Inducers of Motion Sickness in Vehicles: A Systematic Review of Experimental Evidence and Meta-Analysis

Weiyin Xie[a], *Dengbo He*[a,b,c]*, *Genhao Wu*[a]

[a] Robotics and Autonomous Systems Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China
[b] Intelligent Transportation Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China
[c] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong SAR, China

*Corresponding author. Email: dengbohe@hkust-gz.edu.cn

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- Declarations of interest: none.

Highlights

- We conducted a systematic literature review of motion sickness inducers.
- We identified eight categories of motion sickness inducers in vehicles.
- A meta-analysis was conducted to assess the influence of motion cues.
- Research gaps and future research directions have been pointed out.

Abstract

With the development of intelligent cabins and the popularity of smart devices, motion sickness has become an increasing concern. A number of theories have been proposed to explain the cause of motion sickness in vehicles. However, because of the diversity of the dynamical characteristics, road conditions, and in-vehicle human-machine interaction designs, the influence of the inducers on motion sickness in vehicles has not yet been fully quantified. Thus, in this paper, we aim to review and summarize the influential factors of motion sickness in road vehicles through a systematic review. In total, we identified 57 studies related to influential factors of motion sickness in vehicles, of which, 27 were further included for meta-analysis. In total, we identified eight categories of motion sickness inducers in vehicles, including the type of eye view, non-driving-related task availability, existence of artificial motion cues, head dynamic movement, vehicle dynamics, internal layout of vehicle, individual differences, and others. Most inducers had consistent effects on inducing motion sickness; however, inconsistent results have also been observed in vehicle dynamics, head dynamic movement, eye view, individual difference, and artificial motion cues (i.e., cues regarding the motion states of the ego-vehicle provided through in-vehicle auditory, tactile, or visual interfaces). Additional meta-analysis was conducted for motion cues. It was found that only natural present motion cues (i.e., cues regarding relative movement between the ego-vehicle and the environment through the windshield or side windows) and non-visual artificial anticipatory motion cues (i.e., auditory or tactile artificial motion cues regarding the future motion of ego-vehicle) were effective in alleviating motion sickness. Future research directions have been pointed out. Our study can provide insights into the optimization of vehicle design to mitigate motion sickness among occupants.

Keywords: motion sickness; experimental evidence; meta-analysis; systematic literature review

1. Introduction

The intellectualization of the vehicle cabin has become a tendency in the past few years. With the development of microelectronics and communication technologies, an increasing number of infotainment functions (e.g., video streaming in Polestar, Golson, 2021) have become available in vehicles. Even in vehicles without infotainment systems, passengers also tend to spend their commute time on smartphones or tablets (Hamadneh & Esztergár-Kiss, 2022). These technologies can improve the ride experience in vehicles and also bring tremendous economic benefits. For example, according to a recent report, the average commuting time among the 42 biggest cities in China is as high as 72 minutes (Chen, 2021). The commuting time, if being utilized for work, can significantly promote social efficiency. However, although the intellectualization of vehicle is of economic and social value, the public still have concerns about the smart cabin and the motion sickness (or carsickness) in vehicles is one of them.

Motion sickness has been widely studied in past decades, in not just vehicular areas, but also aviation (e.g., Turner et al., 2000), rail transit (e.g., Suzuki et al., 2005), and human-machine interface (HMI) domain, such as virtual reality (e.g., Chang et al., 2020). Motion sickness is usually defined as a kind of physical discomfort caused by passive movement of the human body. The typical symptoms of motion sickness include malaise, nausea, and even emesis (Smyth et al., 2021). Further, some previous research has pointed out that compared to drivers, motion sickness is more likely to occur among passengers (Rolnick & Lubow, 1991), especially when they engage in non-driving-related visual tasks such as reading texts and watching videos (Turner & Griffin, 1999a). For highly susceptible occupants, motion sickness might occur even without engaging in visual tasks. Obviously, motion sickness would impair the user experience and decrease the public acceptance of intelligent cabins in vehicles.

Motion sickness could be predicted based on a mathematical model. For example, motion sickness does value (MSDV), as an objective mathematical approach, was used to quantify the motion sickness induced by vehicle dynamics (Saruchi et al., 2021). However, although the methods of mathematical models can be used to predict motion sickness based on vehicle dynamics or head dynamic movement, they fail to consider the individual differences and the impact of context information (e.g., visual cues). For example, previous research has identified an inconsistency between mathematical estimation and subjective rating (Saruchi et al., 2021). At the same time, physiological signals (e.g. electrocardiogram (ECG), facial skin temperature, and body movement) can also be used to evaluate motion sickness (Keshavarz et al., 2022; Wibirama et al., 2018). For example, Keshavarz et al. (2022) found that changes in facial skin temperature and body movement were the strong indicators of visually induced motion sickness (VIMS) and Wibirama et al. (2018) found that heart rate variability measured by ECG was a reliable indicator of VIMS. However, there is still no standard way of quantifying motion sickness using physiological signals as the accuracies of physiological measurement vary across studies. This might be because physiological responses are highly susceptible to environmental conditions (e.g., the GSR is associated with cabin temperature, Maulsby & Edelberg, 1960) and even cognitive states of participants (e.g., the heart rate increases with increased workload, Meshkati, 1988). Further, participants might be able to self-adapt to inducers of motion sickness (Keshavarz et al., 2022; Smyth et al., 2021), nullifying the effectiveness of physiological signals as measures of motion sickness. From this perspective of view, the subjective ratings might be a more reliable measure of motion sickness. For example, the questionnaire methods, such as the motion sickness assessment questionnaire (MSAQ), MIsery SCale (MISC), fast motion sickness scale (FMS), and simulator sickness questionnaire (SSQ) have been used in numerous studies for the subjective rating of motion sickness (Saruchi et al., 2021).

At the same time, researchers have also been trying to identify the inducers of motion sickness. In general, previous research categorized the motion sickness inducers into two major categories (Saruchi et al., 2021): the occupant-related inducers (e.g., sensory conflict, postural instability, failure to anticipate future movement, head tilting towards lateral acceleration direction during cornering, subjective vertical conflict, psychology, and in-vehicle odor) and vehicle-dynamics-related inducers (e.g., low frequency of vertical oscillation, low frequency of fore-and-aft oscillation, low frequency of lateral oscillation and high lateral acceleration resulted from steering's angle). In order to better explain the causes of motion sickness in vehicles, multiple theories have been proposed. For example, the theory of sensory conflict (Reason & Brand, 1975) attributes the cause of motion sickness to the mismatch of vestibular signals, visual signals, and somatosensory motion cues. Specifically, occupants in a vehicle can visually perceive the movement of the body relative to the environment while the somatosensory motion cues indicate that the body is stationary. These contradictory signals can lead to motion sickness. Thus, providing information regarding the motion states of the ego-vehicle (i.e., motion cues) that are consistent with the vestibular signals may alleviate motion sickness (Yusof et al. 2020). It should be noted that the motion cues can be both artificial motion cues (i.e., cues provided through in-vehicle auditory, tactile, or visual interfaces) and natural motion cues (i.e., cues regarding relative movement between the ego-vehicle and the environment through the windshield or side windows). As another explanation, the theory of postural instability (Riccio & Stoffregen, 1991) states that the occupants' decreased control ability of their bodies in movement can lead to motion sickness, which is the case for passengers in vehicles. Further, the weak motion anticipation of ego-motion among passengers in vehicles has been used to explain the higher susceptibility of motion sickness among passengers compared to that of drivers (Golding & Gresty, 2005).

However, previous research rarely compared the influence of different inducers or theories, which is a major research gap at the current stage, given that motion sickness in vehicles may be attributed to multiple inducers simultaneously (Schmidt et al., 2020) in certain situations and different inducers may contribute differently to motion sickness. Thus, in order to better guide the design of the in-vehicle HMIs and vehicle control algorithms, it is necessary to thoroughly review the literature that targets inducers of motion sickness in vehicles and quantitatively assess the effects of these inducers. Being different from existing review articles on motion sickness (e.g., Saruchi et al., 2021) that focused on the causes, measurements, and solutions of motion sickness in autonomous vehicles, the scope of our study targeted the experimental evidence of motion sickness inducers in vehicles (either controlled by human drivers or driving automation). Considering the potential issues of physiological measures and mathematical models, we adopted subjective measures as the metrics of motion sickness. Specifically, only the experiments using subjective ratings as the measure of motion sickness were included in the literature review and meta-analysis.

2. Methods

2.1. Data Sources and Search

Targeting articles providing experimental evidence on the effects of potential inducers on motion sickness, we elicited the keywords according to the causes of the motion sickness mentioned in previous research. Specifically, as shown in Figure 1, "motion sickness" and "vehicle" (or their synonyms) were mandatory. Then, one of the words related to the inducers of motion sickness (or their synonyms and equivalences) was combined with these two mandatory keywords in the search. Four databases were searched, including Scopus, PubMed, Web of Science, and IEEE Xplore. No temporal restrictions were set. Searches were first conducted on 15th October 2022 and were updated on 15th August 2023. Finally, 626 studies were identified from the search, of which the time span was from the year 1959 to 2023.

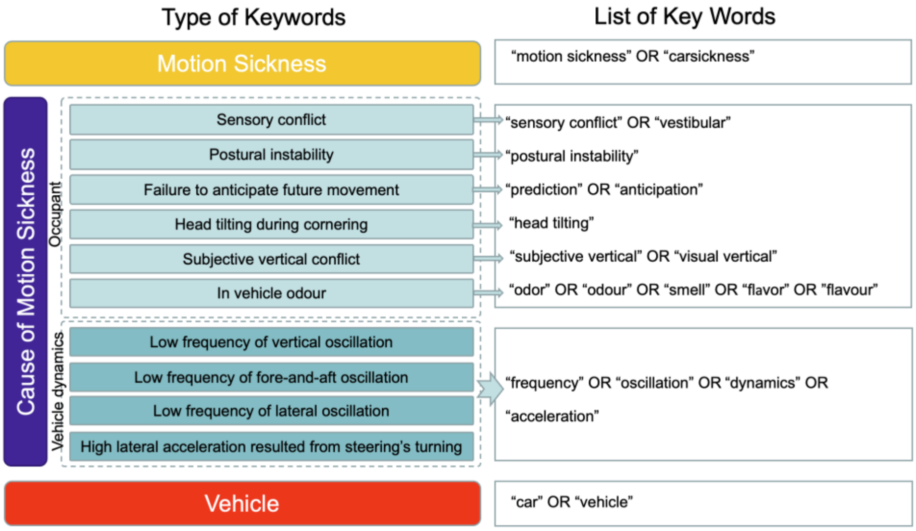


Figure 1. Keywords used for searching

2.2. Inclusion Criteria

As the aim of our study is to review the experimental evidence of motion sickness in vehicles and quantify the inducers, the following criteria were set to further screen the identified literature from keyword search, i.e., the studies should:

- Contain experiments on motion sickness in vehicles (either in a simulated environment or real vehicles on the road). This is because biased responses might be collected using a survey alone (it is difficult to recall the severity of motion sickness accurately if not reported immediately after experiencing it). Further, pure medical, biological, or genetic studies cannot directly provide experimental evidence on the influential factors of motion sickness in vehicles.

- Investigate the influential factors of motion sickness in vehicles and all influential factors must reflect an attribute within a real vehicular/road context, because the motion-sickness-related findings in other transportation methods (e.g., train, ship, and aircraft) may not be directly transferable to motion sickness in vehicles.
- Evaluate the severity of motion sickness using subjective measures, as the physiological measurement or mathematical estimation alone may be less reliable compared to subjective measurement.
- Include at least one continuous or multi-level influential factor of motion sickness as the independent variable and the subjective rating of motion sickness as the dependent variable.

Guided by the above-mentioned criteria, we examined the title and abstract of the identified literature followed by full-text screening. It is noteworthy that, the experimental procedures ought to be executed either within actual vehicles or using driving simulators (i.e. simulators with cabin environment). In cases where the experiments are carried out utilizing alternative simulators (e.g., oscillator, sled) or virtual reality (VR) platforms, it is imperative that the identified influential factors can be transferred to real vehicles. Thus, for the studies where dynamic characteristics of the simulators were used as independent variables, the dynamic characteristics of these simulators must align with the parameters intrinsic to vehicular dynamics, with horizontal (lateral and longitudinal) movement ranging from 0 to 1 Hz (Griffin &

Newman, 2004), and longitudinal and lateral accelerations under 4 m/s² (Bosetti et al., 2014).

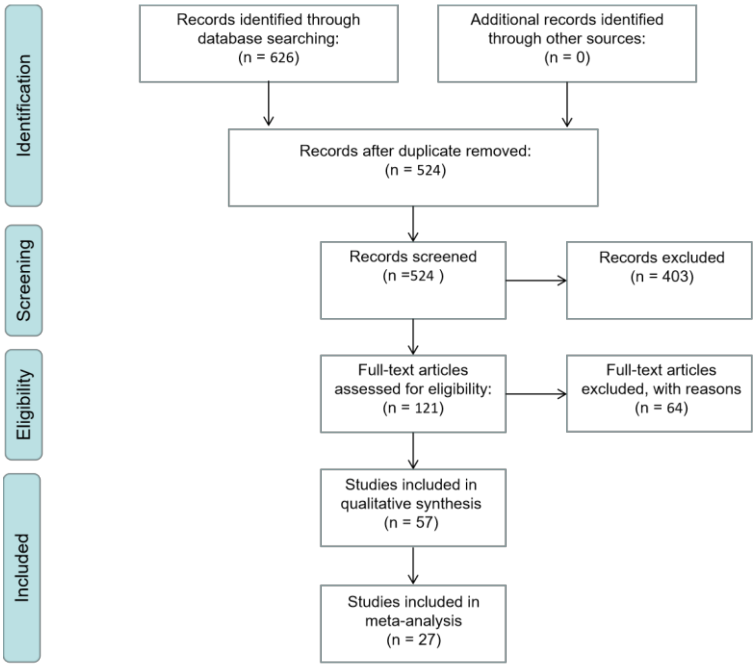


Figure 2. PRISMA Framework for paper selection

The framework of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analysis) was followed during the whole screening process (Figure 2). Two reviewers independently selected the papers following the same procedures. In case of conflicts, two reviewers would negotiate to reach a consensus. Finally, 57 papers were included for qualitative analysis (see Table 1) and 27 papers were used for meta-analysis.

It should be noted that we considered studies that targeted both drivers and passengers in both vehicles controlled by human drivers or driving automation. In the study, if occupants were required to be responsible for driving safety, then they were considered as drivers (4 out of 57 studies); Otherwise, they were considered as passengers (56 out of 57).

Table 1. A summarization of qualified literature (the definitions of the *Category of Motion Cues* and *Treatment* can be found in section 3.1)

Reference	Category of motion cues	Treatment	Experimental environment	Subjective Measurement
Pöhlmann et al., 2022	Others	Partial FOV vs. Full FOV	Virtual reality + rotating chair	MISC
Suwa et al., 2022	Artificial motion cues	Present motion cues (w/ vs. w/o)	Fixed-base simulator (with vertical vibration)	MSSQ/MISC
Sato et al., 2022	Internal layout	Head-fixed vs. earth-fixed coordinate	Fixed-base simulator (with vertical vibration)	MSSQ/MISC
Irmak et al., 2022	Vehicle dynamic	Oscillation (amplitude)	Oscillator (fore-aft)	MSSQs/MISC
Bohrmann et al., 2022	Eye View	Internal vs. external view	Instrumented car	FMS/MSAQ/MSSQs
	Artificial motion cues	Present motion cues with LED (w/ vs. w/o)		
Karjanto et al., 2022	Vehicle dynamic	Driving style (conservative vs. aggressive)	Instrumented car	MSSQ/MSAQ
Li et al., 2022	Eye View	Blindfolded vs. internal vs. external view	6-DoF Simulator	NSQ (points scale unknown)
	Others	Predictability (non- vs. predictable)		
Yunus et al., 2022	Vehicle dynamic	MSDV	Instrumented car	MSSQs/SR
Li & Chen, 2022	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	6-DoF Simulator	MSSQs/MISC
Brietzke et al., 2021a	Eye View	Internal vs. external view	Instrumented car	MSSQs/NSQ (11-points)
	Vehicle dynamic	MSDV		
	Individual difference	Susceptibility to motion sickness		
Hainich et al., 2021	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Instrumented car	MSSQ/SSQ
	Individual difference	Susceptibility to motion sickness		
Irmak et al., 2021	Eye View	Internal vs. external view	Instrumented car	MSSQ/MISC
Maculewicz et al., 2021	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Instrumented car	MSSQ/MISC
de Winkel et al., 2021	Artificial motion cues	Present motion cues (w/ vs. w/o)	Virtual reality + Hexapod motion simulator	MSSQ/FMS
	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)		

Zhao et al., 2019	Others	Predictability (non- vs. predictable)	6-DoF Simulator	SSQ
Kuiper et al., 2020a	Others	Predictability (non- vs. predictable)	Sled	MISC/MSSQ
Kuiper et al., 2020	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Sled	MISC/MSSQ
Mu et al., 2020	Artificial motion cues	Present motion cues (w/ vs. w/o)	Instrumented car	MISC
	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)		
Kuiper et al., 2019	Vehicle dynamic	Oscillation (frequency)	6-DoF Simulator	MSSQ/MISC
Meschtscherjakov et al., 2019	Artificial motion cues	Present motion cues (w/ vs. w/o)	Instrumented car	MSSQs/MSAQ
Ihemedu-Steinke et al., 2018	Artificial motion cues	Present motion cues (w/ vs. w/o)	Virtual reality + 2-DoF simulator	SSQ
Hanau & Popescu, 2017	Artificial motion cues	Present motion cues (w/ vs. w/o)	Bus	MSAQ
Karjanto et al., 2017	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Instrumented car	MSAQ/MSSQ
McGill et al., 2017	Artificial motion cues	Present motion cues (w/ vs. w/o)	Virtual reality + instrumented car	SSQ/MSSQs
Fujita & Nakanishi, 2017	Internal layout	Window shape	Monitor	SSQ
Miksch et al., 2016	Artificial motion cues	Present motion cues (w/ vs. w/o)	Instrumented car	SSQ
Wada & Yoshida, 2016	Eye View	Blindfolded vs. external view	Instrumented car	MSSQ/SR
	Head dynamic movement	Tilt in cornering		
Isu et al., 2014	NDRT availability	No NDRT vs. NDRT	Instrumented car	MSSQ/NSQ (11-points)
Wada et al., 2012	Head dynamic movement	Tilt in cornering	Instrumented car	SR
Butler & Griffin, 2009	Eye View	Blindfolded vs. internal vs. external view	Oscillator (fore-aft, pitch)	Adapted-SR
	Vehicle dynamic	Phase difference (pitch and fore-aft oscillation)		
Morimoto et al., 2008a	NDRT availability	No NDRT vs. NDRT	Instrumented car	NSQ (11-points)
Morimoto et al., 2008b	NDRT availability	No NDRT vs. NDRT	Instrumented car	NSQ (11-points)
	Artificial motion cues	Present motion cues (w/ vs. w/o)		
Kato & Kitazaki, 2008	Artificial motion cues	Present motion cues (w/ vs. w/o)	Instrumented car	Adapted-SR

Kato & Kitazaki, 2006b	Eye View	Blindfolded vs. internal vs. external view	Instrumented car	Adapted-SR
	Artificial motion cues	Present motion cues (w/ vs. w/o)		
Kato & Kitazaki, 2006a	Vehicle dynamic	MSDV	Instrumented car	Adapted-SR
Lin et al., 2005	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Simulator (DoF unknown)	RSSQ
Golding et al., 2001	Vehicle dynamic	Oscillation (frequency)	Instrumented car	MSSQ/SR
Turner & Griffin, 1999b	Vehicle dynamic	MSDV	Bus	IR
Golding et al., 1997	Vehicle dynamic	Oscillation (frequency)	Oscillator (fore-aft)	MSSQ/SR
Probst et al., 1982	Eye View	Blindfolded vs. internal vs. external view	Instrumented car	NSQ (11-points)
Vogel et al., 1982	Others	Seated position (e.g., sitting upright facing forward)	Ambulance car	NSQ (217 points)
Brietzke et al., 2021b	Artificial motion cues	Present motion cues (w/ vs. w/o)	Instrumented car	MSSQs/NSQ (11-points)
	Head dynamic movement	Alignment with gravity-inertial force		
Cho & Kim, 2022	Eye View	Internal vs. external view	Virtual reality + Instrumented car	SSQ
	NDRT availability	No NDRT vs. NDRT		
	Artificial motion cues	Present motion cues (w/ vs. w/o)		
Jones et al., 2019	NDRT availability	No NDRT vs. NDRT	Instrumented car	NSQ (11 points)
	Vehicle dynamic	Driving style (absolute value of acceleration)		
	Individual difference	Susceptibility to motion sickness		
	Individual difference	Age		
DiZio et al., 2018	Vehicle dynamic	Oscillation (frequency)	Instrumented car	NSQ (11 points)
Sugiura et al., 2019	Head dynamic movement	Alignment with gravito-inertial force	Instrumented car	MSSQ/SR
Golding et al., 2003	Head dynamic movement	Alignment with gravito-inertial force	Instrumented car	MSSQ/SR
Wang et al., 2021	Vehicle dynamic	The absolute value of acceleration	Bus	NSQ (5 points)

Yusof et al., 2020	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Instrumented car	MSSQ/MSAQ
Kaplan et al., 2017	Individual difference	Sleep deprivation (4 h vs. 8h)	Oscillator	NSQ (10 points)
Karjanto et al., 2018	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Instrumented car	MSSQ/MSAQ
Jurisch et al., 2020	Vehicle dynamic	The absolute value of acceleration	8-DoF Simulator	MSSQ/MSQ
Salter et al., 2019	Internal layout	Cabin length (short vs. long)	Instrumented car	SSQ/MSSQs
	Internal layout	Direction of seat (0°vs. 10°)		
Kuiper et al., 2018	Internal layout	Display position (high vs. low)	Instrumented car	MISC
Schartmüller & Riener, 2020	Others	No scents vs. Scents (ginger, lavander)	Instrumented car	SSQ
Wijlens et al., 2022	Vehicle dynamic	The absolute value of acceleration	6-DoF Simulator	MSSQs/MISC
Reuten et al., 2023	Artificial motion cues	Anticipatory motion cues (w/ vs. w/o)	Sled	MSSQs/MISC

Note: DoF stands for Degrees of Freedom; SR stands for the Sickness Rating (a 6-point motion sickness rating scale, Golding et al. 2003); Adapted-SR stands for the 6-point motion sickness rating scale adapted from SR, Kato and Kitazaki, 2006a; IR stands for Illness Rating (a 4-points motion sickness rating scale, Lawther & Griffin, 1986); RSSQ stands for the Revised Simulator Sickness Questionnaire; MSQ stands for Motion Sickness Questionnaire (a 78-points motion sickness rating scale, Kennedy et al., 1993); NSQ (n-points) stands for none standardized questionnaires with n number of levels. For all measures of motion sickness, the larger the scale, the more severe the motion sickness. In this table and the following tables, vs. standards for versus, w/ stands for with, and w/o stands for without.

2.3. Meta-analysis

As some inconsistent evidence has been identified in the process of systematic literature review, we further applied the method of meta-analysis to quantify the influence of some potential motion sickness inducers. By integrating the information from relevant studies, meta-analysis could provide a more holistic picture regarding the influence of the potential inducers.

The dependent variable in the meta-analysis was the severity of motion sickness measured by subjective ratings. Different subjective ratings were used in the identified literature, with MSAQ, SSQ, and MISC being the most popular ones. Thus, for the meta-analysis, we adopted the standardized mean difference (SMD, i.e., the difference in mean outcome between groups over the standard deviation of outcome among participants) as the effect size (Higgins & Green, 2008), with the bias removed following Hedges'g (Harrer et al., 2021). It should be noted that if multiple measures were taken in a study, we took the first measure after the administration of motion stimuli for our meta-analysis. The independent variables in the meta-analysis were the presence (versus absence) of the inducers.

The sample size N (i.e., number of trials) and the mean value and standard deviation (SD) of the dependent variables were extracted from the literature directly if available; if only SD was not available, we followed one of the following three equations from the Cochrane handbook (Higgins & Green, 2008) to estimate SD.

$$\mathrm{SD} = \mathrm{SE} \times \sqrt{\mathrm{N}} \qquad (1)$$

$$\mathrm{SD} = \sqrt{\mathrm{N}} \times (\text{upper limit} - \text{lower limit}) / \mathrm{tinv}\,(1 - 0.95, \mathrm{N} - 1) \qquad (2)$$

$$SD = \text{width of IQR} / 1.35 \qquad (3)$$

Where SE was the standard error of the effect size; CI was the 95% confidence interval; IQR was the interquartile range; and tinv returns the t-value corresponding with the two-tailed probability. It is worth mentioning that the adoption of equation (3) was based on the assumption of a normal distribution of the experimental data. In case the distribution of data was not provided, we assumed the normal distribution of the experimental data if the parameter test with the requirement of normal distribution (e.g., t-test) was used in the paper. If none of the above equations worked, we contacted the authors to acquire the SD. If the author did not respond, but the mean was available, we estimated the SDs through a multiple linear regression approach, with the normalized SD as the dependent variable and the normalized mean of the motion sickness severity, the type of cues (natural present motion cues vs. artificial present visual motion cues vs. artificial anticipatory visual motion cues vs. artificial non-visual anticipatory motion cues vs. cue absent), the exposure time and the experimental environment (vehicle vs. simulator) as independent variables (see Section 3.2 for definitions of the levels). For the model selection, we adopted a forward stepwise approach based on the Akaike information criterion (AIC) (Maydeu-Olivares & García-Forero, 2010). Table 2 presents the fitted model (SDs from 8 out of 27 studies were estimated with this approach).

Table 2. Multiple linear regression model for estimating SD

Independent Variables	**Coefficients**	**Standard Errors**	**t**	***p*-value**
Intercept	- 0.068	0.029	-2.317	.03
Mean	0.898	0.038	23.615	< .001

If neither the mean value nor SD were unavailable, but the sample size, median, range, and/or interquartile range were available, we estimated the sample mean and SD following the method by Wan et al. (2014). Finally, if either the mean or the SD can be obtained using the above-mentioned approaches, the study was omitted from the analysis, which led to an exclusion of 1 out of 28 studies.

At the same time, 3 studies only reported the MSAQ difference before and after trials. Assuming that the MSAQ is similar among the population, we adopted the MSAQ value of 15.4 as the pre-trial MSAQ (Karjanto et al., 2018; Karjanto et al., 2022) and estimated the post-trial MSAQ using the difference reported in the studies (3 out of 27). Then, the meta-analysis was performed in R with the "meta" package.

3. Results

In this section, we first discussed the qualitative findings from the literature review. Then we report the meta-analysis results.

3.1. Influential factors

We categorized the inducers that were investigated in the identified literature into the following eight groups:

- Eye view: the locations that the participants were allowed to look at, including internal view (the condition that the side view and front view were blocked and hence participants were not able to perceive the motion of the ego-vehicle), external view (the condition in which the participants have an outside view of the road environment and hence could perceive the motion of the ego-vehicle), and blindfolded view (the condition that participants' eyes were closed or masked, so that they could not see anything).

- Non-driving-related task (NDRT) availability: whether participants were allowed/required to engage in NDRTs or not. Typical NDRTs include watching videos and reading books.
- Artificial motion cues: cues provided through in-vehicle auditory, tactile, or visual interfaces regarding the current (i.e., present motion cues) or future motion states (i.e., anticipatory motion cues) of the ego-vehicle. Typical devices that were used to provide artificial motion cues include bring-in devices (e.g., wristband) and in-vehicle devices (LED mounted in the cabin).
- Head dynamic movement: the motion of occupants' heads in response to vehicle dynamics movements (e.g., turning or accelerating), such as head tilting.
- Vehicle dynamics: including the factors related to the motion of the vehicles, such as oscillation, acceleration, MSDV, and driving style of the driver.
- Internal layout: the internal layout of the vehicle cabin, for example, the length of the cabin, angle of seats, position of in-vehicle displays, and form of windows (e.g., curvature and deformation of windows).
- Individual difference: factors related to the participants, for example, the demographic information (e.g., age and gender), susceptibility to motion sickness, and sleep deprivation.
- Others: other potential inducers that can be related to motion sickness but do not belong to any of the above categories, such as field of view (FOV), predictability

of future motion (e.g., predictable motion vs. unpredictable motion), and odor in vehicles.

A Sankey diagram is further presented to visualize all inducers investigated in the identified literature (see Figure 3), including what has been studied and how much attention the researchers have paid to the inducers. In the diagram, the width of the flow represents the number of literature for each corresponding inducer; the wider the flow, the more attention it has gained from the researchers. From the diagram, it can be observed that the artificial motion cues, vehicle dynamics, and eye views attracted the most attention from previous research. In addition, most of the motion sickness studies were conducted in real cars (e.g., sedans or SUVs), followed by driving simulators. Other studies were conducted using VR headset alone (sitting on a rotating chair), the combination of VR with either car or driving simulators (e.g., a VR-generated virtual environment that is inconsistent with the dynamics of a real car), buses, oscillators, simulators on sled, and monitors alone (e.g., reproducing the curvature and deformation of windows using monitors).

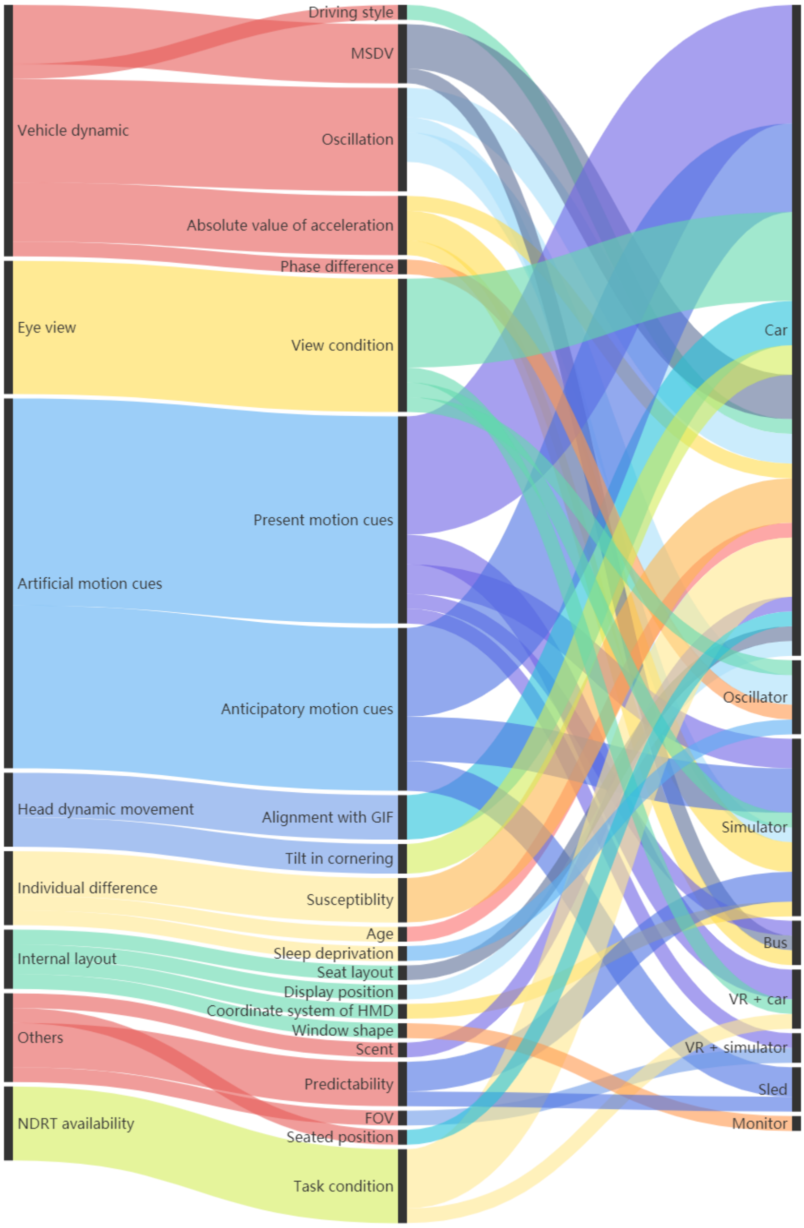


Figure 3. Sankey diagram of summarized influential inducers and experimental environment (definitions of the abbreviations and terms can be found in section 3.1)

3.1.1. Eye View

Nine studies have been identified that investigated the influence of eye view on motion sickness, in which the states of external view, internal view, and blindfolded view were manipulated (see Table 3). The results consistently show that the "internal view" would lead to more severe motion sickness than the "external view". However, the comparisons between "blindfolded view" and "external view" generated inconsistent results in different studies. For example, in a 6-DoF simulator, Li et al. (2022) compared the motion sickness of blindfolded occupants and occupants with an external view (normal view) when the vehicle was controlled by driving automation. The results showed that occupants with an external view experienced more severe motion sickness compared to those who were blindfolded. However, in a vehicle tested on the road, another study conducted by Wada and Yoshida (2016) obtained contradictory results, in which the occupants with an external view experienced significantly lower motion sickness than those with a blindfolded view.

The comparisons between "blindfolded view" and "internal view" also yielded inconsistent results. For example, in Butler & Griffin (2009), two factors were manipulated, i.e., the difference in phase between two kinds of vehicle oscillation (fore-aft & pitch) and the type of eye view (internal vs. blindfolded). Results show that in the in-phase condition (the pitch displacement was in the same phase as the fore-and-aft displacement), the internal view led to more severe motion sickness than the blindfolded view; while in the out-of-phase condition (the pitch displacement was 180° out of phase with the fore-and-aft displacement), blindfolded view led to more severe motion sickness than internal view. These results indicate that the inducing effect of eye view may vary when the vehicle dynamics are different. It may not be enough to draw a unitary conclusion regarding the effects of eye view on motion sickness induction. Future research is needed to further quantify the effects of different inducers as well as their combinations on motion sickness in vehicles.

Table 3. Experiment results for eye view

Reference	**Variable**	**Experimental environment**	**Motion sickness severity**
Bohrmann et al. (2022)	Internal vs. External view	Instrumented car	Internal > External
Li et al. (2022)	Blindfolded vs. External view	6-DoF Simulator	External > Blindfolded
Brietzke et al. (2021a)	Internal vs. External view	Instrumented car	Internal > External
Irmak et al. (2021)	Internal vs. External view	Instrumented car	Internal > External
Wada and Yoshida (2016)	Blindfolded vs. External view	Instrumented car	Blindfolded > External
Butler and Griffin (2009)	Blindfolded vs. Internal vs. External view	Oscillator (fore-aft, pitch)	- In-phase: Internal > Blindfolded > External - Out-of-phase: Blindfolded > Internal > External
Kato and Kitazaki (2006b)	Blindfolded vs. External view	Instrumented car	Blindfolded > External
Probst et al. (1982)	Blindfolded vs. Internal vs. External view	Instrumented car	Internal > Blindfolded > External
Cho and Kim (2022)	Internal vs. External view	VR + Instrumented car	Internal > External

Note: In this table and the following tables, the symbol ">" means that the motion sickness severity before the symbol was higher than that after the symbol.

3.1.2. NDRT availability

In-vehicle tasks that are non-related to driving would be more and more prevalent with the development and popularity of driving automation. We identified four studies that investigated the influence of NDRTs on motion sickness (see Table 4). All these studies indicate that engaging in NDRTs can increase the likelihood of experiencing motion sickness. Further, occupants were found to be more likely to experience motion sickness when reading books compared to when watching videos (Isu et al., 2014).

Table 4. Experiment results for NDRT availability

Reference	Variable	Device	Motion sickness severity
Isu et al. (2014)	No task vs. Video watching vs. Book reading	Instrumented car	Book reading > Video watching > No task
Morimoto et al. (2008a)	No task vs. Movie watching vs. Book reading	Instrumented car	Book reading > Movie watching > No task
Morimoto et al. (2008b)	No task vs. Video watching	Instrumented car	Video watching > No task
Cho and Kim (2022)	No task vs. Book reading	VR + Instrumented car	Book reading > No task
Jones et al. (2019)	No task vs. Tasks (visual search, typing, and reading)	Instrumented car	Tasks > No task

3.1.3. Artificial motion cues

The influence of providing artificial motion cues has been studied in 23 studies (including a study that investigated both types of cues), of which 14 studies investigated the effects of providing present motion cues to alleviate motion sickness in vehicles, while 11 studies focused on providing anticipatory motion cues (see Table 5). It should be noted that in Mu et al. (2020), the navigation information was available to drivers, which can inform both present and anticipatory motion information. According to sensory conflict theory, motion sickness happens when the visually perceived motion is inconsistent with the actual motion sensed by vestibular (Saruchi et al., 2021). Thus, providing artificial motion cues to occupants is believed to reduce this conflict and thus alleviate motion sickness. All of the research we identified provided artificial motion cues to passengers, of which, the motion cue of vehicle presented on HMI has been most commonly explored (13 out of 23). The results from these studies, however, were not consistent. Specifically, 7 out of 14 studies that provided present motion cues and 2 out of 11 studies that provided anticipatory cues found that introducing artificial motion cues would not alleviate motion sickness among occupants. The effectiveness of providing artificial motion cues in alleviating motion sickness will be discussed in the following meta-analysis.

Table 5. Experiment results for artificial motion cues

Reference	**Variable**	**Experimental environment**	**Motion sickness severity (w/ vs. w/o)**
Bohrmann et al. (2022)	Present motion cues (LED)	Instrumented car	No effect
de Winkel et al. (2021)	Present motion cues (LED)	VR + hexapod motion simulator	No effect
Mu et al. (2020)	Present motion cues (HMI)	Instrumented car	Decrease
	Anticipatory motion cues (HMI)	Instrumented car	Decrease
Meschtscherjakov et al. (2019)	Present motion cues (HMI)	Instrumented car	Decrease
Ihemedu-Steinke et al. (2018)	Present motion cues (HMI)	VR + 2-DoF simulator	Decrease
Hanau and Popescu (2017)	Present motion cues (HMI)	Bus	No effect
Miksch et al. (2016)	Present motion cues (HMI)	Instrumented car	Decrease
Morimoto et al. (2008b)	Present motion cues (HMI)	Instrumented car	Decrease
Kato and Kitazaki (2008)	Present motion cues (HMI)	Instrumented car	Decrease
Kato and Kitazaki (2006b)	Present motion cues (HMI)	Instrumented car	Decrease
Brietzke et al. (2021b)	Present motion cues (HMI)	Instrumented car	No effect
Cho and Kim (2022)	Present motion cues (LED)	VR + Instrumented car	No effect
Li and Chen (2022)	Anticipatory motion cues (vibrator)	6-DoF Simulator	Decrease
Yusof et al. (2020)	Anticipatory motion cues (vibrator)	Instrumented car	Decrease
Hainich et al. (2021)	Anticipatory motion cues (HMI)	Instrumented car	Decrease
de Winkel et al. (2021)	Anticipatory motion cues (LED)	VR + hexapod motion simulator	No effect
Karjanto et al. (2018)	Anticipatory motion cues (LED)	Instrumented car	Decrease

Maculewicz and Larsson (2021)	Anticipatory motion cues (audio)	Instrumented car	Decrease
Suwa et al. (2022)	Present motion cues (HMI)	Fixed-base simulator (with vibration)	Decrease
Kuiper et al.(2020)	Anticipatory motion cues (audio)	Sled	No effect
Karjanto et al.(2017)	Anticipatory motion cues (LED)	Instrumented car	Decrease
McGill et al. (2017)	Present motion cues (HMI)	VR + instrumented car	No effect
Reuten et al.(2023)	Anticipatory motion cues (vibrator)	Sled	No effect
Lin et al. (2005)	Anticipatory motion cues (HMI)	Simulator (DoF unknown)	Decrease

3.1.4. Head Dynamic Movement

We identified five studies that investigated the influence of occupants' head dynamic movement on motion sickness. Three of them focused on the alignment of the head to the tilting inertial resultant (gravity and imposed horizontal acceleration, or for short: gravito-inertial force (GIF)); the other two focused on the centrifugal/centripetal head tilting in cornering.

Alignment with GIF: The effects of alignment with GIF on motion sickness are inconclusive. Golding et al. (2003) investigated the influence of active/passive mis-/alignment of head to GIF on motion sickness when the vehicle had fore-and-aft acceleration. In the active mis-/alignment situation the head tilt was actively controlled by participants; while in the passive mis-/alignment situation the head tilt was controlled by an actuated seat. The results showed that active head alignment could postpone the occurrence of moderate nausea compared to active head misalignment. At the same time, in the passive alignment situation, time before reporting sickness was shorter in the aligned condition compared to that in the misaligned condition. Similarly, Sugiura et al. (2019) tested the concept of the lean function of the chassis in order to mitigate motion sickness. With such a function, the occupant's head can be aligned towards the GIF direction and it was found that the motion sickness was significantly alleviated, with a lower percentage of people experiencing severe motion sickness. However, contradictory results have also been observed. In Brietzke et al. (2021b), an actuated seat was designed to compensate for the vehicle's fore-and-aft acceleration so that the spine, thorax, and rotation movement of the occupants' heads can be reduced. The results showed that such an actuated seat was not able to alleviate the motion sickness of occupants.

Tilt in cornering: Changing the head tilt in cornering can affect occupants' susceptibility to motion sickness. Wada et al. (2012) found that the active head-tilt (specifically, adopting a centripetal head-tilt in which participants tilted their heads counter to the direction of centrifugal acceleration) could both postpone the occurrence of motion-sickness-related symptoms and reduce the total symptom scores. Similarly, Wada and Yoshida (2016) found that the centripetal head tilt could reduce the sickness rating significantly.

3.1.5. Vehicle Dynamics

Oscillation: Motion sickness in vehicles was found to be related to both the frequency and the amplitude of the oscillation of the vehicle. In a 6-DoF simulator, Kuiper et al. (2019) found that the participants exposed to the lateral sinus oscillation at 0.2 Hz experienced a higher severity of motion sickness compared to that at 0.35

Hz. However, this difference did not reach a significant level ($p > .05$). Two other studies found that the motion sickness varied with the horizontal (fore-aft) sinus motion frequency of the vehicle, i.e., from 0.1 to 0.4 Hz (Golding et al., 2001) and from 0.35 to 1 Hz (Golding et al., 1997) and the maximum severity of motion sickness was at 0.2 Hz and 0.35 Hz, respectively. DiZio et al. (2018) have compared the influence of a commercial active suspension system (unmitigated ride) and an active cancellation system (mitigated ride) on motion sickness among occupants. The results showed that when the occupants were doing a reading task, the motion sickness could be induced in the frequency range between 0.8 Hz to 8 Hz. The authors attributed the increased motion sickness within this frequency range to the high possibility of retinal slip as a result of the oscillation, because the vestibular-ocular reflex (VOR) that stabilizes the eye in space also has a high gain between 0.8 Hz to 8 Hz. Regarding the influence of the amplitude of the oscillation, Irmak et al. (2022) compared the influence of the amplitude of fore-aft acceleration (1, 1.5, 2, 2.5 m/s^2) on the severity of motion sickness. Results show that the severity of motion sickness (scaled in MISC) increased linearly with the amplitude of oscillation.

The absolute value of acceleration: The absolute value of acceleration may be associated with the severity of motion sickness in vehicles, though no conclusive results have been achieved. For example, in an 8-DoF simulator study, Jurisch et al. (2020) investigated the effects of using an active suspension system on the mitigation of motion sickness, in which the active suspension can reduce the high lateral acceleration of vehicles experienced by passengers. However, no significant benefits have been observed in this study. While in another study, Wang et al. (2021) analyzed the relationship between the motion sickness and bus dynamics. It was found that the time before experiencing motion sickness could be predicted (79.8%) by the lateral acceleration, roll, and pitch angular velocity of the bus. Mixed results were observed by Jones et al. (2019), in which, the authors focused on the association between longitudinal acceleration and motion sickness severity. It was found that when NDRTs were unavailable, no difference in motion sickness between low and moderate acceleration was observed; while when occupants were provided with NDRTs (i.e., visual searching and typing tasks), moderate acceleration led to a higher severity of motion sickness compared to that of low acceleration. The combination of accelerations from different directions was investigated as well. For example, in a simulator study, Wijlens et al. (2022) investigated whether the motion sickness of passengers in an autonomous vehicle was associated with the combination of longitudinal and lateral acceleration. In Condition 1, the vehicle had larger longitudinal but smaller lateral acceleration; in Condition 2, the vehicle had smaller longitudinal but larger lateral acceleration. It was found that the motion sickness in Condition 1 was more severe than that in Condition 2 though the difference did not reach a significant level ($p > .05$).

MSDV: In addition to the absolute value of the lateral acceleration, the MSDV (Wiederkehr & Altpeter, 2013) has also been found to be associated with the severity of motion sickness in passengers and has been commonly adopted in previous research. The MSDV is a mathematically calculated value that can be used to evaluate how vehicle dynamics may lead to motion sickness and can be further categorized as MSDVx and MSDVy, representing the accumulated acceleration in the longitudinal and lateral directions. However, the association between the MSDV and severity of motion sickness ratings is not conclusive either. For example, Turner & Griffin (1999b) found that MSDVx (R^2= 0.77) and MSDVy (R^2 = 0.79) were correlated to the motion sickness of passengers in a bus that was measured by a subjective questionnaire (i.e., a four-point subjective rating of illness and a question about the symptoms of motion sickness). In another study, Kato and Kitazaki (2006a) found that the MSDVs of head lateral motion were significantly correlated with motion sickness ratings in cars. However, in another study focusing on motion sickness in a stop-and-go-scenario, the R^2 of the fitted model was only 2.7% when the eye view condition, MSDV level, and susceptibility to motion sickness were used to predict the motion sickness ratings (Brietzke et al., 2021a). Further, when motion sickness adaption appeared, the MSDV was not able to predict the motion sickness ratings (Yunus et al., 2022).

Driving style: Strictly speaking, driving style cannot be treated as an independent inducer of motion sickness, as the driving style is associated with and can even be defined by a number of factors/inducers described above. For example, an aggressive driving style is commonly associated with large lateral and longitudinal acceleration (Vaiana et al., 2014). However, we still list driving style as an inducer here considering that there are some other characteristics of driving style that are not captured by the above-mentioned factors/inducers, such as the headway distance and the vehicle speed (Khan et al., 2021). Driving style has been found to be associated with drivers' severity of motion sickness in vehicles. For example, Karjanto et al. (2022) found that when NDRTs were allowed for passengers, an aggressive driving style led to more severe motion sickness than that of a conservative driving style among passengers, potentially due to the large absolute acceleration in longitudinal, lateral and vertical directions associated with the aggressive driving style.

Phase difference: The phase difference was defined as the difference between the fore-aft oscillation and the pitch oscillation. Butler and Griffin (2009) found that the phase difference had no significant effect on motion sickness.

3.1.6. Internal Layout

Seat layout: Salter et al. (2019) compared the influence of cabin length (short cabin vs. long cabin), slight seat rotation (0° vs. 10° inboard rotation), and seat orientation (forward vs. rearward facing) on motion sickness. It was found that the cabin length and slight seat rotation were not associated with the severity of motion sickness; while the rearward seating was associated with a higher likelihood of motion sickness compared to that of forward seating.

Display position: The position of the in-vehicle display can affect occupants' head position and their eye view. Previous research found that a higher display position (at the height of the windshield) was more likely to induce motion sickness compared to when the display position was lower (at the height of the glove compartment) (Kuiper et al., 2018). It is explained that, compared to a lower display position, a higher display position led to better visibility of the road environment, which allowed better perception of the motion of the ego-vehicle.

Windows shape: Fujita and Nakanishi (2017) investigated whether and how the warp and deformation of the window can lead to motion sickness in vehicles. Results showed that the vertical deformation of windows was more likely to induce motion sickness than that of horizontal deformation. In addition, if a window had no deformation, then blending the glass of the windows would decrease motion sickness.

Coordinate system of HMD: HMD (Head-mounted display) is a new way of providing information in vehicles. In a simulator study, Sato et al. (2022) investigated the influence of the HMD coordinate system on motion sickness in vehicles when 2D content was displayed in HMD. Two types of coordinates were used, i.e., the head-fixed coordinate (i.e., the content in HMD will move with the motion of occupants' head) and earth-fixed coordinate (i.e., the content in HMD is fixed relative to the ground). It was found that the severity of motion sickness was significantly lower when an earth-fixed HMD was used, as compared to when a head-fixed HMD was used.

3.1.7. Individual Difference

It has been widely acknowledged that individual differences exist in terms of susceptibility to motion sickness (Turner & Griffin, 1999a). Questionnaires have been designed to measure the individual differences in susceptibility to motion sickness, for example, the MSSQ (Motion Sickness Susceptibility Questionnaire) or MSSQs (Motion Sickness Susceptibility Questionnaire—short). As can be expected, a higher susceptibility was found to be associated with a higher likelihood of experiencing motion sickness in most of the identified studies (Jones et al., 2019; Brietzke et al., 2021a; Bohrmann et al., 2022; Meschtscherjakov et al., 2019). However, an insignificant correlation between motion sickness suscepetibility and motion sickness severity has also been reported in one study that investigated the influence of horizontal oscillation on motion sickness using a driving simulator (Kuiper et al., 2019). In addition, the susceptibility to motion sickness has also been found to be associated with occupants' age. For example, Jones et al. (2019) found that occupants aged below 60 were more likely to experience more severe motion sickness compared to those who were above 60. Finally, living habits can also influence the susceptibility to motion sickness. Kaplan et al (2017) found that when exposed to identical linear oscillation, those who had inadequate sleep reported higher levels of motion sickness compared to those with sufficient sleep.

3.1.8. Other Factors

FOV: Pöhlmann et al. (2022) compared the influence of different FOV (full FOV vs. partial FOV) on motion sickness in VR-based simulators but found no significant effect.

Scent: Schartmüller and Riener (2020) investigated the influence of in-vehicle odor (ginger and lavender) on motion sickness but, again, no significant effect has been observed.

Predictability: The motion sickness under automated driving mode and manual driving mode has been compared in two independent driving simulation studies (Li et al., 2022; Zhao et al., 2019). Both studies found that in manual driving mode, active drivers were less likely to get motion sickness, potentially due to the higher predictability of vehicle motion under manual driving mode. Another research compared motion sickness under fore-and-aft motion with different levels of predictability (directionally unpredictable vs. temporally unpredictable vs. fully predictable). The results showed that, in the condition of fully predictable motion, the motion sickness severity was significantly lower than that under two other conditions (Kuiper et al., 2020).

Seated position: A comparative study investigated the occurrence of motion sickness resulting from frequent horizontal linear acceleration in an ambulance car, considering three distinct seated positions: sitting upright facing forward, lying supine with the head pointing forward, and lying supine with the head pointing backward. The findings revealed a notably greater prevalence of motion sickness when seated upright compared to the other two postures. However, no significant difference in motion sickness was observed between the two reclined postures (Vogel et al., 1982).

3.2. Results of Meta-Analysis

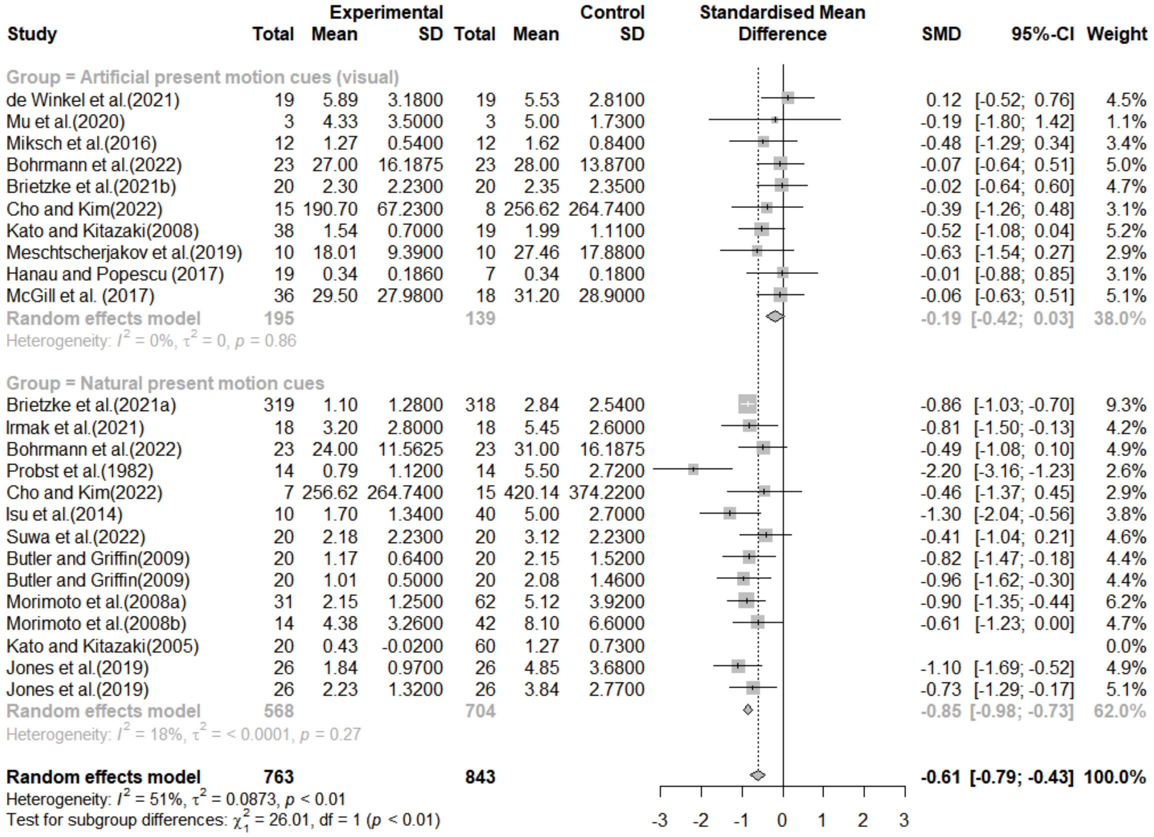
As no conclusive results have been obtained in previous studies, a meta-analysis was conducted to examine the effects of providing motion cues (present motion cues and anticipatory motion cues based on artificial information) on alleviating motion sickness. It should be noted that the presence of the motion cues can be manipulated by more than controlling the availability of artificial motion cues (e.g., by providing navigation information in human-machine interfaces); but can also be manipulated by controlling the eye view and NDRT availability. Specifically, the internal view can block the present motion cue; while with the external view, participants can perceive the present motion cue. Similarly, engaging with NDRTs (e.g., reading a book or watching a video) can affect the perception of the present motion cues as well. Thus, in the meta-analysis, the eye view and NDRT availability were considered as a manipulation of the natural present motion cues (e.g., based on which the occupants can judge the present relative movement between the ego-vehicle and the surrounding environment without using artificial cues). Thus, in the meta-analysis, we further categorized the present motion cues into the artificial present motion cues and the natural present motion cues.

3.2.1. Present Motion Cues

In total, 20 studies encompassing 25 relevant experiments were identified, all of which targeted towards the effect of present motion cues on motion sickness (Table 6). Overall, the effects of natural present motion cues on alleviating motion sickness have been observed in 14 experiments; while the effects of providing artificial present motion cues have been observed in the rest 11 experiments. In all experiments, the artificial present motion cues were conveyed through visual displays, including LED stripes and bring-in devices (e.g., phones and tablets).

For the identified studies, Egger's test was used to examine the publication bias among the identified studies, and no publication bias was observed ($p = 0.13$), indicating that no identified study was systematically unrepresentative of the population of completed studies and disproportionately favored certain outcomes

(Viechtbauer, 2007). Further, the effects of experiments were well-distributed on both sides of the overall mean effect (Figure 5) and the sensitivity test showed that the overall effect was stable, indicating that the influence of each single paper on the overall results was acceptable (Figure 6).



Study	Experimental Total	Experimental Mean	Experimental SD	Control Total	Control Mean	Control SD	Standardised Mean Difference	SMD	95%-CI	Weight
Group = Artificial present motion cues (visual)										
de Winkel et al.(2021)	19	5.89	3.1800	19	5.53	2.8100		0.12	[-0.52; 0.76]	4.5%
Mu et al.(2020)	3	4.33	3.5000	3	5.00	1.7300		-0.19	[-1.80; 1.42]	1.1%
Miksch et al.(2016)	12	1.27	0.5400	12	1.62	0.8400		-0.48	[-1.29; 0.34]	3.4%
Bohrmann et al.(2022)	23	27.00	16.1875	23	28.00	13.8700		-0.07	[-0.64; 0.51]	5.0%
Brietzke et al.(2021b)	20	2.30	2.2300	20	2.35	2.3500		-0.02	[-0.64; 0.60]	4.7%
Cho and Kim(2022)	15	190.70	67.2300	8	256.62	264.7400		-0.39	[-1.26; 0.48]	3.1%
Kato and Kitazaki(2008)	38	1.54	0.7000	19	1.99	1.1100		-0.52	[-1.08; 0.04]	5.2%
Meschtscherjakov et al.(2019)	10	18.01	9.3900	10	27.46	17.8800		-0.63	[-1.54; 0.27]	2.9%
Hanau and Popescu (2017)	19	0.34	0.1860	7	0.34	0.1800		-0.01	[-0.88; 0.85]	3.1%
McGill et al. (2017)	36	29.50	27.9800	18	31.20	28.9000		-0.06	[-0.63; 0.51]	5.1%
Random effects model	195			139				-0.19	[-0.42; 0.03]	38.0%
Heterogeneity: $I^2 = 0\%$, $\tau^2 = 0$, $p = 0.86$										
Group = Natural present motion cues										
Brietzke et al.(2021a)	319	1.10	1.2800	318	2.84	2.5400		-0.86	[-1.03; -0.70]	9.3%
Irmak et al.(2021)	18	3.20	2.8000	18	5.45	2.6000		-0.81	[-1.50; -0.13]	4.2%
Bohrmann et al.(2022)	23	24.00	11.5625	23	31.00	16.1875		-0.49	[-1.08; 0.10]	4.9%
Probst et al.(1982)	14	0.79	1.1200	14	5.50	2.7200		-2.20	[-3.16; -1.23]	2.6%
Cho and Kim(2022)	7	256.62	264.7400	15	420.14	374.2200		-0.46	[-1.37; 0.45]	2.9%
Isu et al.(2014)	10	1.70	1.3400	40	5.00	2.7000		-1.30	[-2.04; -0.56]	3.8%
Suwa et al.(2022)	20	2.18	2.2300	20	3.12	2.2300		-0.41	[-1.04; 0.21]	4.6%
Butler and Griffin(2009)	20	1.17	0.6400	20	2.15	1.5200		-0.82	[-1.47; -0.18]	4.4%
Butler and Griffin(2009)	20	1.01	0.5000	20	2.08	1.4600		-0.96	[-1.62; -0.30]	4.4%
Morimoto et al.(2008a)	31	2.15	1.2500	62	5.12	3.9200		-0.90	[-1.35; -0.44]	6.2%
Morimoto et al.(2008b)	14	4.38	3.2600	42	8.10	6.6000		-0.61	[-1.23; 0.00]	4.7%
Kato and Kitazaki(2005)	20	0.43	-0.0200	60	1.27	0.7300				0.0%
Jones et al.(2019)	26	1.84	0.9700	26	4.85	3.6800		-1.10	[-1.69; -0.52]	4.9%
Jones et al.(2019)	26	2.23	1.3200	26	3.84	2.7700		-0.73	[-1.29; -0.17]	5.1%
Random effects model	568			704				-0.85	[-0.98; -0.73]	62.0%
Heterogeneity: $I^2 = 18\%$, $\tau^2 = < 0.0001$, $p = 0.27$										
Random effects model	**763**			**843**				**-0.61**	**[-0.79; -0.43]**	**100.0%**
Heterogeneity: $I^2 = 51\%$, $\tau^2 = 0.0873$, $p < 0.01$										
Test for subgroup differences: $\chi^2_1 = 26.01$, df = 1 ($p < 0.01$)										

Figure 4. Forest plot for subgroup analysis of present motion cues

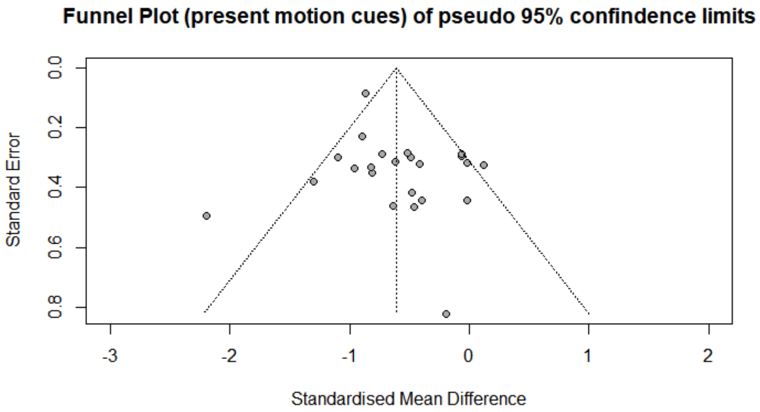
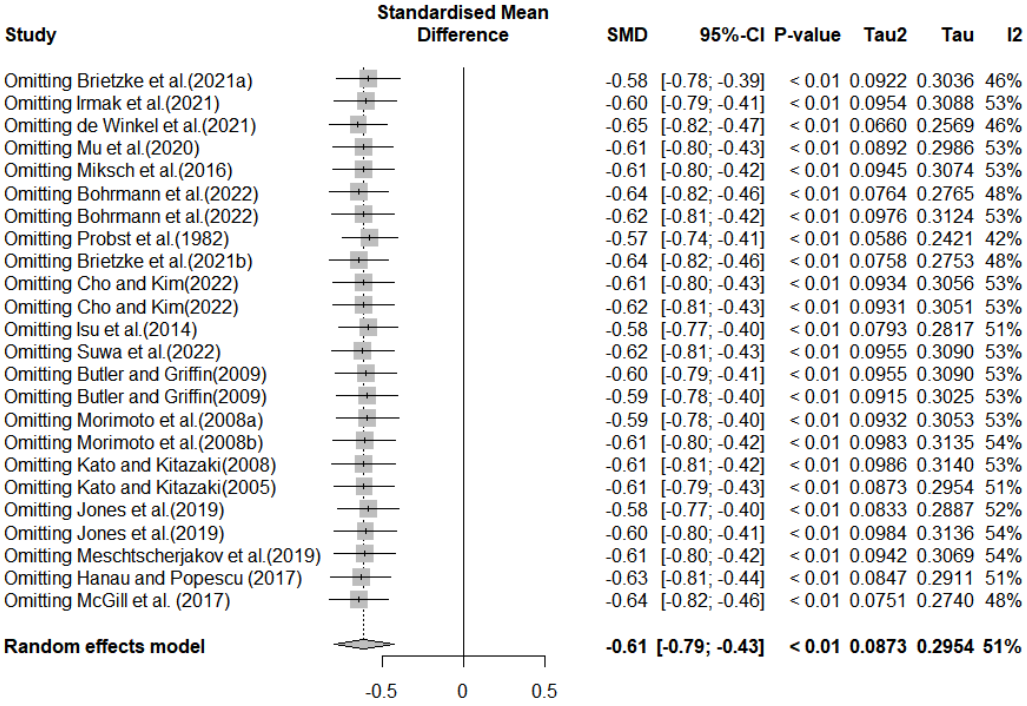


Figure 5. Funnel plot for the test of publication bias regarding present motion cues



Study	SMD	95%-CI	P-value	Tau2	Tau	I2
Omitting Brietzke et al.(2021a)	-0.58	[-0.78; -0.39]	< 0.01	0.0922	0.3036	46%
Omitting Irmak et al.(2021)	-0.60	[-0.79; -0.41]	< 0.01	0.0954	0.3088	53%
Omitting de Winkel et al.(2021)	-0.65	[-0.82; -0.47]	< 0.01	0.0660	0.2569	46%
Omitting Mu et al.(2020)	-0.61	[-0.80; -0.43]	< 0.01	0.0892	0.2986	53%
Omitting Miksch et al.(2016)	-0.61	[-0.80; -0.42]	< 0.01	0.0945	0.3074	53%
Omitting Bohrmann et al.(2022)	-0.64	[-0.82; -0.46]	< 0.01	0.0764	0.2765	48%
Omitting Bohrmann et al.(2022)	-0.62	[-0.81; -0.42]	< 0.01	0.0976	0.3124	53%
Omitting Probst et al.(1982)	-0.57	[-0.74; -0.41]	< 0.01	0.0586	0.2421	42%
Omitting Brietzke et al.(2021b)	-0.64	[-0.82; -0.46]	< 0.01	0.0758	0.2753	48%
Omitting Cho and Kim(2022)	-0.61	[-0.80; -0.43]	< 0.01	0.0934	0.3056	53%
Omitting Cho and Kim(2022)	-0.62	[-0.81; -0.43]	< 0.01	0.0931	0.3051	53%
Omitting Isu et al.(2014)	-0.58	[-0.77; -0.40]	< 0.01	0.0793	0.2817	51%
Omitting Suwa et al.(2022)	-0.62	[-0.81; -0.43]	< 0.01	0.0955	0.3090	53%
Omitting Butler and Griffin(2009)	-0.60	[-0.79; -0.41]	< 0.01	0.0955	0.3090	53%
Omitting Butler and Griffin(2009)	-0.59	[-0.78; -0.40]	< 0.01	0.0915	0.3025	53%
Omitting Morimoto et al.(2008a)	-0.59	[-0.78; -0.40]	< 0.01	0.0932	0.3053	53%
Omitting Morimoto et al.(2008b)	-0.61	[-0.80; -0.42]	< 0.01	0.0983	0.3135	54%
Omitting Kato and Kitazaki(2008)	-0.61	[-0.81; -0.42]	< 0.01	0.0986	0.3140	53%
Omitting Kato and Kitazaki(2005)	-0.61	[-0.79; -0.43]	< 0.01	0.0873	0.2954	51%
Omitting Jones et al.(2019)	-0.58	[-0.77; -0.40]	< 0.01	0.0833	0.2887	52%
Omitting Jones et al.(2019)	-0.60	[-0.80; -0.41]	< 0.01	0.0984	0.3136	54%
Omitting Meschtscherjakov et al.(2019)	-0.61	[-0.80; -0.42]	< 0.01	0.0942	0.3069	54%
Omitting Hanau and Popescu (2017)	-0.63	[-0.81; -0.44]	< 0.01	0.0847	0.2911	51%
Omitting McGill et al. (2017)	-0.64	[-0.82; -0.46]	< 0.01	0.0751	0.2740	48%
Random effects model	**-0.61**	**[-0.79; -0.43]**	**< 0.01**	**0.0873**	**0.2954**	**51%**

Figure 6. Influence analysis of each study for present motion cues

Table 6. Studies included for the meta-analysis of present motion cues

Literature	Baseline Group			Treatment group			Control variable (Baseline vs. Treatment)	Category of inducers	Exposure time (min)	Experimental Environment
	n	Mean	SD	n	Mean	SD				
Brietzke et al. (2021a)	318	2.8	2.5	319	1.1	1.3	Internal view vs. External view	Natural present motion cues	11	Vehicle
Irmak et al. (2021)	18	5.5	2.6	18	3.2	2.8	Internal view vs. External view	Natural present motion cues	30	Vehicle
de Winkel et al. (2021)	19	5.7	2.9	19	5.9	3.3	Present motion cues (w/ vs. w/o)	Artificial present motion cues	10	Simulator
Mu et al. (2020)	3	5	1.7	3	4.3	3.5	Present motion cues (w/ vs. w/o)	Artificial present motion cues	10	Vehicle
Miksch et al. (2016)	12	1.6	0.8	12	1.3	0.5	Present motion cues (w/ vs. w/o)	Artificial present motion cues	10	Vehicle
Bohrmann et al. (2022)	23	28	13.8	23	27	16.2	Present motion cues (w/ vs. w/o)	Artificial present motion cues	20	Vehicle
	23	31	16.2	23	24	11.6	Internal view vs. External view	Natural present motion cues	20	
Probst et al. (1982)	14	5.5	2.7	14	0.8	1.1	Internal view vs. External view	Natural present motion cues	6.33	Vehicle
Brietzke et al. (2021b)	20	2.4	2.4	20	2.3	2.2	Present motion cues (w/ vs. w/o)	Artificial present motion cues	11	Vehicle
Cho and Kim (2022)	15	420.1	374.2	7	256.6	264.7	VR: Internal view vs. External view	Natural present motion cues	5	Vehicle
	8	256.6	264.7	15	190.7	67.2	VR: Present motion cues (w/ vs. w/o)	Artificial present motion cues	5	
Isu et al. (2014)	20	5.3	2.2	10	1.7	1.3	NDRT vs. No NDRT	Natural present motion cues	15	Vehicle
	20	4.7	3.1	10	1.7	1.3	NDRT vs. No NDRT	Natural present motion cues	15	
Suwa et al. (2022)	20	3.1	2.2	20	2.2	2.2	Present motion cues (w/ vs. w/o)	Artificial present motion cues	20	Simulator
Butler and Griffin (2009)	20	2.2	1.5*	20	1.2	0.6*	Internal view vs. External view	Natural present motion cues	30	Simulator
	20	2.1	1.5*	20	1.0	0.5*	Internal view vs. External view	Natural present motion cues	30	
Morimoto et al. (2008a)	62	5.1	3.9*	31	2.2	1.3*	NDRT vs. No NDRT	Natural present motion cues	15	Vehicle
Morimoto et al. (2008b)	42	8.1	6.6*	14	4.4	3.3*	NDRT vs. No NDRT	Natural present motion cues	21	Vehicle
Kato and Kitazaki (2008)	19	2.0	1.1*	38	1.5	0.7*	Present motion cues (w/ vs. w/o)	Artificial present motion cues	30	Vehicle

Kato and Kitazaki (2005)	60	1.3	0.7*	20	0.4	0.0*	NDRT vs. No NDRT	Natural present motion cues	30	Vehicle
Jones et al. (2019)	26	4.85	3.7*	26	1.8	1.0*	NDRT vs. No NDRT	Natural present motion cues	20	Vehicle
	26	3.8	2.8*	26	2.2	1.3*	NDRT vs. No NDRT	Natural present motion cues	20	Vehicle
Meschtscherjakov et al. (2019)	10	27.5	17.9*	10	18.0	9.4*	Present motion cues (w/ vs. w/o)	Artificial present motion cues	20	Vehicle
Hanau and Popescu (2017)	7	0.3	0.2	19	0.3	0.2	Present motion cues (w/ vs. w/o)	Artificial present motion cues	20	Vehicle
McGill et al. (2017)	18	31.2	28.9	36	29.5	28.0	VR: Present motion cues (w/ vs. w/o)	Artificial present motion cues	10	Simulator

Note: In this table and the following tables, the SD stands for standard deviation and n stands for sample size. The SD with * means that the value is estimated through the multiple linear regression model presented in Table 2.

Considering the heterogeneity between the studies ($I^2 = 51\%$, $p < .01$), a random-effects model was adopted for the meta-analysis (see Figure 4). In general, perceiving present motion cues can decrease motion sickness, SMD = - 0.61, with a 95% confidence interval (95%CI) between - 0.79 to - 0.43. Further, to explain the heterogeneous results between studies, meta-regression was conducted to analyze the influence of different factors on motion sickness, including types of cues (natural present motion cues vs. artificial present motion cues), exposure time, and experimental environment (vehicle vs. simulator). For the selection of the models, we adopted a forward stepwise model selection approach based on the AIC. The category of inducers, experimental environment, and exposure time were always kept in the model as they are the variables of interest for this study; while their two-way interactions were added into the model step by step. Table 7 presents the final model. It was found that only the type of cues had a significant effect on the motion sickness severity.

Table 7. The results of meta-regression for present motion cues

Independent Variables	**Coefficients**	**Standard Errors**	**t**	***p*-value**	**95% CI**
Types of cues: Natural present motion cues	-0.6168	0.128	-4.824	.0001	[-0.884, -0.349]
Experimental environment: Simulator	0.1986	0.143	1.394	.2	[-0.100, 0.500]
Exposure time	-0.0005	0.008	-0.063	.95	[-0.017, 0.016]
Intercept	-0.2542	0.168	-1.516	.14	[-0.605, 0.097]

A subgroup analysis for different types of motion cues was then conducted. The heterogeneity of each subgroup becomes lower (natural present motion cue: $I^2 = 18\%$, $p = .3$; Artificial present motion cues: $I^2 = 0.0\%$, $p = .9$) than that of overall heterogeneity. The results for each subgroup showed that only the natural present motion cues (SMD = - 0.85, 95%CI: [- 0.98, - 0.73]) significantly reduced the severity of motion sickness; while the artificial present motion cues had no significant effects (SMD = - 0.19, 95%CI: [-0.42, 0.03]).

The statistical heterogeneity of both subgroups was insignificant, indicating that the variation of outcome within the group was low (Higgins & Green, 2008).

3.2.2. Anticipatory Motion Cues

A meta-analysis was also conducted for the effect of anticipatory motion cues (Table 9). No heterogeneity was observed ($I^2 = 0\%$, $p = 0.6$), thus a fixed effect model (also referred to as "*common effect model*" in R) was used for meta-analysis (Figure 7). It was found that the motion sickness severity can be mitigated by providing anticipatory motion cues (SMD = - 0.35, 95%CI: [-0.56 to -0.14]). An Egger's test was used for the test of publication bias and a sensitivity test was used to analyze the influence of a single experiment on the overall result (see Figure 8 and Figure 9). No publication bias was found ($p = 0.9$) and no single experiment could change the results significantly.

Following the same approach described in section 3.2.1, a meta-regression was constructed to examine the impact of the modality of the cues, exposure time, experimental environment (vehicle vs. simulator), and their interactions on the motion sickness severity. In order to meet the minimal study size criteria for both meta-regression and subgroup analysis (each category should comprise a minimum of 4 studies, Fu et al., 2011), for the modality of the cues, tactile and auditory cues were aggregated as the non-visual cues, whereas other visual information were grouped as the visual cues. None of the factors reached a significant level of .05, as shown in Table 8.

Table 8. The results of meta-regression for anticipatory motion cues

Independent Variables	**Coefficients**	**Standard Errors**	**t**	***p*-value**	**95% CI**
Modal: visual	0.2396	0.251	0.956	.4	[-0.373, -0.853]
Experimental environment: Simulator	0.2826	0.232	1.218	.4	[-0.285, 0.851]
Exposure time	-0.0053	0.018	-0.290	.8	[-0.050, 0.039]
Intercept	-0.5142	0.384	-1.341	.2	[-1.453, 0.424]

Table 9. Studies included for meta-analysis of anticipatory motion cues

Reference	**Baseline**			**Treatment**			**Control Variable**	**Modal of Anticipatory Cues**	**Exposure time (min)**	**Experimental Environment**
	n	mean	SD	n	mean	SD				
Maculewicz and Larsson (2021)	20	3.4	1.7	20	2	1.5	Anticipatory motion cues (w/ vs. w/o) (auditory)	Non-visual	30	Vehicle
de Winkel et al. (2021)	19	5.7	2.9	19	5.8	2.7	Anticipatory motion cues (w/ vs. w/o) (visual)	Visual	10	Simulator
Li and Chen (2022)	20	2.6	1.3	20	1.8	1.3	Anticipatory motion cues (w/ vs. w/o) (tactile)	Non-visual	7	Simulator
Hainich et al. (2021)	8	23.4	15.8	20	13.4	19.0	Anticipatory motion cues (w/ vs. w/o) (visual)	Visual	15	Vehicle
	8	5.6	3.1	8	7.7	7.2	Anticipatory motion cues (w/ vs. w/o) (visual)	Visual	15	Vehicle
Mu et al. (2020)	3	5	1.7	3	4.3	3.5	Anticipatory motion cues (w/ vs. w/o) (visual)	Visual	10	Vehicle
Karjanto et al.(2018)	20	28.3	16.9	20	20.9	5.1	Anticipatory motion cues (w/ vs. w/o) (visual)	Visual	8.5	Vehicle
Kuiper et al.(2020)	20	4.2	1.8	20	3.5	2.2	Anticipatory motion cues (w/ vs. w/o) (auditory)	Non-visual	15	Simulator
Yusof et al.(2020)	20	24.9	16.9	20	20.5	7.5	Anticipatory motion cues (w/ vs. w/o) (tactile)	Non-visual	10	Vehicle
Reuten et al.(2023)	24	3.0	2.0*	72	2.7	1.7*	Anticipatory motion cues (w/ vs. w/o) (tactile)	Non-visual	15	Simulator

We conducted further a subgroup analysis for different cues with different modalities (see Figure 7). No significant heterogeneity was observed for either the visual cues ($I^2 = 0\%$, $p = 0.4$) or the non-visual cues ($I^2 = 0\%$, $p = 0.5$). The synthesis effect size showed that only the non-visual anticipatory cues could reduce motion sickness (SMD = - 0.41, 95%CI: [-0.67 to -0.15]), while the effect of visual anticipatory cues was insignificant (SMD = - 0.24, 95%CI: [-0.61 to 0.13]).

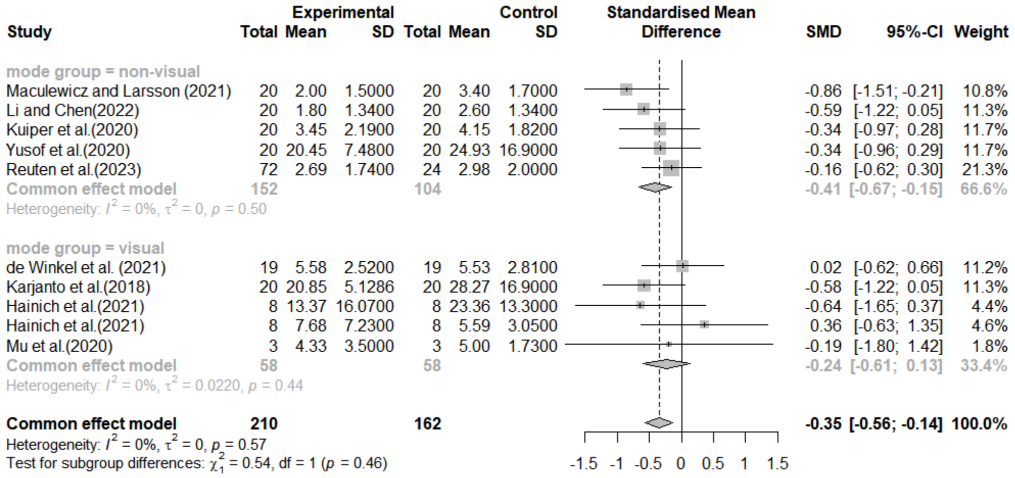


Figure 7. Forest plot for anticipatory motion cues

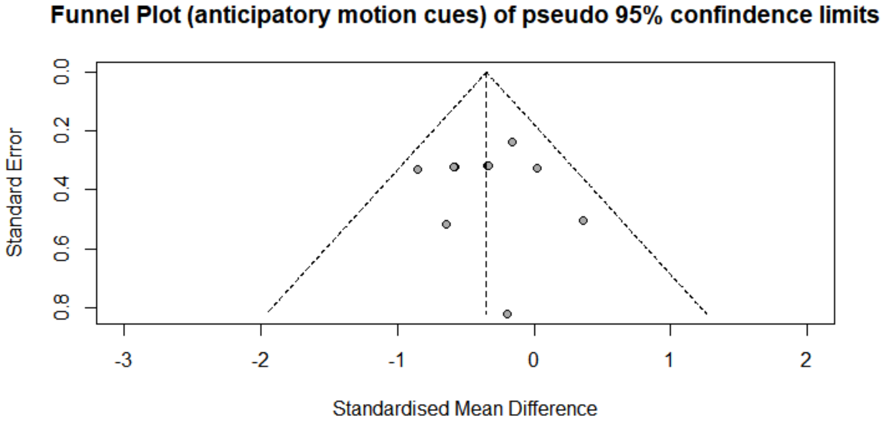


Figure 8. Funnel plot for the test of publication bias regarding anticipatory motion cues

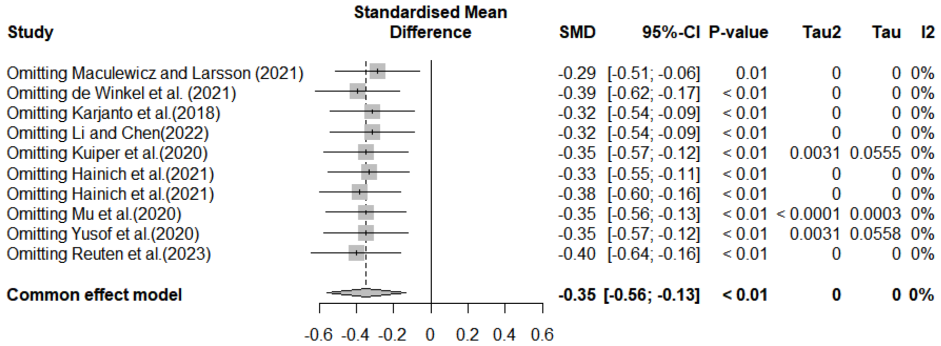


Figure 9. Influence analysis for anticipatory motion cues

3.2.3. A Comparison of The Effect of Cues on Motion Sickness Severity

To further quantify the influence of different cues on motion sickness severity, we performed a Q-test (Borenstein et al., 2021) to compare the effect sizes among natural present motion cues, artificial present motion cues, and artificial anticipatory motion cues. As shown in Table 10, it was found that the natural present motion cues were more effective in reducing motion sickness compared to other types of cues; whereas no difference was observed among other types of cues.

Table 10. Results of the Q-test

Types of motion cues	Natural present motion cues	Artificial present motion cues	Artificial anticipatory motion cues (non-visual)
Artificial present motion cues	Q(1) = 26.51 *p* < 0.001	-	-
Artificial anticipatory motion cues (non-visual)	Q(2) = 11.63 *p* = .003	Q(1) =1.21 *p* = .3	-
Artificial anticipatory motion cues (visual)	Q(2) = 10.4 *p* = .006	Q(1) = .01 *p* = .9	Q(1) = .5 *p* = .5

4. Discussion

With the development of smart cockpits, more and more infotainment systems have been embedded into vehicles. The bring-in devices (e.g., smartphones and tablets) are also becoming increasingly prevalent in vehicles. This raises concerns about motion sickness or car sickness among occupants. Hence, we did a systematic review of experimental evidence of motion sickness inducers and a meta-analysis of inducers whose effectiveness is still inconclusive.

In total, 57 studies were identified following the framework of PRISMA. In general, an increasing number of studies started to investigate the influential factors of motion sickness since 2014 (see Figure 10), potentially due to the rapid development of smart cockpits and the maturation of driving automation. Additionally, starting in 2014, researchers started to pay attention to the influence of internal layout and individual differences on motion sickness.

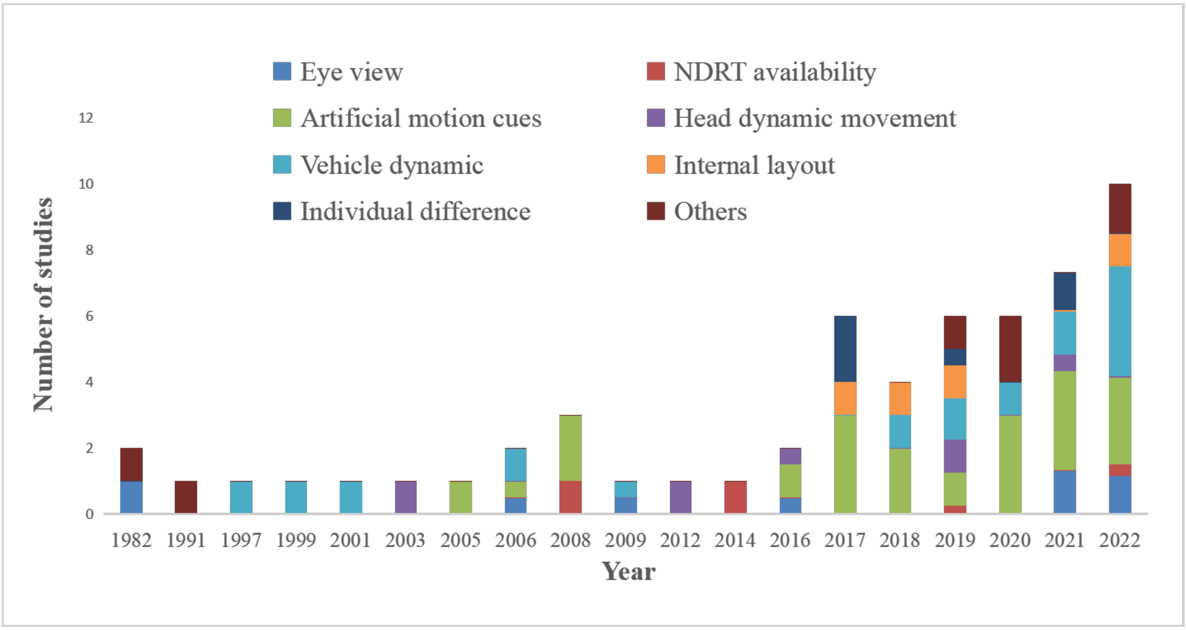


Figure 10. Identified studies on motion sickness in vehicles and the investigated inducers by year (Note: the year 2023 was not included given only one study was identified in 2023).

Based on the results of the included studies, we categorized the inducers of motion sickness in vehicles into eight categories, i.e., eye view (which influences the availability of Natural present motion cues), NDRT availability, artificial motion cues, head dynamic movement, vehicle dynamics, internal layout, individual difference, and others. These 8 categories were further divided into 22 subgroups (see Figure 3). For example, the head dynamic movement can be further categorized into alignment with gravito-inertial force and tilt in cornering.

So far, the effects of providing motion cues have attracted the most attention from researchers, followed by vehicle dynamics and eye view. Different perceptual channels have been used to provide motion cues to occupants in previous research, including visual information, tactile information, and auditory information. Inconsistent results have also been identified regarding providing motion cues. Our meta-analysis provides insights into this discrepancy. We found that in general the present motion cues and anticipatory motion cues were effective in the mitigation of motion sickness. However, only non-visual artificial anticipatory motion cues and natural present motion cues were effective; while neither artificial present motion cues nor visual artificial anticipatory motion cues had effects on mitigating motion sickness. It is possible that occupants' visual channel is more likely to be occupied by other visual information in/outside vehicles; while the auditory/tactical preemption effects (Smith et al., 2009; Wickens et al., 2005) may lead to better effects of non-visual anticipatory cues. Further, the natural present motion cues were more effective in mitigating motion sickness compared to both present and anticipatory artificial motion cues. Further, though some artificial motion cues may alleviate motion sickness, the effect sizes of them are smaller than the natural present motion cues (e.g., non-visual anticipatory cues: SMD = - 0.41 vs. natural present motion cues: SMD = - 0.85). However, this conclusion is highly susceptible to the design of the HMIs that provide the artificial motion cues, which should be investigated systematically.

As for vehicle dynamics, previous research investigated the influence of the oscillation/vibration on motion sickness, including the frequency, phase, amplitude, and the accumulation of acceleration in different directions. The driving style has also been considered. However, for some vehicle-dynamics-related inducers, the conclusion was still inconclusive. The findings regarding individual difference (specifically, the susceptibility to motion sickness) was also inconsistent. Despite the significant positive correlation between susceptibility and motion sickness in most studies, one study (Kuiper et al., 2019) reported an insignificant correlation. This insignificant result in Kuiper et al., (2019) could be attributed to inadequate motion exposure, relatively small sample size, and relatively low mean or variation of MSSQ compared to other studies that obtained significant results.

As for the eye view, it can be considered as being associated with motion cues. Specifically, the blindfold view or internal view removes the motion cues to some extent compared to the external view), which should lead to more server motion sickness compared to the external view. However, inconsistent experimental evidence has been observed when comparing the external view versus the blindfolded view. In the identified literature, 5 out of 6 identified experiments showed that the motion sickness with an external view was less severe than that of a blindfold view, but 1 (out of 6) experiment showed a contradictory result. This study was conducted in a driving simulator and hence the simulator sickness induced by the virtual environment in the external view condition might explain this contradictory result in the study. At the same time, according to the sensory conflict theory, the internal view condition should cause more motion sickness than the blindfold view condition. However, the validity of the sensory conflict theory seems to be correlated with the phase difference between fore-and-aft and pitch oscillation: in the out-of-phase condition, the motion sickness of the blindfold view was more severe than that of the internal view; while in the in-phase condition, more server motion sickness was observed with internal view.

5. Future Work

Among the 57 studies identified in the literature review, passengers were the targeted occupants in 56 studies and only 4 studies investigated motion sickness in drivers. With a high level of driving automation, i.e., SAE Level 3 or higher (SAE International, 2021), however, drivers will be less aware of the vehicle motions and may even be allowed to engage in NDRTs in some conditions. Drivers may have different strategies in allocating their visual attention between NDRTs and driving-related information on the road compared to passengers. Thus, their susceptibility to motion sickness might still be different compared to passengers. Even for SAE Level-2 driving automation (SAE International, 2021), the drivers might be less aware of the future vehicle motion compared to drivers in traditional vehicles. Thus, future research may need to pay more attention to the motion sickness of drivers in vehicles with driving automation.

On the other hand, although previous research explored a wide variety of inducers of motion sickness, little attention has been paid to the interaction effect of these inducers. In other words, how the combination of different inducers may affect motion sickness is still unclear. Actually, previous research has observed several interaction effects between the inducers. For example, with the fore-and-aft oscillation (vehicle dynamics), the mis-/alignment of GIF (head dynamic movement) did not influence motion sickness (Brietzke et al., 2021b); while when there was lateral acceleration, the motion sickness was more severe when the GIF was misaligned (Sugiura et al., 2019). A similar interaction effect between the driving style and NDRTs engagement was also observed (Jones et al., 2019). In vehicles, motion sickness is not solely affected by a single factor. Thus, quantifying the effects of inducer combinations may better support the design of the vehicle in order to alleviate motion sickness. For example, motion sickness can also be affected by the self-adaption capability (Yunus et al., 2022) and individual differences (Turner & Griffin, 1999a). Thus, we should take individual differences into consideration when designing the HMIs that remove the motion sickness inducers.

Finally, with the rapid development of multimodal interaction in intelligent cockpits (MarketResearch, 2023), new in-vehicle HMI technologies have been adopted in vehicles in recent years (e.g., augmented reality, Ohlson, 2022), which may or may not introduce new inducers of motion sickness. Research is needed to evaluate these HMIs from the motion-sickness-induction perspective of view.

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CRediT AUTHORSHIP CONTRIBUTION STATEMNT

Weiyin Xie: Conceptualization, Data curation, Formal analysis, Methodology, Validation, Writing – original draft. Dengbo He: Formal analysis, Funding acquisition, Methodology, Supervision, Validation, Writing – review & editing. Genhao Wu: Data curation, Writing - review & editing.