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SURVEY ARTICLE

Virtual Reality Sickness: A Review of Causes and Measurements

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ABSTRACT

In virtual reality (VR), users can experience symptoms of motion sickness, which is referred to as VR sickness or cybersickness. The symptoms include but are not limited to eye fatigue, disorientation, and nausea, which can impair the VR experience of users. Though many studies have attempted to reduce the discomfort, they produced conflicting results with varying degrees of VR sickness. In particular, a visually improved VR does not necessarily result in decreased VR sickness. To understand these unexpected results, we surveyed the causes of VR sickness and measurement of symptoms. We reorganized the causes of the VR sickness into three major factors (hardware, content, and human factors) and investigated the sub-component of each factor. We then surveyed frequently used measures of VR sickness, both subjective and objective approaches. We also investigated emerging approaches for reducing VR sickness and proposed a multimodal fidelity hypothesis to give an insight into future studies.

1. Introduction

Along with a growing interest in the virtual reality (VR) industry, there are increasing efforts to incorporate VR technology into various fields such as movies, games, and education. During VR experiences, however, some users can suffer from troublesome symptoms that are similar to motion sickness. McCauley called this phenomenon as cybersickness, also known as VR sickness (McCauley & Sharkey, 1992). The major symptoms of VR sickness are eye fatigue, disorientation, and nausea (LaViola Jr, 2000). These uncomfortable feelings can inhibit future VR experiences, so VR sickness is regarded as an urgent problem to solve.

Many researchers have conducted user experiments using VR to investigate the cause of adverse symptoms (Duh et al., 2004; Häkkinen et al., 2002; Keshavarz et al., 2011). Based on the experimental results, several studies have provided guidelines to reduce VR sickness (Carnegie & Rhee, 2015; Y. Y. Kim et al., 2008; L. Rebenitsch, 2015). In this paper, we reviewed the results of existing VR sickness studies and discussed the direction of future research to reduce symptoms. Based on experimental results of 77 user study, we investigated factors causing VR sickness. We also surveyed various methods for reliably measuring symptoms. Using a Sankey diagram, we approached trends in VR sickness from a multifaceted perspective. In this diagram, a series of research processes was represented in a pipeline from the cause of VR sickness to the measurement of symptoms. Through this work, we tried to give an insight into current research findings and plans for future research. In this context, this study aimed to provide profound knowledge about VR sickness and its reduction.

1.1. Scope of VR sickness

Humans perceive their orientation and self-motion through various sensory organs. In particular, humans use information from the vestibular, visual, and proprioceptive senses to acquire a coherent perception of self-motion in a three-dimensional space. Since all the sensory information is processed in synchronization with each other, we can accurately recognize our position and movement in space without any difficulty.

The perceptual system, however, can be disturbed by modern transportation systems (McCauley & Sharkey, 1992). When people ride on a vehicle (e.g., a car, ship, or airplane), they can feel their body moving through the vestibular organs but sometimes they cannot receive corresponding visual information. When the visual information does not match with the dynamic vestibular input, sensory conflicts occur between afferent signals of the current state. If a person repeatedly receives sensory information that is different from their expectations, the person can experience motion sickness (Sherman, 2002).

Moving visual stimuli can also cause motion sickness (Bonato et al., 2008; Chen, Chen, So et al., 2011; Lo & So, 2001; Lubeck et al., 2015; So & Lo, 1999). If the visual stimuli are the dominant sensory input that causes motion sickness, the symptom is named visually induced motion sickness (VIMS) (Keshavarz, Riecke et al., 2015). Depending on the context, VIMS can be referred as gaming sickness, simulator sickness, cinerama sickness, or VR sickness. In particular, cinerama sickness was reported from days of cinema in the early 1900s (Reason & Brand, 1975).

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Many researchers have claimed that this phenomenon might be related to an illusory perception of self-motion, called vection (Bonato et al., 2008; Liu & Uang, 2012; Lubeck et al., 2015; So & Lo, 1999; So, Lo et al., 2001). Even though there is no vestibular input, people feel like they are moving based on visual information under specific conditions. While we normally experience vection for a short period of time in reality (less than a few seconds), the illusion can be prolonged in VR. In virtual reality, dynamic visual stimuli enable a strong experience of vection, in order to induce a higher level of immersion. Our perceptual system expects the vestibular information which corresponds to the moving visual stimuli. The vestibular organ, however, receives limited or minimum input since a user is usually stationary (e.g., sitting or standing still). While conventional motion sickness is usually caused by travel in vehicles, VR users could experience uncomfortable body states (i.e., VIMS) when they merely watch dynamic VR scenes.

It is noted that VR sickness would not be restricted to a subtype of VIMS. Recently, motion simulators have been implemented for better user-experiences in VR. Many people expect that introducing motion simulators enables development of a high-fidelity VR and reduction of VR sickness. However, it may be essential to provide vestibular inputs that are synchronized with the moving visual stimuli in order to produce this positive effect. If asynchronous vestibular information, which does not match temporally and/or spatially with visual information, is delivered, then users can also experience VR sickness. Taken together, considering current VR systems, causes of VR sickness can be extended not only to vection-evoking visual stimulation but also to asynchronous sensory inputs (i.e., visual and vestibular senses).

1.2. Related work

In the early studies of VR sickness, most of the simulation content was navigation or driving. Therefore, content-related factors such as speed and rotational movement of the scene have been considered as potential causes of VR sickness (So & Lo, 1998, 1999). Researchers also started to investigate hardware or individual characteristic factors to find out possible causes of VR sickness.

While previous studies were expected to identify one or two dominant factors for causing VR sickness, the results have shown that, in fact, various factors can contribute to VR sickness (Duh et al., 2004; DiZio & Lackner, 1997; Jaeger & Mourant, 2001; Yang & Sheedy, 2011). Since a VR system derives from a complex combination of hardware technologies and content rendering, it seems plausible that many components of the VR system are involved in users' discomfort. Furthermore, researchers have found that individual differences can affect the level of VR sickness (Dennison et al., 2016; Llorach et al., 2014; Park et al., 2006). Though people experience the same VR content through the same device, the level of discomfort varies depending on an individual's characteristics. Prior studies have focused on which human factors are prominent indices for predicting the severity of users' discomfort. For example, motion sickness history or prior VR experience of users has been widely investigated (Dennison et al., 2016; Stanney et al., 2003).

Meanwhile, methods for quantifying the level of VR sickness have been widely investigated. In order to diagnose and reduce symptoms, it is critical to measure the severity reliably. Depending on methods, users can report their body state via subjective or objective measurements. In early research, most studies used subjective methods such as various types of questionnaires. Recently, there has been an attempt to measure the level of discomfort in objective approaches using postural disturbance or physiological signals.

In this paper, we aimed to review prior VR experiments and find out highly relevant factors of causing VR sickness. We also surveyed suggested measurements of VR sickness and investigated which parameters are promising indices to evaluate users' experience and predict discomfort. Lastly, we proposed a multimodal fidelity hypothesis to clarify the relationship between fidelity and VR sickness.

2. Method

2.1. Data selection

This review aimed to investigate the causes and measures of VR sickness. For the review, we searched in Google Scholar with relevant keywords. In the initial search, the terms 'VR sickness', 'cybersickness', 'motion sickness', 'simulator sickness', 'visually induced motion sickness', 'virtual reality', and 'HMD' were included. The range of publication period was 1992 to 2019, and the results provided 518 papers. To maintain our research scope, we excluded the research that focused on VR training or therapy. Also, we only included human studies of healthy adults, which means studies with patients (e.g., abnormal vestibular function, migraine, stroke, etc.) were not covered. Only experimental data with at least one measurement method, either subjective or objective, were included in the data list. Finally, forward and backward citation searching (Crameri et al., 2019) was applied to include highly relevant and/or cited articles that were missed from the search engine. After all, 77 experimental results were selected for the further analysis.

2.2. Data analysis

2.2.1. Classification

The collected articles investigated either causes or measures of VR sickness. Five articles investigated the relationship between subjective and objective measurements of VR sickness rather than causes of symptoms. The remainder investigated the cause of VR sickness and demonstrated how certain factors of the VR system could influence the user's discomfort. Depending on the aim of the research, experimental articles that investigated the causes of VR sickness were classified into three categories. In this study, we reorganized the causes of symptoms into three different domains: hardware, content, and human factors.

(1) Hardware factors include any manipulation on the VR devices such as display type, display mode, time delay, and so on.
(2) Content factors cover variations in VR scene or scenario by changing graphics or task-related features (e.g., duration and controllability).
(3) Human factors include individual differences which are related with VR sickness.

If an article simultaneously dealt with more than one independent variable (e.g., investigating both display type and gender effects on VR sickness), this article was counted separately into relevant categories (e.g., categorized into both hardware and human factors section).

2.2.2. Sankey diagram

We presented a Sankey diagram for each cause of VR sickness. A Sankey diagram provided an overview of the pipeline of VR sickness research. From the causes of VR sickness to measuring discomfort of the user, the diagram allowed an understanding of how previous works were related to each other and which parts can be improved in future research.

To draw a Sankey diagram, we used "Multilevel Sankeys" from Google charts (https://developers.google.com/chart/interactive/docs/gallery/sankey). The width of flow represented the number of articles, which means that a wider flow refers to more previous studies in a certain topic or measurement. Generally, each article had a weight value of 1. In cases where a study used various subjective (or objective) measurements simultaneously, we divided the weight (i.e., 1) into the number of used measurements. For example, van Emmerik used both misery scale (MISC) and simulator sickness questionnaire (SSQ) for subjective measurements (Van Emmerik et al., 2011). In this case, the weight of each measurement was 0.5. In the study by Dennison et al. (2016), seven objective measurements and two subjective measurements were simultaneously used and there were fourteen combinations of evaluating VR sickness. Here, the weight of each combination was 0.071 (1/14). The diagrams aimed to visualize the number of previous research based on the quantitative way. Therefore, we did not take into account the sample size of each study for calculating the weight. The experimental variables, objective measurements, subjective measurements, and weight values for individual articles were described in tables (Tables 1, 3, and 4). Based on information from these tables, Sankey diagrams for each of the VR sickness factors were drawn (Figures 1, 2, and 3).

3. Result

Based on the database, we surveyed 1) which factors are closely related to causing VR sickness in terms of hardware, content, and human factors (3.1. Causes of VR sickness), 2) how the level of VR sickness can be measured using both subjective and objective methods (3.2. Measures of VR sickness), 3) approaches to alleviate VR sickness (3.3. Emerging approaches for reducing VR Sickness), 4) fidelity effect on VR sickness and proposed a hypothesis (3.4. Multimodal fidelity hypothesis).

3.1. Causes of VR sickness

3.1.1. Hardware

Hardware is a critical factor that determines the quality of VR. A certain specification of hardware must be supported in order to deliver the content to a user as intended by a developer. In early studies of VR sickness, symptoms were oftentimes speculated to originate from poor performance of the hardware, and it was thought that user's discomfort would be reduced as VR technology matured (L. R. Rebenitsch, 2015). However, VR sickness has not been resolved yet by the improved performance of the hardware.

Among 77 experimental studies, 28 articles investigated the hardware effect on VR sickness (Table 1). Four articles examined more than one device-related factor simultaneously (Benzeroual & Allison, 2013; DiZio & Lackner, 1997; Häkkinen et al., 2002; Sharples et al., 2008). The most frequently studied topic was display-related factors. Since display devices deliver VR content, researchers have focused on whether any specific features of the technology can cause VR sickness. In particular, an introduction of Oculus has led to a growing interest in hardware effects on users' discomfort.

3.1.1.1. Display type and mode. Many studies have been conducted to investigate changes in users' responses according to the advance in hardware (Keshavarz et al., 2011; K. Kim et al., 2014; Sharples et al., 2008; Vlad et al., 2013). For example, effects of display types (e.g., screen, CAVE, HMD, etc.) or various HMD subtypes on user-experiences have been investigated (Table 2). In particular, the advent of the latest generation of HMD devices facilitated hardware-related research. These devices were the commercial release of consumer grade; therefore, it became more crucial to overcome VR sickness issues and to allow broader people to enjoy VR in their daily lives. Applying various techniques to HMDs (Pohl et al., 2013; van Waveren, 2016), there has been increasing interest to minimize symptoms through hardware-based approaches.

Several experimental results showed, however, that users reported a higher SSQ score when they wore a HMD (Dennison et al., 2016; K. Kim et al., 2014). This may be originated from 3D visualization which enables the depth perception of virtual objects. While the HMD allowed rendering of stereoscopic images, other types of display such as monitors and large screens without shutter glasses delivered monoscopic images to users. Though the stereoscopic content seemed more realistic and can provide high-fidelity VR, several studies showed that this advantage can lead to more severe VR sickness (Dennison et al., 2016; K. Kim et al., 2014; Naqvi et al., 2015). These results can be associated with the degree of discrepancy between expected and perceived sensory information. Stereoscopic rendering can induce strong feelings of vection so that a user expects corresponding vestibular inputs. However, those inputs were not available in most of previous studies, which can result in an increased degree of sensory conflict.

Table 1. References of dealing with hardware factors.

Reference	Main topic	Variables	Objective measurement	Subjective measurement	Weight value
DiZio and Lackner (1997)	Time Delay	Latency	Postural sway	etc. (Graybiel categorization)	1
	etc.	Weight of HMD	Postural sway	etc. (Graybiel categorization)	1
Howarth (1999)	Display type	HMD subtypes	Eye-related measures	Not measured	1
Draper et al. (2001)	Time Delay	Latency	Postural sway	SSQ	0.5
	Time Delay	Latency	Postural sway	Sickness scale (Verbal sickness rating)	0.5
Jaeger and Mourant (2001)	etc.	Mode of locomotion	Not measured	SSQ	0.5
	etc.	Mode of locomotion	Not measured	VEPAB	0.5
Häkkinen et al. (2002)	Display mode	Stereoscopic vs. Monoscopic	Postural sway	SSQ	1
	Display type	HMD vs. TV	Postural sway	SSQ	1
Duh et al. (2004)	Display mode	Stereoscopic vs. Monoscopic	Postural sway	SSQ	1
Shigemasu et al. (2006)	Field of view	Hardware FOV	Not measured	SSQ	1
Harvey and Howarth (2007)	Field of view	Hardware FOV	SKT	Nausea scale (Bagshaw and Stott's sickness scale)	1
Y. Y. Kim et al. (2008)	Field of view	Hardware FOV	ECG	SSQ	0.125
	Field of view	Hardware FOV	EDA	SSQ	0.125
	Field of view	Hardware FOV	EEG	SSQ	0.125
	Field of view	Hardware FOV	EGG	SSQ	0.125
	Field of view	Hardware FOV	Eye-related measures	SSQ	0.125
	Field of view	Hardware FOV	PPG	SSQ	0.125
	Field of view	Hardware FOV	RSP	SSQ	0.125
	Field of view	Hardware FOV	SKT	SSQ	0.125
Sharples et al. (2008)	Display type	HMD vs. Monitor vs. Theater vs. Screen	Not measured	SSQ	1
	etc.	Luminance	Not measured	SSQ	1
Toet et al. (2008)	Field of view	Internal/external FOV ratio	Not measured	MISC	1
Bos et al. (2010)	Field of view	Internal/external FOV ratio	Not measured	MISC	1
Hicks and Durbin (2011)	etc.	Engineering simulator subtypes	Not measured	SSQ	1
Keshavarz et al. (2011)	Display type	HMD vs. Screen	Not measured	FMS	0.5
	Display type	HMD vs. Screen	Not measured	etc. (Sickness questionnaire)	0.5
Van Emmerik et al. (2011)	Field of view	Internal/external FOV ratio	Postural sway	MISC	0.5
	Field of view	Internal/external FOV ratio	Postural sway	SSQ	0.5
Yang and Sheedy (2011)	Display mode	Stereoscopic vs. Monoscopic	Eye-related measures	etc. (A visual and physical discomfort questionnaire)	1
Benzeroual and Allison (2013)	Display mode	Stereoscopic vs. Monoscopic	Not measured	SSQ	0.5
	Display mode	Stereoscopic vs. Monoscopic	Not measured	Task performance	0.5
	etc.	Interaction type (Gamepad vs. Kinect)	Not measured	SSQ	0.5
	etc.	Interaction type (Gamepad vs. Kinect)	Not measured	Task performance	0.5
Naqvi et al. (2013)	Display mode	Stereoscopic vs. Monoscopic	ECG	SSQ	0.5
	Display mode	Stereoscopic vs. Monoscopic	EEG	SSQ	0.5
Vlad et al. (2013)	Display type	3D glasses vs. 3D TV	Not measured	SSQ	1
Keshavarz and Hecht (2014)	Additional modality	Pleasant music	Not measured	FMS	0.5
	Additional modality	Pleasant music	Not measured	SSQ	0.5
K. Kim et al. (2014)	Display type	HMD vs. Monitor vs. CAVE	EDA	etc. (Beck Anxiety Inventory (BAI))	0.250
	Display type	HMD vs. Monitor vs. CAVE	EDA	etc. (Self Assessment Manikin (SAM))	0.250
	Display type	HMD vs. Monitor vs. CAVE	EDA	SSQ	0.250
	Display type	HMD vs. Monitor vs. CAVE	EDA	Task performance	0.250
Llorach et al. (2014)	etc.	Interaction type (Game controller vs. Position estimation system)	Not measured	SSQ	1
Ishio et al. (2015)	etc.	Display resolution	Postural sway	SSQ	1
Keshavarz, Stelzmann et al. (2015)	Additional modality	Pleasant odors	Not measured	FMS	0.5
	Additional modality	Pleasant odors	Not measured	SSQ	0.5
Naqvi et al. (2015)	Display mode	Stereoscopic vs. Monoscopic	EEG	SSQ	1
Plouzeau et al. (2015)	Additional modality	Proprioceptive vibrations	Not measured	SSQ	0.5
	Additional modality	Proprioceptive vibrations	Not measured	Task performance	0.5
Dennison et al. (2016)	Display type	HMD vs. Monitor	ECG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Display type	HMD vs. Monitor	EDA	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Display type	HMD vs. Monitor	EGG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Display type	HMD vs. Monitor	Eye-related measures	Nausea scale (Bagshaw and Stott's sickness scale)	0.071

(*Continued*)

Table 1. (Continued).

Reference	Main topic	Variables	Objective measurement	Subjective measurement	Weight value
	Display type	HMD vs. Monitor	Postural sway	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Display type	HMD vs. Monitor	PPG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Display type	HMD vs. Monitor	RSP	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Display type	HMD vs. Monitor	ECG	SSQ	0.071
	Display type	HMD vs. Monitor	EDA	SSQ	0.071
	Display type	HMD vs. Monitor	EGG	SSQ	0.071
	Display type	HMD vs. Monitor	Eye-related measures	SSQ	0.071
	Display type	HMD vs. Monitor	Postural sway	SSQ	0.071
	Display type	HMD vs. Monitor	PPG	SSQ	0.071
	Display type	HMD vs. Monitor	RSP	SSQ	0.071
D'Amour et al. (2017)	Additional modality	Airflow and seat vibration	Not measured	FMS	0.5
	Additional modality	Airflow and seat vibration	Not measured	SSQ	0.5

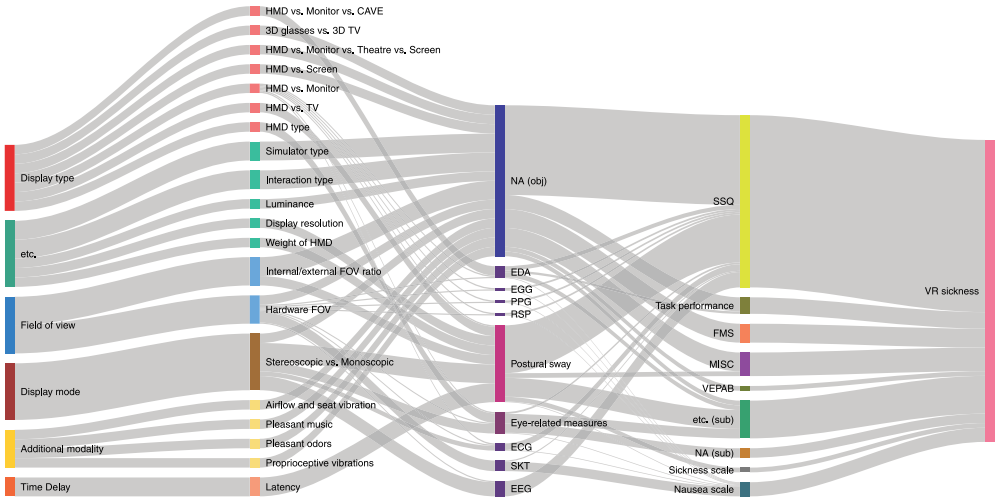

Figure 1. A Sankey diagram of hardware-related research.

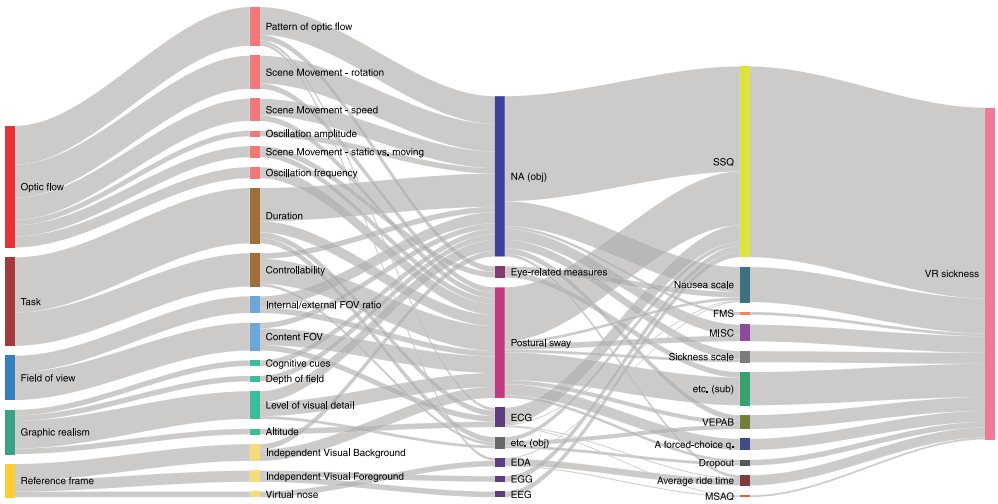

Figure 2. A Sankey diagram of content-related research.

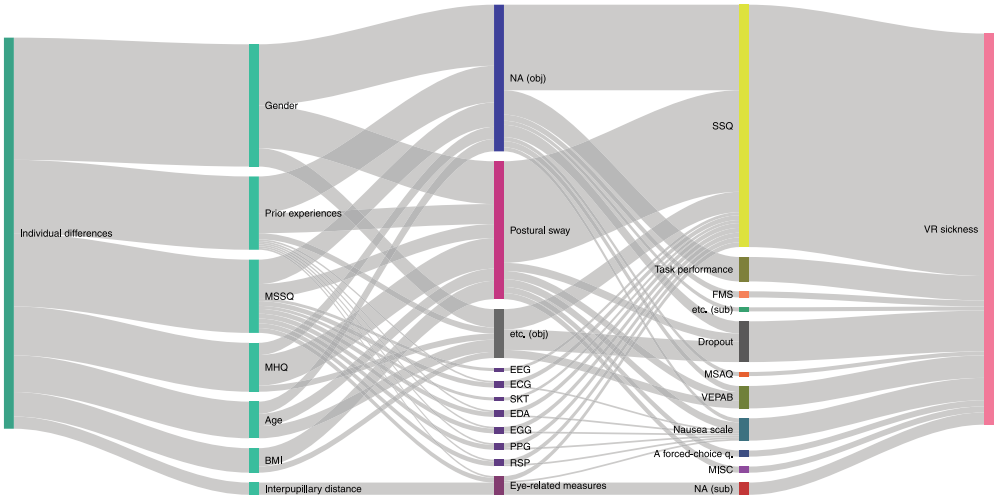

Figure 3. A Sankey diagram of human factors-related research.

Table 2. Details of the experimental setup in device-related research.

Reference	Display device	Display mode	Field of view (FOV) (degree)	VR content	Result
Howarth (1999)	HMD (Virtual i-glasses)	Bi-ocular	30 × 23.6	Heretic (PC game)	No differences
	HMD (Virtuality)	Bi-ocular	60 × 46.8		
	HMD (Division)	Stereoscopic	105 × 41		
Sharples et al. (2008)	HMD (Virtual research V8)	-	60	Virtual factory	HMD
	Desktop	-	-		
	Reality theater	-	150 × 43		
	Projection screen	-	-		
Keshavarz et al. (2011)	HMD (NVisor SX)	Monoscopic	48 × 36	A video taken with a camera mounted to the dashboard of a car	Powerwall
	Powerwall	Stereoscopic	48 × 36		
Vlad et al. (2013)	3D glasses (Prototype head-mounted device)	Stereoscopic	28	Still images of four different test scenes	3D glasses
	3D TV (Panasonic TC-P50VT20)	Stereoscopic	46		
K. Kim et al. (2014)	HMD (eMagin Z800 3DVisor)	Stereoscopic	40	A modified 3D version of the Stroop task	HMD
	Desktop	Monoscopic	63		
	Six wall CAVE (Duke immersive Virtual Environment (DiVE))	Stereoscopic	-		
Dennison et al. (2016)	HMD (Oculus Rift DK2)	Stereoscopic	100 × 100	Half Life 2	HMD
	Monitor (Samsung S27A550H)	Monoscopic	60 × 40		

3.1.1.2. Hardware FOV. The field of view (FOV) is the range of the observable world. In particular, the hardware FOV is a maximum visual angle of a display device. The term is also referred to external FOV, display FOV, physical FOV, and real FOV. A variety of methods have been proposed for adjusting the hardware FOV to reduce VR sickness. For example, the size of display or distance between user and screen were changed (Harvey & Howarth, 2007; Shigemasu et al., 2006) to manipulate the degree of FOV. Furthermore, Y. Y. Kim et al. (2008) applied a dynamic FOV system to a participant using the electrophysiological signals of the participant (Y. Y. Kim et al., 2008). Many experimental results consistently showed that reducing the hardware FOV was effective for alleviating users' discomfort, especially during acceleration and rotational movements.

Meanwhile, several studies investigated the relationship between hardware FOV and content FOV (e.g., internal/external FOV ratio) and has demonstrated mixed results. Draper et al. (2001) calculated the ratio between hardware and content FOV as an 'image scale factor.' Depending on its value, three types of image scale factor were assigned: minification (hardware FOV < content FOV), neutral (hardware FOV = content FOV), and magnification (hardware FOV > content FOV). Participants experienced all three types of VR and reported that the level of discomfort was lowest under the neutral condition. However, subsequent studies showed opposite results (Bos et al., 2010; Toet et al., 2008; Van Emmerik et al., 2011). That is, participants showed greater VR sickness when the FOV of the hardware and content were matched. The inconsistency between studies might originate from the difference in experimental settings. While the hardware FOV of Draper et al. (2001) was 25 degrees, other studies were 90 degrees or more. Also, participants of Draper's experiment were allowed to move their bodies; on the other hand, other studies constrained the movement of participants.

3.1.1.3. Latency. When a user actively navigates or searches in VR, it is necessary to accurately calculate the body movement and transmit the image corresponding to the motion. However, this process can cause a time difference between what the user expected to see and what was actually viewed, which is closely related to VR sickness (Rebenitsch & Owen,

Table 3. References of dealing with content factors.

Reference	Main topic	Variables	Objective measurement	Subjective measurement	Weight value
DiZio and Lackner (1997)	Field of view	Content FOV	Postural sway	etc. (Graybiel categorization system)	1
Stanney and Kennedy (1998)	Task	Duration	Postural sway	SSQ	0.250
	Task	Duration	Postural sway	VEPAB	0.250
	Task	Duration	etc. (eye-hand coordination)	SSQ	0.250
	Task	Duration	etc. (eye-hand coordination)	VEPAB	0.250
So and Lo (1998)	Optic flow	Scene Movement – rotation	Not measured	Nausea scale	0.5
	Optic flow	Scene Movement – rotation	Not measured	SSQ	0.5
So and Lo (1999)	Optic flow	Scene Movement – rotation	Not measured	Nausea scale	0.5
	Optic flow	Scene Movement – rotation	Not measured	SSQ	0.5
	Task	Duration	Not measured	Nausea scale	0.5
	Task	Duration	Not measured	SSQ	0.5
Draper et al. (2001)	Field of view	Content FOV	Postural sway	Sickness scale (Verbal sickness rating)	0.5
	Field of view	Content FOV	Postural sway	SSQ	0.5
Duh, Lin et al. (2001)	Field of view	Content FOV	Postural sway	etc. (Subjective difficulty rating)	1
	Graphic realism	Level of visual detail	Postural sway	etc. (Subjective difficulty rating)	1
Duh, Parker et al. (2001)	Reference frame	Independent Visual Background	Postural sway	etc. (Subjective difficulty rating)	1
	Optic flow	Oscillation frequency	Postural sway	etc. (Subjective difficulty rating)	1
Jaeger and Mourant (2001)	Graphic realism	Level of visual detail	Not measured	SSQ	0.5
	Graphic realism	Level of visual detail	Not measured	VEPAB	0.5
	Task	Duration	Not measured	SSQ	0.5
	Task	Duration	Not measured	VEPAB	0.5
Kingdon et al. (2001)	Graphic realism	Level of visual detail	Postural sway	SSQ	1
	Task	Controllability	Postural sway	SSQ	1
	Task	Duration	Postural sway	SSQ	1
Lo and So (2001)	Optic flow	Scene Movement – rotation	Not measured	Nausea scale	0.5
	Optic flow	Scene Movement – rotation	Not measured	SSQ	0.5
	Task	Duration	Not measured	Nausea scale	0.5
	Task	Duration	Not measured	SSQ	0.5
So, Lo et al. (2001)	Optic flow	Scene Movement – speed	Not measured	Nausea scale	0.5
	Optic flow	Scene Movement – speed	Not measured	SSQ	0.5
	Task	Duration	Not measured	Nausea scale	0.5
	Task	Duration	Not measured	SSQ	0.5
So, Ho et al. (2001)	Optic flow	Scene Movement – speed	Not measured	Nausea scale	0.5
	Optic flow	Scene Movement – speed	Not measured	SSQ	0.5
Lin et al. (2002)	Reference frame	Independent Visual Background	Not measured	SSQ	1
Stanney et al. (2002)	Task	Duration	Not measured	SSQ	1
Stanney et al. (2003)	Graphic realism	Level of visual detail	Postural sway	Dropout	0.167
	Graphic realism	Level of visual detail	Postural sway	SSQ	0.167
	Graphic realism	Level of visual detail	Postural sway	VEPAB	0.167
	Graphic realism	Level of visual detail	etc. (eye-hand coordination)	Dropout	0.167
	Graphic realism	Level of visual detail	etc. (eye-hand coordination)	SSQ	0.167
	Graphic realism	Level of visual detail	etc. (eye-hand coordination)	VEPAB	0.167
	Task	Controllability	etc. (eye-hand coordination)	Dropout	0.167
	Task	Controllability	etc. (eye-hand coordination)	SSQ	0.167
	Task	Controllability	etc. (eye-hand coordination)	VEPAB	0.167
	Task	Controllability	Postural sway	Dropout	0.167

(*Continued*)

Table 3. (Continued).

Reference	Main topic	Variables	Objective measurement	Subjective measurement	Weight value
	Task	Controllability	Postural sway	SSQ	0.167
	Task	Controllability	Postural sway	VEPAB	0.167
	Task	Duration	etc. (eye-hand coordination)	Dropout	0.167
	Task	Duration	etc. (eye-hand coordination)	SSQ	0.167
	Task	Duration	etc. (eye-hand coordination)	VEPAB	0.167
	Task	Duration	Postural sway	Dropout	0.167
	Task	Duration	Postural sway	SSQ	0.167
	Task	Duration	Postural sway	VEPAB	0.167
Duh et al. (2004)	Reference frame	Independent Visual Background	Postural sway	SSQ	1
	Optic flow	Oscillation frequency	Postural sway	SSQ	1
Shigemasu et al. (2006)	Optic flow	Oscillation amplitude	Not measured	SSQ	1
Bubka et al. (2007)	Optic flow	Pattern of optic flow	Not measured	SSQ	1
Diels et al. (2007)	Optic flow	Pattern of optic flow	Eye-related measures	Nausea scale (Bagshaw and Stott's sickness scale)	1
Palmisano et al. (2007)	Optic flow	Pattern of optic flow	Not measured	Sickness scale (Subjective Symptoms of Motion Sickness (SSMS))	0.5
	Optic flow	Pattern of optic flow	Not measured	SSQ	0.5
Bonato et al. (2008)	Optic flow	Number of motion axis	Not measured	SSQ	1
Sharples et al. (2008)	Task	Controllability	Not measured	SSQ	1
Toet et al. (2008)	Field of view	Internal/external FOV ratio	Not measured	MISC	1
Watanabe and Ujike (2008)	Graphic realism	Altitude	ECG	SSQ	1
	Task	Duration	ECG	SSQ	1
Bonato et al. (2009)	Optic flow	Number of motion axis	Not measured	SSQ	1
Bos et al. (2010)	Field of view	Internal/external FOV ratio	Not measured	MISC	1
Dong and Stoffregen (2010)	Task	Controllability	Postural sway	A forced-choice Question	0.5
	Task	Controllability	Postural sway	SSQ	0.5
Chen, Chen, So et al. (2011)	Optic flow	Scene Movement – rotation	Postural sway	Nausea scale	0.5
	Optic flow	Scene Movement – rotation	Postural sway	SSQ	0.5
Chen, Dong, et al. (2011)	Task	Controllability	Postural sway	A forced-choice Question	1
Dong et al. (2011)	Task	Controllability	Postural sway	A forced-choice Question	0.5
	Task	Controllability	Postural sway	SSQ	0.5
Keshavarz and Hecht (2011a)	Optic flow	Scene Movement – rotation	Not measured	FMS	0.5
	Optic flow	Scene Movement – rotation	Not measured	SSQ	0.5
Liu and Uang (2012)	Task	Duration	Not measured	SSQ	1
Van Emmerik et al. (2011)	Field of view	Internal/external FOV ratio	Postural sway	MISC	0.5
	Field of view	Internal/external FOV ratio	Postural sway	SSQ	0.5
Yang and Sheedy (2011)	Optic flow	Scene Movement	Eye-related measures	etc. (A visual and physical discomfort questionnaire)	1
Golding et al. (2012)	Graphic realism	Cognitive cues	Not measured	Sickness scale (Subjective sickness rating)	0.5
	Graphic realism	Cognitive cues	Not measured	etc. (Total symptom score)	0.5
Hwang et al. (2012)	Reference frame	Independent Visual Foreground	EGG	SSQ	1
Liu and Uang (2012)	Optic flow	Pattern of optic flow	Not measured	SSQ	1
	Optic flow	Scene Movement – speed	Not measured	SSQ	1
Chang et al. (2013)	Reference frame	Independent Visual Foreground	EEG	SSQ	1
Carnegie and Rhee (2015)	Graphic realism	Depth of field	Not measured	SSQ	1
Chardonnet et al. (2015)	Optic flow	Scene Movement – speed	Postural sway	SSQ	1
Davis et al. (2015)	Graphic realism	Level of visual detail	Not measured	Average ride time	0.5
	Graphic realism	Level of visual detail	Not measured	Nausea scale (Nausea scale rating)	0.5
Kobayashi et al. (2015)	Field of view	Content FOV	ECG	SSQ	1
Lubeck et al. (2015)	Optic flow	Scene Movement	Postural sway	MISC	0.5
	Optic flow	Scene Movement	Postural sway	SSQ	0.5
Whittinghill et al. (2015)	Reference frame	Virtual nose	EDA	Average ride time	1
Fernandes and Feiner (2016)	Field of view	Content FOV	Not measured	Sickness scale (Discomfort score)	0.5
	Field of view	Content FOV	Not measured	SSQ	0.5

(*Continued*)

Table 3. (Continued).

Reference	Main topic	Variables	Objective measurement	Subjective measurement	Weight value
Mazloumi Gavgani et al. (2017)	Optic flow	Pattern of optic flow	ECG	Average ride time	0.167
	Optic flow	Pattern of optic flow	ECG	MSAQ	0.167
	Optic flow	Pattern of optic flow	ECG	Nausea scale (Nausea scale rating)	0.167
	Optic flow	Pattern of optic flow	EDA	Average ride time	0.167
	Optic flow	Pattern of optic flow	EDA	MSAQ	0.167
	Optic flow	Pattern of optic flow	EDA	Nausea scale (Nausea scale rating)	0.167
Palmisano et al. (2017)	Optic flow	Pattern of optic flow	Not measured	SSQ	1

2016). For example, in the real world when users move their head from right to left, the surrounding scene also moves in the same direction (spatial feature) with the same speed (temporal feature) as expected. In the VR, however, a time delay in the motion tracking process of the HMD occurs, which can lead to VR sickness. This process has known to be related to the human's vestibulo-ocular reflex (VOR). When a person rotates head with eyes open, the vestibular and visual systems complementally move each other to stabilize visual images on the retina. The technical limitations of the HMD disturb the reflex and can cause motion sickness (Bronstein et al., 2020). Lawson suggested that it is required to design a virtual environment that can help a user to suppress one's VOR to lessen unpleasant symptoms (Lawson, 2014).

A series of experiments demonstrated the latency effect on VR sickness. In the study by DiZio and Lackner (1997), four conditions of time delay (67 ms, 167 ms, 267 ms, 367 ms) were constructed, and users were asked to freely navigate a virtual harbor. The result showed that as the time delay increased, the severity of VR sickness also increased. However, in the study of Draper et al. (2001), there was no difference in the degree of subjective discomfort for each time delay condition (48 ms, 125 ms, 250 ms). Interestingly, even though the user could clearly recognize the time lag in the 250 ms condition, it did not lead to more severe VR sickness. The researcher suggested that if the lag was constant during the VR experience (i.e., fixed time delay), the user can adapt to this time delay and successfully predict the surrounding. However, if the time delay was variable, users' discomfort would be increased.

Unlike in the experiments, applying a VR content in a real-world context requires complex interaction between users and content. Therefore, minimizing the time delay or, at least, keeping the size of the time lag consistent might be critical to reduce the VR sickness. Recently, Seo et al. (2017) suggested a sensor-based prediction method to reduce the motion-to-photon latency in an HMD.

3.1.1.4. Flicker. Display flickering has been known to be a cause of VR sickness (Kolasinski, 1995; LaViola Jr, 2000; Renkewitz & Alexander, 2007), which can be visually disturbing as well as influencing the user's eye health. Noticing flicker can be influenced by the display's refresh rate, luminance, and field of view (FOV) (Renkewitz & Alexander, 2007). With a brighter screen, a higher refresh rate is required to prevent flicker effect. Also, if the display size becomes bigger, the user is more likely to experience flicker at the edges of the screen (LaViola Jr, 2000). Due to the improvement of hardware performance in recent years, some researchers claimed that flicker is no longer a major factor for VR sickness (L. R. Rebenitsch, 2015). However, there is an individual difference in flicker perception (Renkewitz & Alexander, 2007), so it is important to consider the individual sensitivity in implementing a VR system.

3.1.1.5. Brief discussion. According to the survey, many researchers have focused on display devices among various hardware aspects. A Sankey diagram of hardware also confirmed that display-related factors such as display type, display mode, and field of view (FOV) were widely investigated (Figure 1). It seems plausible that the advent of the latest generation of HMD triggered a wide range of studies demonstrating how this new device could influence user experiences. Also, the time delay of the device has been paid attention to solve VR sickness. Given that an interactive VR system is getting popular, it becomes critical to investigate how the latency effect can affect user experience. Lastly, earlier research claimed that the flickering of a display device could evoke users' discomfort (Kolasinski, 1995; LaViola Jr, 2000; Renkewitz & Alexander, 2007). These days, however, the advance in VR technology enables the displays to deliver VR content without flicker.

For measuring VR sickness, most of previous works have used subjective measures rather than objective measures (Figure 1). The most frequently used method was the simulator sickness questionnaire (SSQ). On the other hand, postural sway was widely used for objective measures. Though hardware factors usually focused on the effect of display devices, only a few studies used eye-related measurements. More experimental evidence is needed to elucidate the display effect on physical changes in the eyes. An HMD with an eye-tracking function would be one of the promising methods.

3.1.2. Content

VR content is an essential factor which determines the degree of VR fidelity as well as VR sickness. As developers have tried to implement a higher fidelity of VR, details of the content are becoming more complicated. Advances in hardware systems enabled to render such a realistic virtual scene. However, these efforts did not necessarily lead to better user experiences. Many studies have found that several content-related factors can be associated with VR sickness (Bonato et al., 2008; Davis et al., 2015; Jaeger & Mourant, 2001; Keshavarz & Hecht, 2011a; Liu & Uang, 2012).

Table 4. References of dealing with human factors.

Reference	Main topic	Variables	Objective measurement	Subjective measurement	Weight value
Howarth (1999)	Individual differences	Interpupillary Distance	Eye-related measures	Not measured	1
K. M. Stanney et al. (1999)	Individual differences	Gender	Postural sway	SSQ	1
	Individual differences	MHQ	Postural sway	SSQ	1
Jaeger and Mourant (2001)	Individual differences	Gender	Not measured	SSQ	0.5
	Individual differences	Gender	Not measured	VEPAB	0.5
Kingdon et al. (2001)	Individual differences	BMI	Postural sway	SSQ	1
	Individual differences	MHQ	Postural sway	SSQ	1
Graeber and Stanney (2002)	Individual differences	Gender	Not measured	Dropout	0.5
	Individual differences	Gender	Not measured	SSQ	0.5
	Individual differences	MHQ	Not measured	Dropout	0.5
	Individual differences	MHQ	Not measured	SSQ	0.5
Häkkinen et al. (2002)	Individual differences	Age	Postural sway	SSQ	1
	Individual differences	Gender	Postural sway	SSQ	1
Stanney et al. (2003)	Individual differences	BMI	etc. (eye-hand coordination)	Dropout	0.167
	Individual differences	BMI	etc. (eye-hand coordination)	SSQ	0.167
	Individual differences	BMI	etc. (eye-hand coordination)	VEPAB	0.167
	Individual differences	BMI	Postural sway	Dropout	0.167
	Individual differences	BMI	Postural sway	SSQ	0.167
	Individual differences	BMI	Postural sway	VEPAB	0.167
	Individual differences	Gender	etc. (eye-hand coordination)	Dropout	0.167
	Individual differences	Gender	etc. (eye-hand coordination)	SSQ	0.167
	Individual differences	Gender	etc. (eye-hand coordination)	VEPAB	0.167
	Individual differences	Gender	Postural sway	Dropout	0.167
	Individual differences	Gender	Postural sway	SSQ	0.167
	Individual differences	Gender	Postural sway	VEPAB	0.167
	Individual differences	MHQ	etc. (eye-hand coordination)	Dropout	0.167
	Individual differences	MHQ	etc. (eye-hand coordination)	SSQ	0.167
	Individual differences	MHQ	etc. (eye-hand coordination)	VEPAB	0.167
	Individual differences	MHQ	Postural sway	Dropout	0.167
	Individual differences	MHQ	Postural sway	SSQ	0.167
	Individual differences	MHQ	Postural sway	VEPAB	0.167
	Individual differences	Prior experiences	etc. (eye-hand coordination)	Dropout	0.167
	Individual differences	Prior experiences	etc. (eye-hand coordination)	SSQ	0.167
	Individual differences	Prior experiences	etc. (eye-hand coordination)	VEPAB	0.167
	Individual differences	Prior experiences	Postural sway	Dropout	0.167
	Individual differences	Prior experiences	Postural sway	SSQ	0.167
	Individual differences	Prior experiences	Postural sway	VEPAB	0.167
Y. Y. Kim et al. (2005)	Individual differences	MSSQ	ECG	SSQ	0.125
	Individual differences	MSSQ	EDA	SSQ	0.125
	Individual differences	MSSQ	EEG	SSQ	0.125
	Individual differences	MSSQ	EGG	SSQ	0.125
	Individual differences	MSSQ	Eye-related measures	SSQ	0.125
	Individual differences	MSSQ	PPG	SSQ	0.125
	Individual differences	MSSQ	RSP	SSQ	0.125
	Individual differences	MSSQ	SKT	SSQ	0.125
Park et al. (2006)	Individual differences	Age	Not measured	Dropout	0.5
	Individual differences	Age	Not measured	SSQ	0.5
	Individual differences	Gender	Not measured	Dropout	0.5
	Individual differences	Gender	Not measured	SSQ	0.5
Y. Y. Kim et al. (2008)	Individual differences	MSSQ	ECG	SSQ	0.125
	Individual differences	MSSQ	EDA	SSQ	0.125
	Individual differences	MSSQ	EEG	SSQ	0.125
	Individual differences	MSSQ	EGG	SSQ	0.125
	Individual differences	MSSQ	Eye-related measures	SSQ	0.125
	Individual differences	MSSQ	PPG	SSQ	0.125
	Individual differences	MSSQ	RSP	SSQ	0.125
	Individual differences	MSSQ	SKT	SSQ	0.125
Chen, Chen, So et al. (2011)	Individual differences	Gender	Postural sway	Nausea scale	0.5
	Individual differences	Gender	Postural sway	SSQ	0.5
Benzeroual and Allison (2013)	Individual differences	MSSQ	Not measured	SSQ	0.5
	Individual differences	MSSQ	Not measured	Task performance	0.5
	Individual differences	Prior experiences	Not measured	SSQ	0.5
	Individual differences	Prior experiences	Not measured	Task performance	0.5
Keshavarz and Hecht (2014)	Individual differences	Gender	Not measured	FMS	0.5
	Individual differences	Gender	Not measured	SSQ	0.5

(*Continued*)

Table 4. (Continued).

Reference	Main topic	Variables	Objective measurement	Subjective measurement	Weight value
Llorach et al. (2014)	Individual differences	Age	Not measured	SSQ	1
	Individual differences	Gender	Not measured	SSQ	1
	Individual differences	Prior experiences	Not measured	SSQ	1
Lubeck et al. (2015)	Individual differences	MSSQ	Postural sway	MISC	0.5
	Individual differences	MSSQ	Postural sway	SSQ	0.5
Dennison et al. (2016)	Individual differences	MSSQ	ECG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	MSSQ	ECG	SSQ	0.071
	Individual differences	MSSQ	EDA	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	MSSQ	EDA	SSQ	0.071
	Individual differences	MSSQ	EGG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	MSSQ	EGG	SSQ	0.071
	Individual differences	MSSQ	Eye-related measures	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	MSSQ	Eye-related measures	SSQ	0.071
	Individual differences	MSSQ	Postural sway	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	MSSQ	Postural sway	SSQ	0.071
	Individual differences	MSSQ	PPG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	MSSQ	PPG	SSQ	0.071
	Individual differences	MSSQ	RSP	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	MSSQ	RSP	SSQ	0.071
	Individual differences	Prior experiences	ECG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	Prior experiences	ECG	SSQ	0.071
	Individual differences	Prior experiences	EDA	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	Prior experiences	EDA	SSQ	0.071
	Individual differences	Prior experiences	EGG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	Prior experiences	EGG	SSQ	0.071
	Individual differences	Prior experiences	Eye-related measures	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	Prior experiences	Eye-related measures	SSQ	0.071
	Individual differences	Prior experiences	Postural sway	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	Prior experiences	Postural sway	SSQ	0.071
	Individual differences	Prior experiences	PPG	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	Prior experiences	PPG	SSQ	0.071
	Individual differences	Prior experiences	RSP	Nausea scale (Bagshaw and Stott's sickness scale)	0.071
	Individual differences	Prior experiences	RSP	SSQ	0.071
Freitag et al. (2016)	Individual differences	Gender	Not measured	SSQ	0.5
	Individual differences	Gender	Not measured	Task performance	0.5
	Individual differences	Prior experiences	Not measured	SSQ	0.5
	Individual differences	Prior experiences	Not measured	Task performance	0.5
Nesbitt et al. (2017)	Individual differences	MSSQ	Not measured	etc. (Reaction time)	0.333
	Individual differences	MSSQ	Not measured	MSAQ	0.333
	Individual differences	MSSQ	Not measured	Nausea scale (Nausea scale rating)	0.333
Stoffregen et al. (2017)	Individual differences	Prior experiences	Postural sway	A forced-choice Question	0.5
	Individual differences	Prior experiences	Postural sway	SSQ	0.5

Forty-seven articles in the data list investigated the content effects on VR sickness. Ten articles examined more than one content-related factor at the same time (Table 3). Research topics were categorized into five different aspects of VR content: optical flow, graphic realism, reference frame, content FOV, and task. For measuring users' discomfort, a variety of subjective methods were used. On the other hand, relatively limited numbers of objective measurements were applied to record physiological changes due to manipulating VR content.

3.1.2.1. Optical flow. It has been widely observed that humans become more nauseous when they see moving visual content than static content (Bonato et al., 2008; Chen, Chen, So et al., 2011; Lo & So, 2001; Lubeck et al., 2015; So & Lo, 1999). Moving stimuli produce the optical flow of the VR scene which enables a person to experience illusory self-motion (i.e., vection). Many researchers have investigated which features of optical flow can cause a user to experience a strong feeling of vection and VR sickness.

Among various parameters for causing optical flow, the degree of the speed and the number of moving axes of VR content have been widely investigated to understand the relationship between optical flow and VR sickness. Considering the speed of the VR scene, previous studies have shown that

users report more severe VR sickness as the movement becomes faster (Chardonnet et al., 2015; Liu & Uang, 2012; So, Lo et al., 2001). So, Lo et al. (2001) investigated the effects of navigation speed on the level of motion sickness after VR exposure. The root mean squares for eight speed conditions (3, 4, 6, 8, 10, 24, 30, and 59 m/s) in the fore-and-aft axis were used to manipulate the VR content. Results showed that the severity of nausea and vection increased as speeds raised from 3 m/s to 10 m/s. However, the positive correlation between the speed and VR sickness disappeared if the velocity exceeded 10 m/s. The user reported the highest discomfort at 10 m/s and maintained (or slightly decreased) the level of VR sickness up to 60 m/s. The author claimed that the degree of illusory self-motion determined participant's discomforts. That is, the range of scene velocity which induces stronger vection can be associated with causing VR sickness. If the speed of the VR scene was too fast, then users might not experience discomfort due to weak feelings of presence.

Moreover, oscillatory frequencies or amplitudes inducing adverse effects on users have been widely investigated (Duh, Parker et al., 2001; Duh et al., 2004; Shigemasu et al., 2006). According to the experiments, participants frequently showed discomfort at approximately 0.2–0.3 Hz. Golding and Gresty (2016) suggested a "biodynamic hypothesis," which explained that 0.2–0.3 Hz can lead to ambiguity in selecting the appropriate tactic for movements. The authors claimed that the motion around these frequencies will challenge human motor control and, consequently, result in motion sickness.

In terms of the number of motion axes, users have shown greater discomfort when they experienced a VR scene with rotational movements compared to translational movements (Bonato et al., 2009; Keshavarz & Hecht, 2011a; Lo & So, 2001; So & Lo, 1998). The rotational motions for the x, y, and z-axes can be represented as roll, pitch, and yaw, respectively, and the human body was not more sensitive to rotational motion in any particular axis (Lo & So, 2001). When more than two axes were involved in the rotational movement, participants experienced higher VR sickness. Bonato et al. (2009) investigated the difference in user's discomforts during single- axis or dual-axis rotations. The result demonstrated that participants reported significantly greater discomforts when they experienced both pitch and yaw movements compared to only pitch movement. The study of Keshavarz and Hecht (2011a) also confirmed that a rotational movement of more than one axis contributed to severe nausea symptoms compared to a single axis movement. Interestingly, however, there was no difference in the degree of VR sickness between the rotational movement in two or three axes.

Many authors stated that the level of VR sickness can be closely related to vection (Bonato et al., 2008; Liu & Uang, 2012; Lubeck et al., 2015; So & Lo, 1999; So, Lo et al., 2001). When a user feels strong illusory self-movement due to the optical flow, the person is likely to experience higher immersion in VR and expect corresponding vestibular information. If the VR system cannot provide appropriate sensory input, the system can cause motion sickness. However, several studies have drawn inconclusive results regarding these assertions. For example, a meta-analysis by Lawson (2014) showed that only 3 of 10 previous studies found a significant correlation between vection and VR sickness (Lawson, 2014). Keshavarz also reviewed the relationship between vection and VIMS and concluded that vection alone is not enough to cause users' discomfort (Keshavarz, Riecke et al., 2015).

3.1.2.2. Graphic realism. Developers have tried to visualize more sophisticated and high-quality VR scenes to increase users' immersion. Among various approaches, manipulating the level of visual details was widely applied. For example, participants watched more complicated visual scenes with different altitudes (Kingdon et al., 2001; Watanabe & Ujike, 2008), or details of the texture were added to manipulate graphic realism (Davis et al., 2015; Jaeger & Mourant, 2001). Besides changing the visual aspect of VR, the level of graphic realism was manipulated by providing cognitive cues. In the study of Golding et al. (2012), the authors implemented two VR conditions with different levels of realism by changing the direction of a virtual camera; up-right or inverted. While the up-right scene was assigned to a higher realism condition, the inverted scene was set to a lower level of graphic realism since the reversed world was unfamiliar for most of the users.

The studies mentioned above tried to render more realistic scenes, which provide higher visual fidelity of VR content. However, those efforts did not necessarily correlate to better user experiences in VR. Participants who experienced better graphic realism conditions tended to show a higher level of discomfort. This unexpected result might originate from the sensory discrepancy between visual and vestibular information. For example, most participants were allowed to navigate in the VR passively and received limited vestibular information, sitting in their seats or holding their jaws in a chin-rest (Davis et al., 2015; Jaeger & Mourant, 2001; Kingdon et al., 2001). This asymmetric interaction can increase the conflict between sensory information. In other words, as the visual stimulus becomes more similar to reality, the user is more immersed in the VR and expects vestibular inputs corresponding to the visual stimulation. However, users cannot acquire such vestibular information, so the degree of conflicts as well as VR sickness increases.

3.1.2.3. Reference frame. Several studies have rendered fixed visual stimuli regardless of the moving VR content (Duh, Parker et al., 2001; Duh et al., 2004; Hwang et al., 2012; Lin et al., 2002). For example, clouds or trees were displayed at the same location irrespective of the motion of the content (Lin et al., 2002). Also, grid patterns were rendered on the front or back of the VR scene (Duh, Parker et al., 2001; Duh et al., 2004; Hwang et al., 2012). When the fixed visual stimuli were added, user's symptoms of VR sickness significantly decreased in both subjective and objective aspects. Participants reported lower SSQ scores and their electrogastric signals showed that users experienced less nausea if the VR content had grid patterns (Hwang et al., 2012). In addition, when a virtual nose was rendered on a VR scene, users enjoyed the content for an average of 94.2 seconds longer (Whittinghill et al., 2015). Prothero et al. (1999) argued that various types of fixed visual stimuli mentioned above can serve as a frame of reference which helps the user to perceive one's position

accurately in VR. Also, the authors claimed that the reference frame can serve visual stimuli that match the human inertial self-motion system and reduce sensory conflict.

3.1.2.4. Content FOV. Besides manipulating the hardware FOV, previous research has applied various types of visual effects to change the FOV of a virtual camera. In accordance with the results of hardware FOV, many studies have demonstrated that narrowing the content FOV is effective at relieving both subjective and objective symptoms of VR sickness (Duh, Lin et al., 2001; Fernandes & Feiner, 2016; Kobayashi et al., 2015). In the study by Fernandes and Feiner (2016), symptoms of VR sickness were alleviated even though the user did not recognize the reduced FOV. Also, reducing the edge of the screen or rendering a cockpit on the flight simulation was used to narrow down the content FOV. It is important to reduce the FOV to an appropriate level. If the FOV becomes too narrow, users will not feel a sense of immersion in VR. Also, when exploring VR, greater head movements are needed due to the restricted FOV, which may cause VR sickness.

3.1.2.5. Duration. Even in the short exposure of virtual content (< 10 min), users can experience VR sickness (Dennison et al., 2016). In addition, several studies have shown that more than 10 minutes of exposure to VR can be associated with symptoms of sickness, and the longer the exposure time, the greater the degree of VR sickness (Liu & Uang, 2012; Lo & So, 2001; Stanney et al., 2003; So & Lo, 1999; So, Lo et al., 2001). Stanney et al. (2003) demonstrated that there was a strong positive correlation between exposure duration and SSQ scores. All sub-scales of SSQ (i.e., SSQ nausea, SSQ oculomotor, and SSQ disorientation) increased as users experienced VR longer. It is required to set an appropriate experience time when implementing VR. Oculus Lift's guidebook suggests a regular break in the VR experience, or to remind a user of how much time they have spent in VR (Yao et al., 2014).

The weight of the device may influence the duration effect on users' discomfort. In particular, when experiencing VR using an HMD, wearing a heavy object on the head for a long time can cause discomfort to the user regardless of the VR content. Recently, L. R. Rebenitsch (2015) investigated the difference in user experience depending on the weight of HMDs. Participants experienced VR wearing two different HMDs (Sony Glasstron LDI-D100B; 340 or 490 gram) and reported their discomfort. The result showed that there was no significant weight effect on the degree of VR sickness, but some users reported the inconvenience of using the heavier device.

3.1.2.6. Controllability. Depending on the purpose and content of the VR, various types of VR are available which can be divided into active or passive experiences. Passive navigation restricts the user's active interactions (e.g., searching for virtual environments using the body) during the VR experience. Several studies have shown that users who experienced passive navigation reported severe VR sickness (Dong & Stoffregen, 2010; Dong et al., 2011; Jaeger & Mourant, 2001; Sharples et al., 2008; Y.-C. Chen et al., 2011). In particular, by setting up a yoked-control group, the result demonstrated that user experiences became worse if the participant lost controllability in VR and were forced to watch the VR scene passively (Y.-C. Chen et al., 2011).

3.1.2.7. Brief discussion. In this section, we reviewed various approaches to manipulating VR content for changing the level of VR sickness. A Sankey diagram for VR content showed that four research topics were widely investigated (Figure 2). Specifically, investigating the optical flow of VR content has been a priority VR sickness research. As VR sickness is closely related to perceiving moving images, it has become essential to determine which aspects of moving images (e.g., velocity, rotational pattern, oscillation amplitude) are associated with causing VR sickness. According to the experimental results, the occurrence of VR sickness has been related to the specific motion that induces a strong vection rather than the absolute size of the optical flow.

For studies regarding the level of graphic realism, unexpected results were observed; that is, the improved visual quality of VR did not necessarily lead to reduced VR sickness. Instead, participants showed less discomfort when they experienced a lower level of realism. Golding suggested that the human brain may "quarantine" visual stimuli that were apparently absurd (i.e., low-level realism that was hard to experience in the real world), leading to being less likely to feel sick (Golding et al., 2012).

Among various visual effects, rendering reference frames or narrowing the FOV of a virtual camera was applied to reduce VR sickness. More research is needed to elucidate how these methods can affect the human cognitive system and decrease discomfort. Moreover, it would be helpful to develop a guideline for VR content that can minimize the level of VR sickness while maintaining user immersion and presence.

Meanwhile, task-related factors such as duration of VR experience and controllability of the user have also been investigated. The results of manipulating VR duration confirmed that a total recommended time for VR experience should be provided to prevent users from experiencing an uncomfortable body state. Moreover, it is suggested to allow users to move their bodies (at least, the upper part of the body) freely during the experience. According to Bos et al. (2008), this might be associated with an internal model of the human perceptual system. If a person can move his/her body voluntarily, the internal model of the brain can be actively updated, which helps to cope with conflicting sensory information.

In line with the Sankey diagram of hardware (Figure 1), the SSQ and postural sway were the most frequently used measures for subjective and objective levels of VR sickness, respectively. Further experimentation using various types of objective measurements is required to investigate the effect of VR content on physiological responses.

3.1.3. Human factors

It is often observed that the severity of VR sickness differs between users, although users experience the same VR content through the same device. Many researchers have focused that various human factors can be associated with the

phenomenon. Demographic factors and various characteristics of the users themselves were widely investigated.

Nineteen articles in the data list examined the effect of the human factor on VR sickness (Table 4). Compared to other categories, the studies of human factors have tended to consider two or more variables at the same time (e.g., observing the effects of age and gender simultaneously). About half of the articles (i.e., 10 articles) investigated the effects of multiple human factors at once.

While manipulating human factors, each study recorded users' responses using subjective or objective measures. Questionnaires, especially SSQ, were widely used methods for the subjective measure. Meanwhile, postural sway has been investigated to compensate for the limitations of questionnaires.

3.1.3.1. Age. A number of studies have investigated whether users' age can affect the level of VR sickness. However, experiments have shown mixed results. According to Häkkinen et al. (2002), subjects aged 18 to 41 were given HMDs and experienced a virtual race environment. The result showed that an older age group showed a significant increase in SSQ-O scores compared to a younger age group. Park et al. (2006) also found that an older group (70 ~ 90 years) showed a higher dropout rate than a younger group (21 ~ 50 years). However, a meta-analysis by Saredakis et al. (2020) showed the opposite result. That is, individuals whose mean age lower than 35 reported a higher total SSQ score compared with the older age group. More studies are needed to explain the age effect on VR sickness since other variables such as motion sickness susceptibility and prior VR experiences are also closely related to age.

While the age range of VR users is becoming more diverse in recent years, most research subjects were limited to young people in their 20 s. To establish a reliable safety guideline of VR devices, research on a broader age group will be required. In particular, it is important to consider a change of physical ability (e.g., vision sensitivity) as part of the developmental process.

3.1.3.2. Gender. Inconsistent results have been drawn for the gender differences in VR sickness. Several studies showed that women are more susceptible to VR sickness and reported higher SSQ scores than men (Freitag et al., 2016; Häkkinen et al., 2002; Jaeger & Mourant, 2001; Stanney et al., 1999). However, Lawson (2014) demonstrated that it is inconclusive to claim gender differences in VR sickness based on the review of 46 previous studies (Lawson, 2014). According to his report, only 26 among 46 studies (i.e., 56.5 %) showed higher levels of VR sickness susceptibility in females compared to males. Also, a meta-analysis by Saredakis et al. (2020) did not find a significant correlation between gender and the severity of discomfort.

Then, why some women experience more severe VR sickness than men? It might be originated from various sources such as gender differences in FOV (Kolasinski, 1995), hormone levels (Clemes & Howarth, 2005), and motion sickness history (Stanney et al., 2020).

3.1.3.3. Prior VR experiences and motion sickness susceptibility. It is well known that the severity of VR sickness can be decreased when users repeatedly experience the same VR content. In the study of Freitag et al. (2016), users who have no prior experience in VR reported greater discomfort showing higher SSQ scores and poorer task performance in VR. Therefore, it is important to consider a user's previous VR experience when providing VR content. Stanney et al. (2003) showed that a person who had more history of adverse experiences during various types of riding can undergo a higher severity of VR sickness.

Motion sickness susceptibility is an important index for predicting the degree of VR sickness. Several studies showed that a person who was vulnerable to motion sickness was likely to report higher discomfort in VR (Benzeroual & Allison, 2013; Llorach et al., 2014; Stanney et al., 2003). In most cases, Motion History Questionnaire (MHQ) (Kennedy & Graybiel, 1965) or Motion Sickness Susceptibility Questionnaire (MSSQ) (Golding, 1998) were used to quantify one's susceptibility. According to Stanney et al. (2003), MHQ scores showed a positive correlation with SSQ. A higher MHQ group reported more severe VR sickness, showing a 39.9 % higher SSQ score. Also, a person with a higher MSSQ score took a shorter time to report nausea (Golding, 1998).

In the study of Benzeroual and Allison (2013), a significant interaction effect between MSSQ score and display mode was observed. Users with higher susceptibility reported greater discomfort when viewing stereoscopic images than monoscopic images. The result indicated that difference in depth perception could be associated with susceptibility to motion sickness, which might result in inducing VR sickness.

3.1.3.4. Brief discussion. According to a Sankey diagram, the effects of individual differences such as age, gender, and motion sickness susceptibility on VR sickness have been widely investigated (Figure 3). In particular, it has shown that the susceptibility of an individual to motion sickness can be a promising predictor for experiencing VR sickness. This result indicates that an occurrence of VR sickness could be partly because of motion sickness susceptibility. Based on these experimental results, the same quality of the VR system can provide different user experiences depending on various human factors.

3.2. Measures of VR sickness

The entire articles (i.e., 77 experimental studies) measured the level of VR sickness using at least one methodological approach. According to previous results, there are either subjective or objective measurements that can reflect the users' discomfort. The most widely used methods for measuring VR sickness are questionnaires based on self-reporting. The questionnaire method is intuitive and easy to describe one's current state. However, the severity of users' discomfort is usually collected after the VR experience, which does not reflect VR sickness in real-time. Also, the level of severity where the user judges their state as VR sickness can be different among users. For example, some people can feel dizziness when they experience VR sickness, but others judge their condition based on

nausea. Therefore, alternative measurements have been required that can objectively measure the level of sickness. The researchers have found several measurements that can reflect physiological changes due to VR sickness. Postural sway and various electrophysiological signals such as electroencephalogram (EEG), electrogastrogram (EGG), and electrocardiogram (ECG) have been investigated in order to discover a promising objective measurement.

3.2.1. Subjective measures

Various types of questionnaires have been used for self-reporting of the severity of VR sickness by participants. Among 77 experimental studies, 76 studies acquired subjective measurements of VR sickness. Since thirty-five studies used more than one subjective measurement, the total number of subjective measurements was 117. Among them, the most widely used measurement was the SSQ, developed by Kennedy et al. (1993) (Figure 4). The SSQ consists of 16 items and answers from 0 to 3 depending on the severity of participant's symptoms. The SSQ can be divided into three subscales (i.e., nausea, oculomotor, and disorientation). A higher the SSQ score indicates that the participant experienced more severe VR sickness. If the total SSQ score is higher than 33.3 points, the participant can be judged to experience high severity of discomfort (Stanney et al., 2014).

Since the SSQ contains many questions which consider multiple dimensions of symptoms, researchers developed questionnaires that are relatively concise and quick to report. Fast Motion sickness Scale (FMS) (Keshavarz & Hecht, 2011a, 2011b, 2014) and the misery scale (MISC) (Bos et al., 2010; Lubeck et al., 2015; Van Emmerik et al., 2011) are well-known unidimensional questionnaires (Table 5). The FMS was developed by Keshavarz and Hecht (2011b), and a participant verbally reports the level of discomfort every minute. FMS presents a range of scores (0: no sickness at all, 20: severe sickness) and the participant is required to report a score based on the individual's criterion. The MISC also reports a score between 0 and 10 depending on the participant's sickness severity. In line with these two measurements, many researchers invented various versions of Sickness scale to measure the level of users' overall discomfort. Depending on the study, various version of scales could be used and the names of measurements were slightly different among studies (Table 6). The Nausea scale contains various nausea-related symptoms, including burping, sweating, increased salivation,

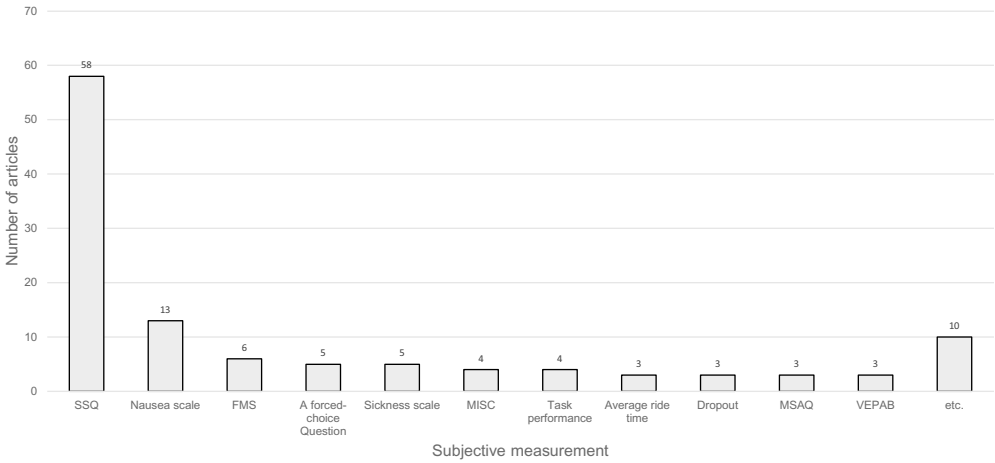

Figure 4. A frequency of use in subjective measurements for VR sickness.

Table 5. Major subjective measurements and their details.

Questionnaire	# Items	Rating scales	Subscales/Details	Reference	# Articles
SSQ	16	4-point	SSQ-Nausea (SSQ-N) SSQ-Oculomotor (SSQ-O) SSQ-Disorientation (SSQ-D)	Kennedy et al. (1993)	58
FMS	1	21-point	Unidimensional construct	Keshavarz and Hecht (2011b)	6
A forced-choice question	1	Yes or No choice about motion sickness incidence	Unidimensional construct	Chen, Dong, et al. (2011)	5
MISC	1	11-point	Unidimensional construct	Bos et al. (2010)	4
Task performance	-	-	Accuracy of task performance Average task completion time	Freitag et al. (2016)	4
Average ride time	-	-	Total time spent in virtual reality	Whittinghill et al. (2015)	3
Dropout	-	-	Rate of abandonment	Park et al. (2006)	3
Motion Sickness Assessment Questionnaire (MSAQ)	8	9-point	Gastrointestinal Central Peripheral Sopite-related	Gianaros et al. (2001)	3
VEPAB (Virtual Environment Performance Assessment Battery)	-	-	A set of tasks in the VR comprising vision, locomotion, tracking, object manipulation, and reaction time	Lampton et al. (1994)	3

and emetic responses. Nausea scale also has various versions of the name and scale, but most of them require a participant to report the degree of nausea as a single number based on the rating scales (Table 6) (Lo & So, 2001; So & Lo, 1999; So, Lo et al., 2001). A forced-choice question is a simple yes or no choice about experiencing motion sickness in VR. The question is usually used for dividing participants into sick or healthy groups for VR sickness. The Motion Sickness Assessment Questionnaire (MSAQ) invented by Gianaros et al. (2001) has fewer number of questions and a broader rating scale than SSQ. Also, MSAQ has four subscales which consider multi-dimensional aspects of motion sickness. Several studies adopted a Virtual Environment Performance Assessment Battery (VEPAB) (Lampton et al., 1994) which measures human performance in the VR using various tasks (e.g., vision, locomotion, tracking, object manipulation, and reaction time tasks).

Subjective measurements have some limitations. First, there are individual differences in determining the level of one's discomfort. The critical point where the individual decides to report VR sickness can vary. For example, some people use a sense of dizziness to judge VR sickness, but others can judge their condition based on symptoms of nausea. Second, most questionnaires are collected after finishing the VR experience, which does not reflect users' discomfort in real time. Therefore, it has been difficult to investigate time-varying factors which can predict VR sickness. For these reasons, there is a growing demand for new indices that can implicitly measure VR sickness with higher accuracy and consistency (Tables 5, 7). For example, there have been attempts to evaluate users' experience based on performance in the VR, including the total time spent in virtual reality (Whittinghill et al., 2015), the accuracy of task performance (Freitag et al., 2016), response time to a visual stimulus (Nesbitt et al., 2017), and the rate of abandonment (Graeber & Stanney, 2002; Stanney et al., 2002; Park et al., 2006). Although some of these methods still rely on subjective judgment, they can evaluate user's experience less explicitly than existing questionnaires.

3.2.2. Objective measures

In order to overcome the limitations of subjective measurements, the researchers have tried to find objective measurements that are highly correlated with self-reports. Mostly, postural sway or electrophysiological changes were measured. Participants stood on a motion platform, and their position information in the VR was recorded (Duh, Abi-Rached et al., 2001; Chardonnet et al., 2015; Dong & Stoffregen, 2010; Villard et al., 2008; Y.-C. Chen et al., 2011). Changes in the individual's psychophysical state during the VR experience were also measured in real time (Hwang et al., 2012; Y. Y. Kim et al., 2005; Kiryu et al., 2007; Kobayashi et al., 2015; Roberts & Gallimore, 2005). After the recording, correlation analysis between each objective measurement and the subjective discomfort level was conducted to determine promising indices for VR sickness . Only 42 of the 77 experimental studies adopted objective measurements. Nine studies used two or more measurements simultaneously. Therefore, the total amount of objective measurements was 72. Postural sway is the most widely measured, followed by changes in ECG, eye-related measures, EGG, and other physiological signals (e.g., EEG, skin conductivity, respiration, and etc.) (Figure 5, Table 8).

For postural sway, the user's axial movements or changes in the center of pressure (COP) were measured during the VR exposure. Several studies have revealed that these measurements can predict the occurrence of VR sickness (Chardonnet et al., 2015; Dong & Stoffregen, 2010; Villard et al., 2008) or have a positive correlation with subjective self-reports (Duh, Abi-Rached et al., 2001). The study of Y. Y. Kim et al. (2005) is a representative study investigating physiological correlates of VR sickness. Various electrophysiological indices were selected and

Table 6. Details in Nausea scale and Sickness scale.

Questionnaire	Synonym	Rating scales	Reference	# Articles
Nausea scale	Nausea scale	7-point	So, Lo et al. (2001)	6
	Bagshaw and Stott's sickness scale	4-point	Dennison et al. (2016)	3
	Nausea scale rating	11-point	Davis et al. (2015)	3
	Nausea visual analogue scale (VAS)	4-point	Farmer et al. (2015)	1
Sickness scale	Sickness rating (SR) scale	6-point	Golding et al. (2012)	1
	Discomfort score	11-point	Fernandes and Feiner (2016)	1
	Subjective Symptoms of Motion Sickness (SSMS)	4-point	Palmisano et al. (2007)	1
	Verbal sickness rating	4-point	Draper et al. (2001)	1
	VIMSL level (VIMSL)	5-point	Liu et al. (2017)	1

Table 7. Details in miscellaneous subjective measurements.

	Type	Details	Reference	# Articles
etc.	Subjective difficulty rating	Difficulty in maintaining the Rhomberg stance; 10-point scale	Duh, Lin et al. (2001)	2
	A visual and physical discomfort questionnaire	Assessing visual and physical discomfort answering 15 questions with a 5-point scale	Yang and Sheedy (2011)	1
	Anxiety VAS	Measuring anxiety level; 4-point scale	Farmer et al. (2015)	1
	Beck Anxiety Inventory (BAI)	Measuring the severity of an individual's anxiety; 4-point scale	K. Kim et al. (2014)	1
	Graybiel categorization system	Measuring motion sickness symptoms	DiZio and Lackner (1997)	1
	Reaction time	Deary-Liewald Reaction Time Task (response time to a visual stimulus)	Nesbitt et al. (2017)	1
	Self Assessment Manikin (SAM)	Assessing emotional arousal and valence; 9-point scale	K. Kim et al. (2014)	1
	Sickness questionnaire	A questionnaire containing a total of 15 binary items.	Keshavarz et al. (2011)	1
	Total symptom score	Measuring the severity of each VR sickness symptom; 4-point scale	Golding et al. (2012)	1

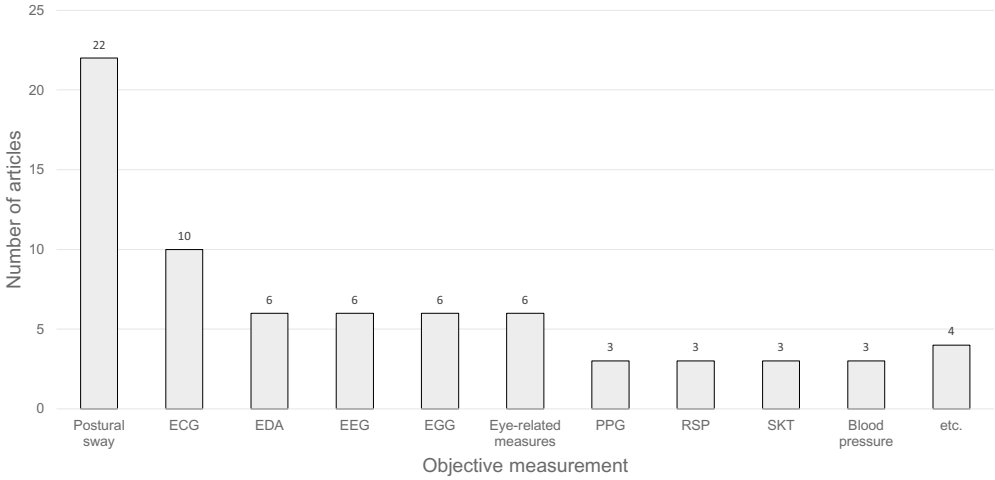

Figure 5. A frequency of use in objective measurements for VR sickness.

Table 8. Objective measurements and their details.

Measurements	Details	Reference	# Articles
Postural sway	Center of pressure (COP) (also referred as center of gravity (COG) or center of balance (COB))	Palmisano et al. (2018)	22
	Sway path length or sway area	Lubeck et al. (2015)	
	Limb position using standardized pointing test	Stanney et al. (1999)	
	Head angular position	Draper et al. (2001)	
	Spatial magnitude of movement in terms of the standard deviation of position of the head and torso	Stoffregen et al. (2017)	
Electrocardiogram (ECG)	LF/HF ratio	Kiryu et al. (2007)	10
	Heart rate and heart period	Y. Y. Kim et al. (2005)	
	HRV parameters (SDRR, RMSSD)	Mazloumi Gavgani et al. (2017)	
Electrogastrogram (EGG)	Gastric tachyarrhythmia	Farmer et al. (2015); Y. Y. Kim et al. (2005)	6
Eye-related measures	Eyeblink rate by recording EOG signal	Y. Y. Kim et al. (2005)	6
	Variation in eye position	Diels et al. (2007)	
	Vergence and Accommodative Responses	Yang and Sheedy (2011)	
	Distance heterophoria	Howarth (1999)	
Electrodermal activity (EDA)	Fingertip/forehead skin conductance level	Dennison et al. (2016); Y. Y. Kim et al. (2005)	6
Electroencephalogram (EEG)	Relative delta power and beta power	Y. Y. Kim et al. (2005)	6
Photoplethysmogram (PPG)	Photoplethysmogram maximum amplitude	Y. Y. Kim et al. (2008, 2005)	3
	PPG peaks		
Respiration pneumogram (RSP)	Respiratory sinus arrhythmia	Dennison et al. (2016); Y. Y. Kim et al. (2005)	3
	Respiration rate (breathing rate)		
Skin temperature (SKT)	Fingertip/forearms skin temperature	Harvey and Howarth (2007); Y. Y. Kim et al. (2005)	3
Blood pressure	Blood pressure during VR experiences	Farmer et al. (2015)	3

recorded before, during, and after the VR experience. Among them, electrogastrogram (EGG), eye blink, heart period, and the delta and beta power bands of electroencephalogram (EEG) showed VR sickness-specific responses (Y. Y. Kim et al., 2005). Recent studies have shown that the ratio of low frequency to high frequency (LF/HF ratio) of electrocardiogram (ECG) is related to the level of VR sickness (Diels et al., 2007; Kiryu et al., 2007; Kobayashi et al., 2015). Also, a few studies measured blood pressure, fMRI, and hormonal level for VR sickness (Table 9).

3.3. Emerging approaches for reducing VR Sickness

3.3.1. Depth of field

Recently, using dynamic depth of field (DoF) was proposed for better user-experiences (Carnegie & Rhee, 2015). In relation to VR sickness, the researchers have noted that there is a difference in processing the depth of field between the human eye and the hardware (especially HMD) (Duchowski et al., 2014; Hoffman et al., 2008). The human eyes can automatically focus on an object (or a certain part of the scene) to

Table 9. Details in miscellaneous objective measurements.

	Type	Details	Reference	# Articles
etc.	Eye-hand coordination	Measuring proprioceptive aftereffects after VR exposure	Stanney et al. (2003)	2
	fMRI	Brain activity during nauseous experiences	Farmer et al. (2015)	1
	Vasopressin and ghrelin	Hormonal patterns of the nausea	Farmer et al. (2015)	1

which attention is paid, while other scenes are out-of-focus (i.e., shallow depth of field). On the other hand, when exploring the surroundings through an HMD device, all objects are on the same screen regardless of the user's visual attention (i.e., deep depth of field). Researchers have shown that this difference can exacerbate eye-related symptoms, causing a strain on eye movements (Carnegie & Rhee, 2015; Duchowski et al., 2014; Hoffman et al., 2008).

In the study of Carnegie and Rhee (2015), participants were allowed to actively navigate in the VR with an adjusted depth of field. To imitate the visual perception in the real world, the central part of the VR scene was clearly focused while the rest of the scene was blurred. The users showed lower SSQ scores when they experienced a dynamic depth of field condition compared to no manipulation (i.e., with all parts of the image being sharp). Like the method of reducing the FOV, dynamic depth of field can serve to decrease the amount of visual input which causes sensory conflicts. Also, if a developer can assure that a VR user will focus on a certain part of the scene, mainly the center, this method can reduce the computational cost of rendering the image.

3.3.2. Additional sensory information

To develop a high-fidelity VR which can decrease users' discomfort, it is crucial to implement a virtual environment that provides multisensory information. If only the visual aspect of the VR scene is stressed and other sensory information is limited, the user is more likely to experience sensory conflicts and suffer from VR sickness. In other words, a VR system that can alleviate discomfort would be one where the virtual environment provides multimodal information.

For example, several suggestions have proposed providing additional sensory information (e.g., auditory, olfactory, and tactile information) for alleviating VR sickness. By adding multisensory information to the VR, the user can successfully handle the mismatch between the sensory information since additional inputs are available in the multimodal VR. Previous studies showed that when participants experienced a VR with pleasant music or aroma, they reported less VR sickness compared to when there was no additional sensory input (Keshavarz & Hecht, 2014; Keshavarz, Stelzmann et al., 2015). These results indicated that the psychological and emotional state of the user in the VR also can influence on the degree of VR sickness. By providing a multisensory virtual environment, the degree of sensory conflicts may be reduced, and users' discomfort also decreased.

Tactile stimulation has drawn mixed results. The level of VR sickness mitigated when participants experienced a vibration stimulus corresponding to the visual stimulus (Plouzeau et al., 2015) or exposed to airflow (D'Amour et al., 2017). If the tactile information was provided synchronously with visual information, or at least that the participant was not aware of the time difference between the multisensory information, the person was likely to have better user experiences in VR. However, Paroz and Potter (2018) failed to replicate the airflow effect on reducing VR sickness, which might be due to the small sample size and granularity of the data.

3.4. Multimodal fidelity hypothesis

Many researchers have tried to implement a more realistic virtual environment to reduce VR sickness (Davis et al., 2015; Keshavarz & Hecht, 2014). They have thought that increasing the level of fidelity, which generally refers to how realistic the rendering of a virtual environment is, can help users to enjoy better VR experiences. However, our review showed inconsistent results regarding the effect of high-fidelity VR on user's discomfort. Several studies indicated that a visually improved VR failed to result in decreased VR sickness (Bubka et al., 2007; Davis et al., 2015; Stanney et al., 2003). Contrarily, other studies showed that users' discomfort alleviated in a more realistic VR as researchers intended (D'Amour et al., 2017; Keshavarz & Hecht, 2014; Keshavarz, Stelzmann et al., 2015). By reviewing the characteristics of each study, we found that these mixed results may have originated from the different experimental approaches to manipulate the level of fidelity. The quality of sensory information in high-fidelity VR varied between studies, and this difference might influence users' discomfort. Based on this finding, we hypothesized that the high level of fidelity can bring a varying degree of VR sickness depending on the available sensory information in VR. Therefore, we assumed that not only visual information but also other sensory inputs such as vestibular, auditory, and proprioceptive information should be considered to clarify fidelity effects on VR sickness. We named this assumption as a multimodal fidelity hypothesis and tried to demonstrate the assertion through a meta-analysis.

Figure 6 is a flow chart for categorizing each VR system (or VR experiment) in terms of the multimodal fidelity hypothesis. The main idea is determining the number of sensory modalities provided in a specific VR system. For the first step, we broadly divided each system into two categories based on any explicit statement for describing a participant's body movement. If authors restricted a participant's body and clearly stated the procedure in a paragraph, we assigned the study in a single modality system. If the experiment allowed voluntary body movement, the system was classified as multiple modalities since the VR provided at least two sensory inputs; visual and vestibular information. Then, we classified the multimodal system into two different types considering which sensory information was manipulated to implement a high-fidelity virtual environment. While a Type B system modified the visual aspects of the virtual world, a Type C system offered various sensory information except vision to implement a real-like VR. Based on these criteria, we can classify the type of VR system into one of three categories. After the assignment, we selected previous studies using SSQ to compare results in a unified approach

Previous experimental results can partly support the hypothesis. We selected 23 articles from the database that described the SSQ scores of each experimental condition using figures or tables. Based on these scores, we compared each experiment depending on the classification of the VR system. Figure 7 shows the opposite direction of fidelity effects on VR sickness in accordance with the VR type. Participants showed less discomfort in high-fidelity virtual

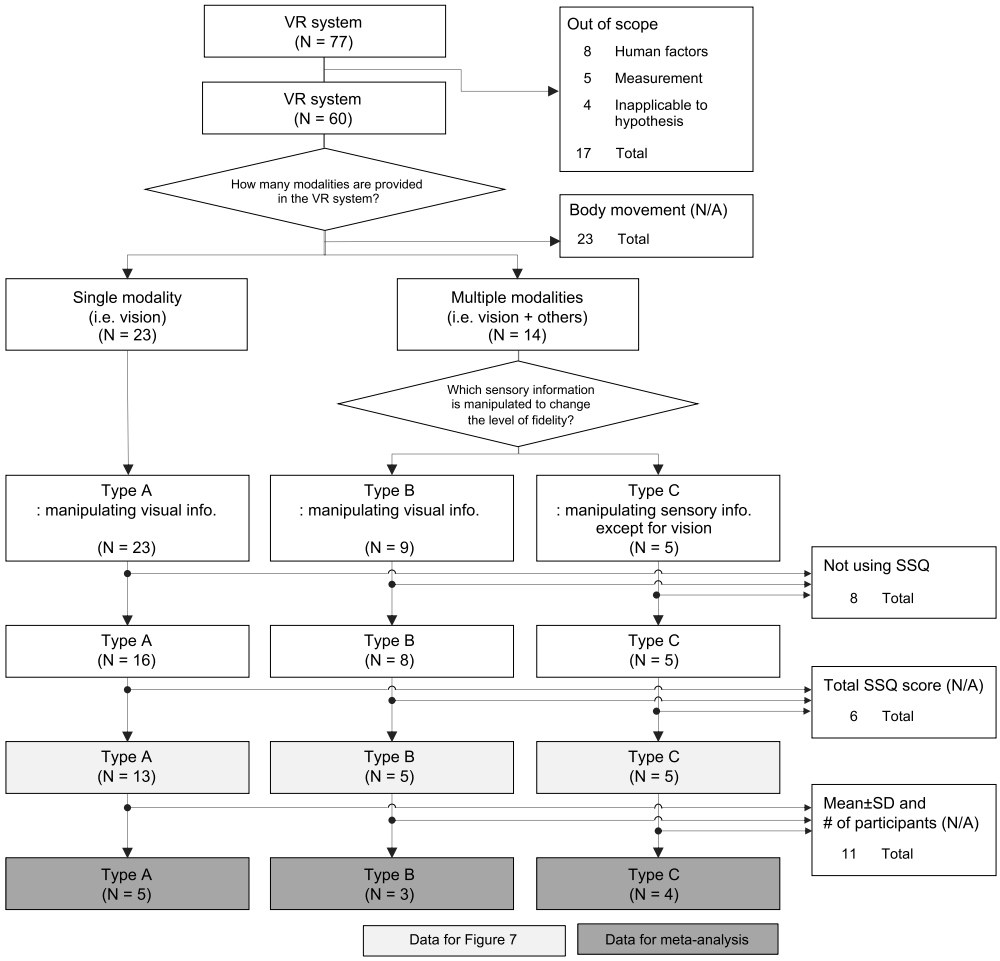

Figure 6. A flow chart of classifying the VR system based on the multimodal fidelity framework.

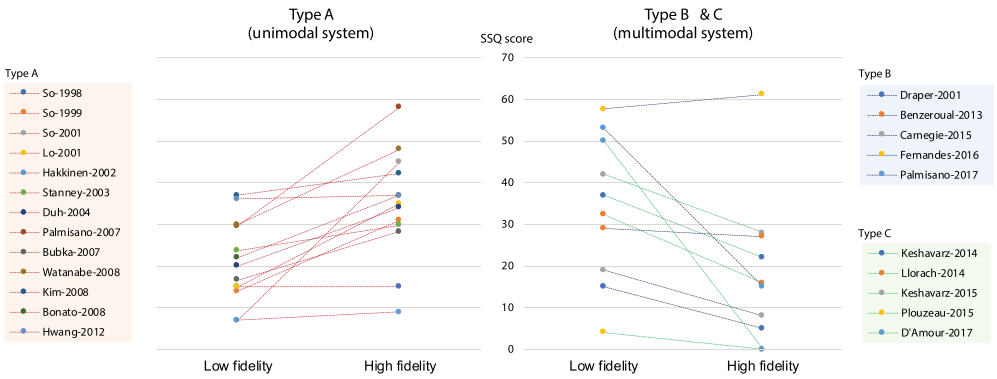

Figure 7. The relationship between the level of VR fidelity and VR sickness depending on the type of VR system.

environments if the VR provided multiple sensory information. If the VR was a unimodal system, a higher level of fidelity can exacerbate adverse symptoms.

For further analyses, a meta-analysis was conducted to investigate whether statistical differences can be found in fidelity effects on VR sickness depending on the system types. Among 23 data from Figure 7, 12 studies provided the mean (SD) of total SSQ scores and the number of participants for each experimental condition (Table 10). All analyses were performed with a random-effects model due to substantial variance between studies. Because the SSQ score is continuous data, the standardized mean difference (SMD) with 95% confidence intervals (CIs) was calculated. Higgins I^2 statistic and Egger's t-test were used for testing the heterogeneity and publication bias, respectively. All statistical analyses were performed using a Comprehensive Meta Analysis (CMA, version 3.3.070).

Figure 8 shows the forest plots and the results of meta-analyses in each VR system. For the unimodal system (Type A), there was a significant heterogeneity in overall studies

Table 10. Details in data used in meta-analyses.

Reference	Type	Exp. Condition: Low fidelity / High fidelity	Total SSQ Mean (SD)	N
Stanney et al. (2003)				
study 1	A	Simple	26.7 (26.6)	240
		Complex	27.0 (27.1)	240
study 2	A	Streamlined (3DOF)	27.2 (33.5)	240
		Complete (6DOF)	32.3 (36.4)	240
Bubka et al. (2007)	A	Contracting	16.6 (12.4)	16
		Expanding	28.3 (8.1)	16
Palmisano et al. (2007)	A	Non-oscillating displays	29.7 (24.7)	16
		Oscillating displays	58.2 (32.2)	16
Bonato et al. (2008)	A	Steady condition	21.6 (21.4)	14
		Alternating condition	36.9 (29.6)	14
Hwang et al. (2012)	A	Rest frame	36.1 (28.4)	20
		No rest frame	36.9 (26.6)	20
Benzeroual and Allison (2013)	B	2D	29.2 (26.2)	26
		3D	25.8 (15.3)	26
Fernandes and Feiner (2016)	B	Smaller FOV	48.1 (30.2)	6
		Larger FOV	48.4 (44.4)	9
Palmisano et al. (2017)	B	Inversely compensated condition	53.2 (39.9)	13
		Compensated condition	15.0 (20.7)	13
Llorach et al. (2014)	C	Gamepad	32.3 (29.3)	55
		Position estimation system	15.9 (14.8)	61
Keshavarz and Hecht (2014)	C	No music (control)	40.8 (28.0)	21
		Pleasant music	29.5 (18.3)	43
Keshavarz, Stelzmann et al. (2015)	C	No odor (control)	41.8 (27.7)	22
		Pleasant odor	27.2 (20.1)	11
D'Amour et al. (2017)	C	Control	50.0 (33.4)	21
		Airflow and vibration	35.6 (22.3)	19

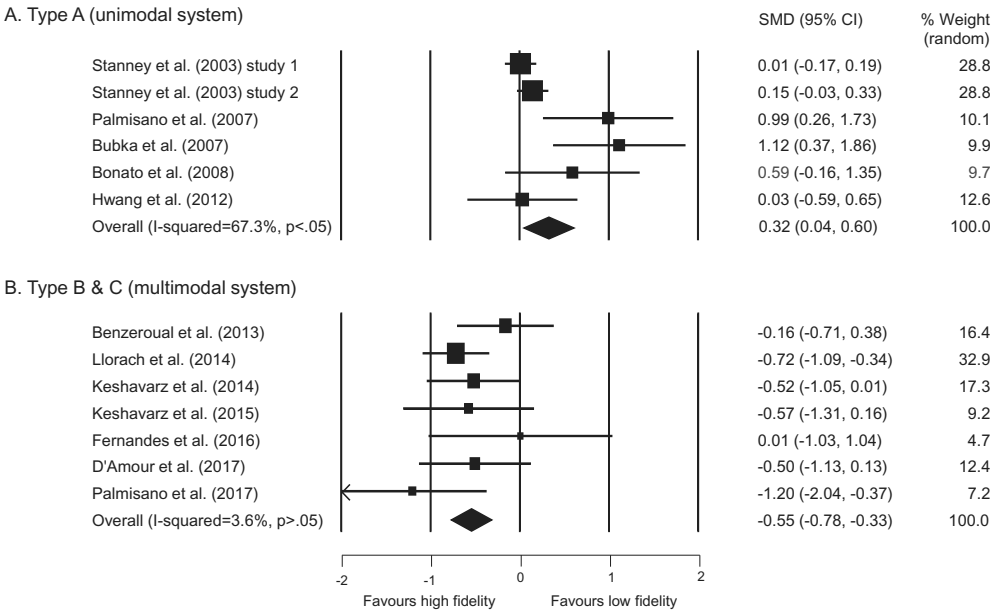

Figure 8. Forest plots of each VR system.

(I^2 = 67.3 %, p < .05). A random-effects model indicated a significant fidelity effect on VR sickness, showing that high-fidelity VR increased the level of sickness (SMD = 0.32, Z = 2.22, p = .03). However, we found a publication bias (Egger's t = 2.53, p = .03) so that Duval and Tweedie's trim-and-fill method was performed. The adjusted results showed that the range of SMD shifted into −0.19–0.44, indicating no strong evidence for fidelity effects on VR sickness in the unimodal VR system (Figure 9). Contrarily, the multimodal VR system (Types B and C) showed opposite results. The heterogeneity between studies was low (I^2 = 3.6 %, p > .05) and a significant difference between fidelity conditions was found, showing that high-fidelity VR decreased the level of discomfort (SMD = −0.55, Z = −4.79, p = .00). A publication bias was not found (Egger's t = 0.41, p = .35).

These results indicated that increased fidelity can alleviate the user's discomfort only when the virtual environment can provide synchronous multimodal information to users. Interestingly, if the system only delivered visual information to a user, increasing fidelity might not be an effective way to reduce adverse symptoms. The findings suggest that it is critical to minimize the asymmetry between sensory information for mitigating discomfort because

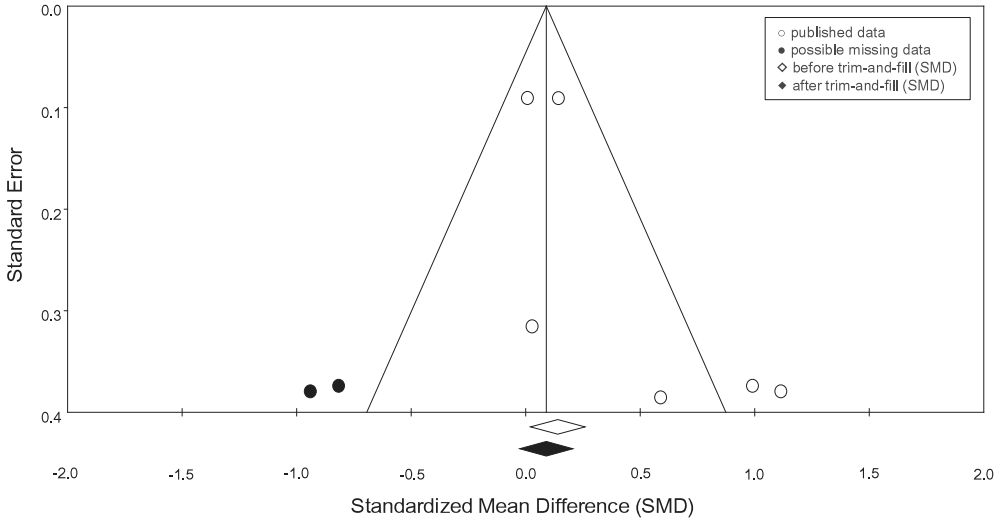

Figure 9. An adjusted funnel plot of the unimodal VR system after the trim-and-fill.

VR sickness has been known to be related to not intra- but inter-sensory conflict. The multimodal fidelity hypothesis might provide a new insight into the relationship between fidelity and VR sickness. More experimental data are needed to overcome the publication bias and to confirm the assertion.

4. Discussion

VR sickness has been a high-priority topic in the virtual reality industry. Despite various efforts, there have been mixed results on how to alleviate users' discomfort. In this paper, we aimed to review previous research on VR sickness and provide directions for future studies by surveying sickness-evoking factors and investigating the measurement of symptoms.

Three major causes of VR sickness -hardware, content, and human factors- were surveyed. For the hardware factors, effects of device-related features such as display types and display mode on VR sickness were widely investigated. Content factors covered various features associated with the VR scene, such as optical flow, graphic realism, rendering reference frames, and task-related features. Several demographic features such as age, gender, and motion sickness history were included in human factors. We presented a Sankey diagram of each factor which illustrated the research trends as well as the pipeline of investigating VR sickness. The diagram aimed to provide promising directions for the following research by showing the stream of earlier approaches.

According to the survey, not a single but multiple factors of a VR system are related to users' discomfort. Though there has been an effort to reveal a few prominent factors for determining the VR sickness, this review showed a multi-faceted characteristic of VR sickness. Therefore, it is required to consider the various components of the virtual environment simultaneously to design a user-friendly VR scenario. It is also necessary to establish a standardized form of the experimental set-up, which ensures the comparison between studies. Since there is a wide variety of equipment and content to implement a VR system, it has been challenging to compare each VR experiment and produce a consistent result. Until a standardized experimental setup is established, researchers are required to describe details about device specifications and features of VR content in their article.

It is also critical to reliably measure symptoms of VR sickness. While most studies have relied on subjective reports of the VR user, there has been a growing interest in objective indices such as postural sway or electrophysiological signals (Chardonnet et al., 2015; Dong & Stoffregen, 2010; Y. Y. Kim et al., 2005). In this paper, we surveyed both subjective and objective measurements that were widely used for previous experiments and described the feature of each measurement. Though various indices were suggested to measure the level of sickness accurately, questionnaires have been the most commonly used methods. More experimental evidence is required for a better estimate of VR sickness.

Conflicting results regarding fidelity effects on VR sickness motivated the proposal of a multimodal fidelity hypothesis. Using meta-analyses, we attempted to provide statistical evidence for supporting the idea. The results showed that high-fidelity effects on VR sickness can vary depending on the number of modalities in a virtual scene. This finding suggests that multisensory information might be required to reduce the level of discomfort. Taken together, this paper provides a comprehensive review of VR sickness from its causes to measurements and contributes a clearer understanding of how to alleviate adverse symptoms.

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