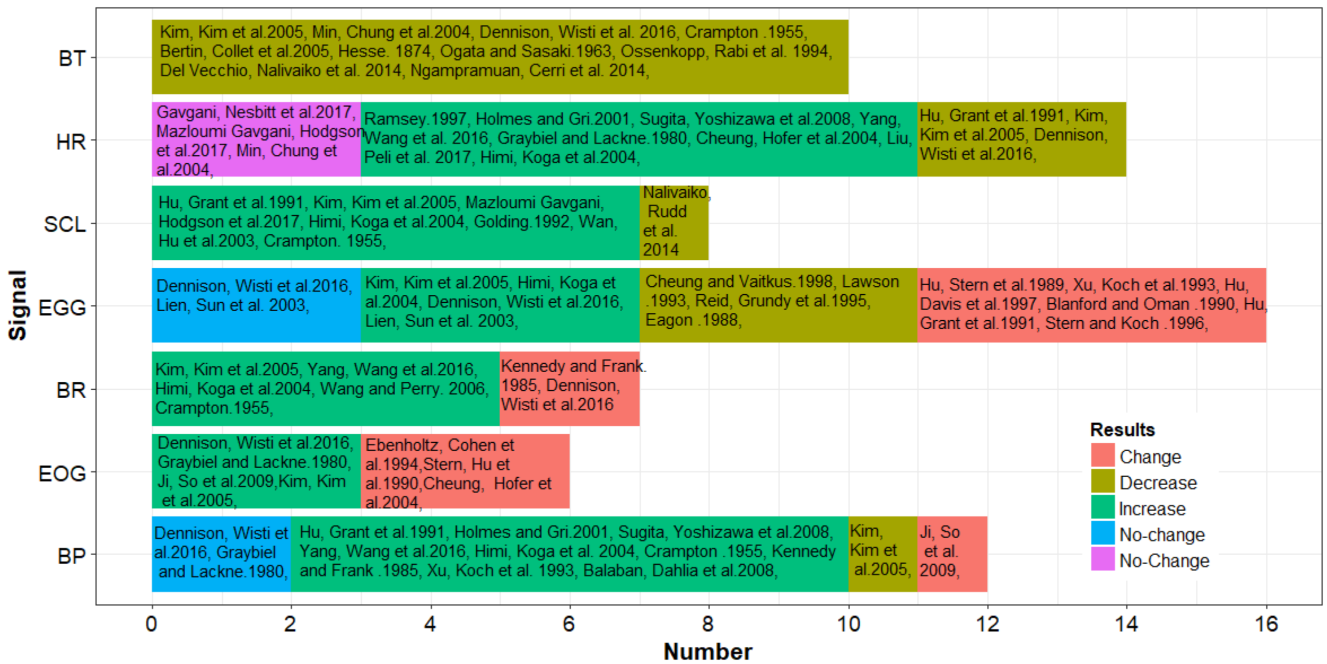
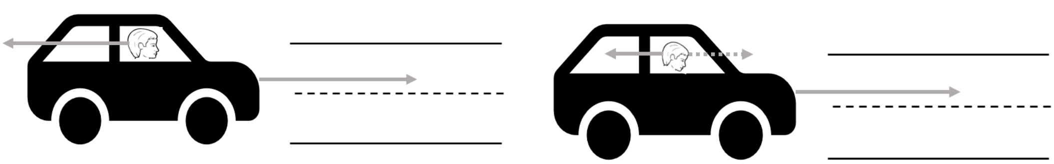


FIGURE 5. Similarity results among different papers based on studying physiological signals. Increasing and decreasing physiological activation can be shown by some papers while others failed to show these changes.



(a) Without vection (b) With vection

FIGURE 6. a) passengers feel acceleration stimulus without introducing the vection, b) Pseudo-acceleration helps to feel less MS as a result of the acceleration stimulus.

A. DIFFERENCES IN STIMULATION RESOURCES

Multi-sensory information causes conflict as there is a mismatch between subjects' experiences and sensory information. Several factors impact the result of research work. One reason is that different researchers used different stimulation to induce MS. A few researchers used visual stimulation [8], [74], [88] while others used vestibular stimulation [20], [21].

B. DIFFERENCES IN SET-UP

Different researchers used varying set up and trails for their research that can impact the result of a test. For example, some researchers compared the severity of MS when watching or playing with 2D and 3D displays [114], [120]. Similarly other papers considered driving simulator [8], [74], [78] while others studied in sea [119], [125], [126] or flight conditions [41], [104]. The direction of stimulation is important and assessed by some studies [91], [107], [123]. Different scenarios may provoke varied levels and rates of nausea symptoms. For example, in Helix coaster riding the severity of sickness symptoms is more than Parrot coaster [117].

C. MS THRESHOLD

MS thresholds are subjective and vary between individuals. In this measure, participants pressed the joystick button when feeling MS. As there was only one degree of variability within this measure, an accurate representation of the degree of MS may not be recorded. This feeling is varied among different subjects. As a result, the physiological changes, which are recorded at onset of cybersickness/MS is not the same among other subjects [84].

Time delay, being the point at which the button is pressed when a subject is feeling MS may vary between subjects and is a factor that may change the result of physiological rates like EEG power band at MS [84].

D. BIO FEATURES

- **Gender** is another factor increasing the susceptibility of cybersickness/MS. Women have a greater feeling of cybersickness compared to men [129] because they do not have wide eyed vision to the same extent [130].
- **Age** is another factor that should be considered. People in their early years of life (2 − 12) experienced more cybersickness/MS than other age groups. Particularly, when subjects are around 50 years old, the occurrence of sickness is almost rare, while children are more susceptible to cybersickness [2]. Other work stands exactly the opposite [131].
- **Health condition** may increase the susceptibility of cybersickness/MS when subjects were exposed to the virtual environment. Any feelings such as upset stomach, flu, ear infection, hangover, stress, headache, fatigue, sleep loss or respiratory illness lead to a perception of MS [132].
- **Individuals' activation** in the virtual environment is important. Participants who take part in virtual environments and do some activations such as driving or playing experience less cybersickness than passive participants and players [133], [134]. This is due to the expectation that drivers or players can predict their performance.
- **Flicker** causes eye fatigue [135] and lack of accurate head tracking increases the susceptibility of cybersickness [129]. Some factors such as lateral and fore-and-aft motion, longitudinal and lateral seat position, forward visibility, air temperature, time of departure are important factors to increase the level of sickness of passengers who are seated on the bus [136]. Other items such as field of view [137], the time duration of virtual navigation [138], virtual oscillatory [139] or double-axis rotation [140] contribute to induce more cybersickness, as compared to a stationary scene [139] or single axis [140] and direction of virtual motion [107], [141]. Some activities such as reading, texting, talking on the phone, watching movies/TV, playing games and working in downwards gaze aggravated and sleeping or watching the road did not worsen MS [142].

E. DIFFERENCES IN MEASURING PROTOCOL

Different techniques are used to measure the body sweating [104], [107], [109]. One method is recording the galvanic skin response. The other one is to assess the changes in sweating rate based on measuring the water vapour through a capsule placed on the skin [143]. The second method is done with delay as measurement after re-absorption is required [108], [116]. Firstly, the sweating fills the ducts of glands. Then, it breaks the elastic resistance wall.

F. DIFFERENCES IN POSITION OF RECORDING

Position of electrodes may increase the diversity of results when recording EEG signals. Stern et al. Six different shapes of electrodes in different experiments were used [99]. Orthogonal shape of electrodes produced different tachygastric occurrences [144]. Tachygastric divides into a high and low level. In the low level, basic electrical rhythm is correlated with nausea activities. As a result, when participants are immersed into the virtual environment, there is either no or small change in tachygastric activities [145].

Another difference in results is in regard to the position of sensors affected from sweating [146]. Fingers and forehead were more sensitive to provocation. Comparing between palmar and dorsal, palmar showed the action (thermal response) simultaneously and dorsal showed it with delay [107], [147]. Finally, another difference in results is due to the phasic and tonic response. Phasic forehead and tonic finger had the highest and lowest changes when subjects were exposed to the virtual environments [148]. There is a negative and positive correlation among parasympathetic and sympathetic nervous systems with gastric tachyarrhythmia activation. As a result, these nervous systems play an important role in inducing sickness in virtual environment [91], [102].

G. DIFFERENCES IN SIZE OF DISPLAY AND DURATION OF TIME

The severity of cybersickness while using a small screen display such as the HMD increased significantly in comparison with large screen displays such as monitor [103]. Different results have been obtained based on the virtual conditions and time. For example, the mean Cybersickness is 39 when the subjects were exposed to 9.5 minutes multiple screen projection (Lo and So 2001), while it is less than 39 when using the HMD for over 20 minutes [10].

H. ELIMINATING MS IN REAL AND VIRTUAL ENVIRONMENT

Pre-movement is introduced to reduce the level of nausea symptoms. Vection leads passengers to move their center of gravity before acceleration happens and causes them to feel less MS. If the acceleration stimulates, the severity of MS can be decreased by inducing the pre-movement. Fig. 6 configures participant's position before and after introducing vection. In this regard, pseudo-acceleration helps participants to have less backward movement after acceleration. In this experiment, four strain gauges were used to measure the balance of the body and motion of the passengers at the center of gravity. Pseudo visual information induces vection for drivers. This could help passengers feel less symptoms of MS after stimulation [17]

Transcranial direct current stimulation (tDCS) is a brain stimulation for treatment of mental disorders particularly for subjects feeling MS in a real and virtual environment. It applies positive (anodal) or negative (cathodal) current to the brain through electrodes. Then, it facilitates the depolarization or hyperpolarization of neurons. In other words, it works by strengthening or weakening synaptic transmission between neurons. Therefore, anodal tDCS can ameliorate the symptoms of disorientation and postural instability. It relieves the sensory conflict by modulating the cortical excitability of the brain area [149], [150].

Moreover, long term vehicle vibration aggravates the nausea and discomfort feeling of drivers. One solution is to introduce the fuzzy tuned slicing mode controller to reduce the suspension of vehicle vibrations since this type of controller is more likely to reduce the magnitude of body movement and pitch motion, and improve the ride comfort [151]. Stroboscopic vision reduces the effect of MS. When subjects lead to oscillatory visual pictures for 10-15 minutes, they feel discomfort. Subjects did not experience feeling when a strobe light is adapted into the scenario. This device flashes over hundred times per seconds. It adjusts rotation speeds and transfers that objects that are stationary while rotating [152] Finally, vibration and airflow to decrease the effect of MS [153]. Drugs such as Dexamethasone can suppress the effects of MS [154] and pill such as Cannabidiolic acid prevents the occurrence of it [155].

V. CONCLUSION

MS is the disturbance in sense of balance and stability caused by a conflict between human sensory inputs. Hence, repeated motion such as riding in a car, ship, flight or playing in a virtual environment can cause discrepancy between visually perceived motion and the vestibular system's motion sensation. This leads to uncomfortable feelings and symptoms such as malaise, pallor, cold sweating, nausea, vomiting and light-headedness. Solving this problem requires methods to detect, predict and analyse the possibility and onset of MS precisely. The purpose of this review paper is to comprehensively review and discuss the current studies on MS, its symptoms and measurement methods.

In addition, it introduces practical and theatrical methods to minimize and eliminate MS. This review study introduces the different source of MS stimulation and compares the results of different physiological measurement in various studies and set-ups. This study provides all necessary information for measuring and analysing MS in different applications and provides better insights to differing results in similar studies. Based on the current research, the occurrence and severity of MS do not occur only through stimulation. Some factors aggravate the existence of MS such as age, gender, previous experience, health conditions, fatigue, and visual display.

Surface Electrodes should be placed in the best locations of the body to collect signals with higher accuracy. In return, results and processing of data can be achieved with much greater accuracy. In order to reduce the level of MS, some methods are suggested in this study. One option is to reduce the acceleration of the stimulation or implement the fuzzy tuned slicing mode controller. Factors such as repetitive stimulation and a comfortable chair for participants should also be considered. Additionally, implementing the fuzzy slicing mode controller, repetitive stimulations, matching the vestibular system with optic flow and reducing brightness of the lateral scene or homogenizing the road side can be utilized.

In the future, MS research in both real and virtual environments needs objective measurements as they contain a wide range of information and can be used for various applications. The fusion of these measurements can be used to detect MS and more importantly, predict MS. The most critical component of future work will be to study the source MS through objective measurement. Researchers have mostly studied the relationship between physiological changes and conflict among vestibular and visual. However, only a few physiological measurement studies are available about illusory self- motion. Changes in physiological signals when experiencing vection will help us to con- firm the traditional subjective report and also improve our knowledge towards vection.

CONFLICT OF INTEREST

The authors have no conflict of interest to mention.

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