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RESEARCH ARTICLE

The Visual Effects Associated with Head-Mounted Displays

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Abstract

Objectives: To investigate Visually-Induced Motion Sickness (VIMS) and visual effects associated with the Head-Mounted Displays (HMDs) most commonly used in Virtual Reality (VR) systems.

Methods: A comprehensive search query was performed on the Medline/PubMed, EMBASE, CENTRAL, ACM Digital Library, and IEEE Xplore databases. We identified population-based studies that evaluated HMDs as an independent factor for visual discomfort. Potential variables relevant to HMD discomfort, including system features (e.g. optical characteristics), subject characteristics (e.g. gender), and task characteristics (e.g. duration, vection, and task content) were reviewed. Total severity scores of Simulator Sickness Questionnaires (SSQT), oculomotor scores of Simulator Sickness Questionnaires (SSQO), and Visual Strain Questionnaires scores (VSQ) were used to measure HMD discomfort impact.

Results: We analyzed data for 1040 participants from a total of seventeen studies, all published between 1998 and 2015. Our review demonstrated that exposure to HMDs resulted in higher SSQT and SSQO mean change scores, compared with exposure to traditional displays such as TV and desktop computer displays. Furthermore, HMD exposure duration had a significant impact on the mean change scores of SSQT, SSQO, and VSQ. Our analysis also showed that HMD discomfort was affected by all three of the variables we evaluated.

Conclusion: This meta-analysis qualifies the risk factors causing discomfort after exposure to HMDs. We recommend that HMD manufacturers increase their awareness of, and address, these visual discomfort issues in their products.

Keywords

Head-mounted display, Virtual reality, Virtual environment, Visual discomfort

Abbreviations

HMD: Head-Mounted Display; NED: Near-to-Eye Display; VE: Virtual Environment; VR: Virtual Reality; 2D: Two-Dimensional; S3D: Stereoscopic Three-Dimensional; IPD: Inter-Pupillary Distance; FOV: Field of View; VIMS: Visually-Induced Motion Sickness; D: Disorientation; O: Oculomotor disturbance; N: Nausea; SSQ: Simulator Sickness Questionnaire; VSQ: Visual Strain Questionnaire; DK2: Developmental Kit 2; CI: Confidence Interval; SS: Simulator Sickness

Introduction

In recent years, Virtual Reality (VR) has become more commonplace, with rapid adoption into daily life. VR is a non-invasive simulation technology that provides an immersive, realistic, three-dimensional (3D) computer-simulated environment in which people perform tasks and experience activities as if they were in the real world. The most direct experience of VR is provided by fully immersive VR systems. The most widely adopted VR systems display is a simulated environment through special wearable head-mounted visual displays (HMDs). HMDs have evolved over the past five years from tethered systems comprising of screens and lenses fitted into a helmet, to relatively inexpensive systems that utilize mobile smart devices and fit

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into a light weight lens system. The optics within the HMDs vary from monocular (one eye view), binocular (both eyes view screen) and dichoptic (both eyes view different screen/image or image can be stereoscopic, adding depth cues). Recent advancements in hardware have included eye tracking and the use of multifocal optics.

Although HMDs have recently been introduced to the general public, they are not a new phenomenon (Table 1). As early as the 1960s, computer graphics pioneer Ivan Sutherland developed the first HMD, which made it possible to overlay virtual images on the real world [1,2]. HMD technology gradually evolved through the 1970s with use across military, industry, scientific research and entertainment domains. The early commercially available HMDs had limited applications due to their narrow Field-Of-View (FOV) and inherent cumbersomeness in weight, physical restrictions, and system parameters. Recent advancements have been directed toward making HMDs more comfortable for longer duration of use. Recent HMD products including Samsung Gear, HTC Vive, Oculus Rift, FOVE, and Google Daydream have become commercially available and increasingly commonplace as a result of technical advancements. For example, the latest version of the Oculus Rift at this time, the Development Kit 2 (DK2), has a higher resolution, higher refresh rate (i.e., the frequency with which a display's image is updated), lower persistence (which aids in removing motion blur) and more advanced positional tracking allowing for precise movement, when compared to its predecessor. FOVE has introduced eye tracking with real time foveal rendering to improve user experience. HMD technology advancement and cost reduction has increased its potential for widespread use.

Visually induced motion sickness (VIMS) or simulation sickness, remains an obstacle to the widespread adoption and commercial development of technologies associated with VR based HMDs [3,4]. With occlusive HMD systems, which by definition, is the distinguishing factor of virtual reality vs. augmented and mixed reality systems, a user is dependent on the VR system for sensory input. This dependency involves synchrony in sensory input, and the lack of this synchrony lends to visual-vestibular mismatch. The symptoms of visual-vestibular mismatch include nausea, stomach discomfort, disorientation, postural instability and visual discomfort.

It is commonly accepted that the symptoms of nausea and instability result from various sensory input conflicts, including conflicting position and movement cues, leading to a disharmonious effect on the visual and vestibular systems [5,6]. In addition, specific types of HMDs might have mismatch problems with the user's visual system due to improper optical design, resulting in convergence-accommodation conflict and visual discomfort or fatigue [7-13].

Table 1: Optical characteristics of representative head mounted displays in the systematically reviewed articles.

Representative HMDs	Year	Weight (g)	FOV (°) horizontal/ vertical/diagonal	Resolution (pi × els)	Luminance (cd/m²)	Inter-ocular dist (mm)	Luminance difference (%)	Vertical misalignment (°)
Virtual Research Flight Helmet	1991	1670	100° diagonal	360 × 40	-	-	-	-
Virtual research V6	1995	821	60° diagonal	370 × 277	-	52 - 74	-	-
Virtual research V8	1998	820	60° diagonal	640 × 480	-	52 - 74	-	-
Virtual Vision Sport	c.1993	140	17.3° horizontal	160 × 250	3.9	-	-	-
Sony Glasstron PLM-50	1996	-	33.75° diagonal	-	-	-	-	-
Division PV100	1998	-	60° × 46.8°	-	-	-	-	-
ProView™ × L 50	1998	-	35° diagonal	1024 × 768	-	-	-	-
Virtual I/O i-glasses™	1995	226	30° × 23.6°	263 × 230	38	60	-	-
Visette 2	2000	-	105° × 41°	-	-	-	-	-
EyeTrek FMD-700	2000	105	28.5 × 21.1 × 35.5	800 × 600	-	-	-	-
Emagin Z800 3DVisor	2005	226.8	40° diagonal	800 × 600	-	-	-	-
EMG iTheater BP4L	2005	78	23.2° × 17.4° × 29.0°	320 × 240	136	63	22	0.5
MicroOptical MyVu MA-0341	2006	70	12° × 8.8° × 14.9°	320 × 240	97	62	5	0
Vuzi × iWear AV920	2008	82	22.7° × 17.6° × 28.7°	640 × 480	24	63	3	0.8
Zeiss Cinemizer 1488-603	2008	115	20.8° × 15.4° × 25.9°	640 × 480	72	62	14	0.1
NVIS nVisor S × 111	2010	1300	102° × 64°	1280 × 1024	-	55-73	-	-
Google Glass	2013	50	14° diagonal	640 × 360	-	-	-	-
Oculus Rift DK 1	2012	220	110° horizontal	640 × 800	-	-	-	-
Oculus Rift DK 2	2014	320	100° horizontal	960 × 1080	-	-	-	-
InViso e-case	2000	-	34 diagonals	800 × 600	109	-	-	-
InViso e-shades	2000	-	32 diagonals	800 × 600	78	-	-	-

Early evaluation of the side effects of HMDs showed variable and inconsistent results. Notably, Peli reported no objective functional visual differences between HMDs and conventional desktop computer displays [14].

Conversely, other early studies reported high incidence of visual discomfort including eyestrain, dry eye, tearing, foreign body sensation, feeling of pressure in the eyes, aching around the eyes, headache, blurred vision, and difficulty in focusing. For example, Mon-Williams, et al. found that following a 10-minute exposure to a stereoscopic VR display, 60% of study participants reported symptoms of eyestrain, headache, and nausea [15]. This finding has been confirmed in a number of more recent studies [16-26].

Other visual problems such as myopia, heterophoria, fixation disparity, accommodation-vergence disorders, and abnormal Tear Break-Up Time (TBUT) also have been reported [15,18,20,21,24,27,28]. Using HMDs may cause accommodative spasm that in turn may lead to a transient myopia [20]. Continued conflict between convergence-accommodation, the user's Inter-Pupillary Distance (IPD), and/or the systems' Inter-Optical Distance (IOD) may lead to heterophoria and fixation disparity changes [15,20,29-31]. Moreover, visual symptoms are not necessarily limited to the time of actual Virtual Environment (VE) immersion; rather, visual changes including visual fatigue, reduced visual acuity and heterophoria may continue after terminating exposure to HMD-based VE [25,32-34].

Meta-analysis and Systematic Reviews on the Role of HMDS in Visual Discomfort

As a result of the recent advancements in the industry of virtual technology, the growing side effects associated with it require thorough documentation and characterization. To our knowledge, there has been no review article on the role of HMDs in visual discomfort. The current existing body of literature shows mixed results and different roles for different influential variables. While some HMDs studies have found significant negative impact on visual comfort, others have not. Biocca suggested that the cause of VR-induced sickness could be a technical problem, which would disappear as the technology advanced [35]. Unfortunately, this has not been the experience so far as technological advancements have not significantly reduced visual problems [12,13,36-47] (Table 2). Therefore, the extent to which HMD design impacts visual discomfort is unclear.

We conducted a meta-analytic review of publications related to the visual effects of HMDs. By compil-

Table 2: Summary of empirical data from head mounted display meta-analysis studies.

Author	Country	Subjects Male Female	Mean age Age range (years)	HMD[a] (s) Used	Time of exposure	Results
Jaeger [48]	USA	60 42M 18F	(18 - 40)	Unidentified HMD	13 - 23 min	Females were significantly more affected than males by simulator activities. Longer time intervals were associated with significantly greater symptoms of SS[b] and perceived discomfort. Comparison of scores between distance judgment and movement production activities produced no significant results. Individuals who used the static simulator were significantly more affected than those with similar exposure times in the dynamic simulator.
Blom [45]	Spain	31 13M 18F	27.3 ± 7.1	NVIS nVisor SX111	Two exposures of 6 - 7 min	Limited evidence of sickness, including rotated conditions. This may be due to improved technologies or differences in tasks, or it may be because in our experiment participants had a virtual body.
Kolasinski [49]	USA	40 20M 20F	22.7 ± 4.7 (19 - 46)	i-glasses™	20 min	Sickness could be severe and may involve lingering and/or delayed effects. Gender differences in mean sickness scores were not statistically significant. A significant negative correlation between IPD[c] and eyestrain symptoms and between sickness scores and final level reached in Ascent.
Moss [34]	USA	80 30M 50F	19.5 (18 - 24)	ProView™ XL 50	Varied	Compared with no added delay, an additional 200 ms of display delay did not result in increased SS. However, SS was greater when peripheral vision was occluded than when it was not. Peripheral vision moderated the effects of image scale factor and delay on head movement velocity.

Ehrlich [50]	USA	57 23M 34F	22.8 ± 5.1 (18 - 43)	Various unidentified HMDs	Not Stated	Dropouts experienced significantly more nausea than did finishers. The most severe symptom for dropouts was primarily disorientation followed by nausea. For finishers the most severe symptom was also disorientation but followed equally by either nausea or oculomotor discomfort.
Stanney [32]	USA	60	Not Stated	Virtual Research V6	15 - 45 min	Subjective symptomatology experienced by users after VE[d] exposure is substantial, persistent and statistically significant.
Stanney [33]	USA	34 20M 14F	25.8 ± 4.7	Kaiser Electro - Optics Virtual Immersion	30 min	When post-discomfort was compared to a pre-baseline, participants reported more sickness afterward. Change in felt limb position resulted in subjects pointing higher and slightly to the left; the latter difference was not statistically significant.
Ling [43]	Netherlands	86	28.0 ± 6.3 (18 - 70)	eMagin Z800	17 min	No significant effect of stereoscopy on simulator sickness compared with non-stereoscopic viewing conditions. No significant correlation between SS score and level of presence.
Lubos [46]	Germany	27 9M 18F	21.78 (19 - 25)	Oculus Rift DK1	36 min	Increase in simulator sickness over the experiment time was significant.
Lubos [47]	Germany	12 9M 3F	25.33 (19 - 36)	Oculus Rift DK1	26 min	No significant effect of increase in simulator sickness over the experiment time.
Draper [51]	USA	E1:11 6M 5F E2:10 6M 4F	E1:28.5 (19 - 39), E2:27.4 (23 - 36)	Virtual i/O i-glasses™	10, 20, 30 min	SS symptoms were significantly greater in minification (0.5) and magnification (2.0) image scale factor conditions than in neutral condition (1.0). SS did not vary with time delay changes.
Pölönen [52]	Finland	78 38M 40F	33.5 (21 - 53)	iTheater	40 min	NED[e] use induced slight sickness, but many of these shortcomings could be diminished with improved NED headset ergonomics and display quality.
Pölönen [37]	Finland	97 48M 49F	33.8 (23 - 45)	iTheater, MyVu, Vuzix, Zeiss	40 min	All NEDs induced eyestrain and sickness symptoms; magnitude of these symptoms varied according to the device. Adverse symptoms were related to problems with the display optics and design, text layout, headset fit, use context, individual differences.
Merhi [53]	USA	24 13M 11F	22 (17 - 35)	Visette - Pro	up to 50 min	Commercial console video game systems can induce motion sickness.
Sharples [54]	UK	71 38M 33/F	Not Given	Virtual research V8	30 min	Higher reported symptoms (nausea) in HMD compared with desktop viewing and in HMD compared with reality theatre viewing (nausea, oculomotor symptoms, disorientation).
Takada [44]	Japan	13	23 ± 6.2	iWear AV920	2 min	3-D movies can affect lateral body sway, thereby causing VIMS[f].
Järvenpää [39]	Finland	232 123M 109F	34.5 (21 - 53)	Five unidentified HMDs, likely including HMDs from Toni Järvenpää [50]	40 min, 95 min	Determination of NED characteristics helps to predict the subjective experiences, but the nature of the relation between subjective and objective findings is complex and depends on several NED-, user- and task-related features.

[a]HMD: HZead-Mounted Display; [b]SS: Simulator Sickness; [c]IPD: Inter-Pupillary Distance; [d]VE: Virtual Environment; [e]NED: Near to Eye Display; [f]VIMS: Visually-Induced Motion sickness.

ing data from multiple independent studies, this study allowed for a broad review and large population sample size in assessing the role of HMDs in visual discomfort. Furthermore, we systematically reviewed factors that might potentially affect the role of HMDs in visual discomfort. These factors included the characteristics of the systems, the participants (i.e., gender), and the tasks (i.e., duration, vection, and content).

Methods

Study selection

We performed an extensive and systematic review of scientific literature. The database search included Medline/PubMed (US National Institutes of Health/National Library of Medicine), Embase (Elsevier), ProQuest Central, ACM Digital Library (Association for Computing Machinery), and IEEE Xplore Digital Library (Institute of Electrical and Electronics Engineers). These databases were searched using the following keywords: VR, virtual environment (VE), HMDs, VIMS, SS, SSQ, VSQ, visual fatigue, and visual problems.

Only papers from peer-reviewed journals and large national conference proceedings were selected for inclusion in our study. For the relevant trials lacking data, we also attempted to contact the corresponding author by email for further unpublished but potentially relevant data; none of these contacts resulted in receipt of additional data. Unpublished data and abstracts were not included. No language restrictions were imposed.

The inclusion criteria consisted of any of the following: (1) Human studies evaluating visual system-related problems in HMD-based VE, (2) Studies involving self-reported questionnaires (SSQ and VSQ). Studies for visual problems without HMD-based VE, case studies with fewer than three participants, or studies without enough data to evaluate the impact of HMDs on visual discomfort were excluded.

Evaluation methods of HMD-induced VIMS and visual discomfort

Visually Induced Motion Sickness (VIMS) can be measured by psychological and physiological methods. The

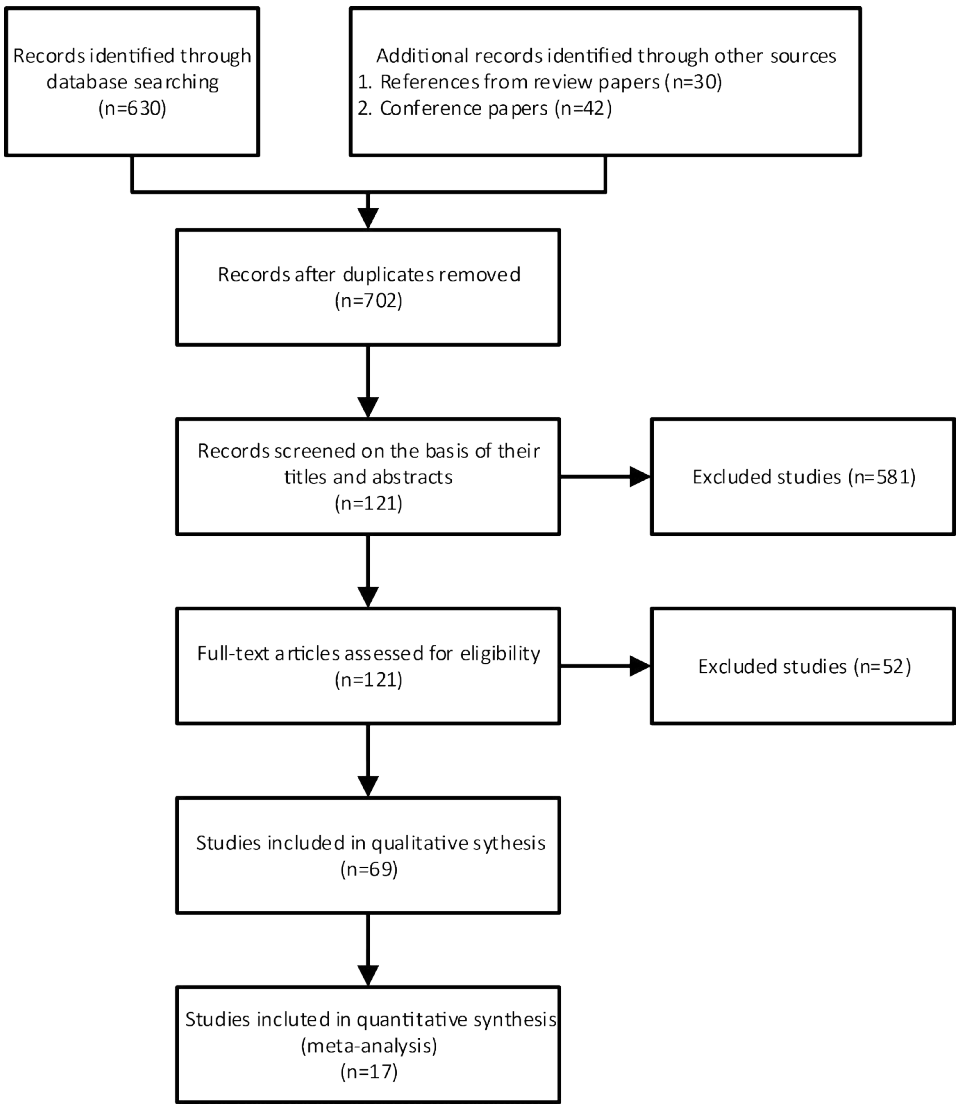

Figure 1: A forest plot diagram of mean change of the total severity score of simulator sickness questionnaire (SSQT) in pre- and post-HMDs exposure (Chi^2 = chi-square statistic; CI = confidence interval; df = degrees of freedom; I^2 = I-square heterogeneity statistic; IV = inverse variance; SE = standard error; *P* = *P* value; Z = Z-statistic).

Simulator Sickness Questionnaire (SSQ), a self-reported measurement, is a well-known psychological method and the gold standard for measuring the extent of VIMS [4,55]. The questionnaire consists of three components: nausea (SSQN), disorientation (SSQD), and oculomotor symptoms (SSQO). The total score of SSQ (SSQT) is an aggregate score of the three components.

The SSQ contains 16 items (i.e general disomfot, fatigue, eye strain, nausea), and each item is scored on a 4-point scale in which 0 = none, 1 = slight, 2 = moderate and 3 = severe [56]. Given that the discomfort caused by HMDs is often connected to visual symptoms, the Visual Strain Questionnaire (VSQ), a more detailed visual strain-related questionnaire, was used to measure the severity of eyestrain symptoms (e.g. tired, sore or aching, irritated, watering or runny, dry, hot and burning eyes; blurred or double vision; and general visual discomfort) [57]. 57 These symptoms of eyestrain are also often connected to computer vision syndrome [58-61]. In this study, the SSQ and VSQ were used to verify the occurrence of VIMS. Figure 1, Figure 2, Figure 3, and Figure 4 compare the mean score of SSQT, SSQO, and VSQ

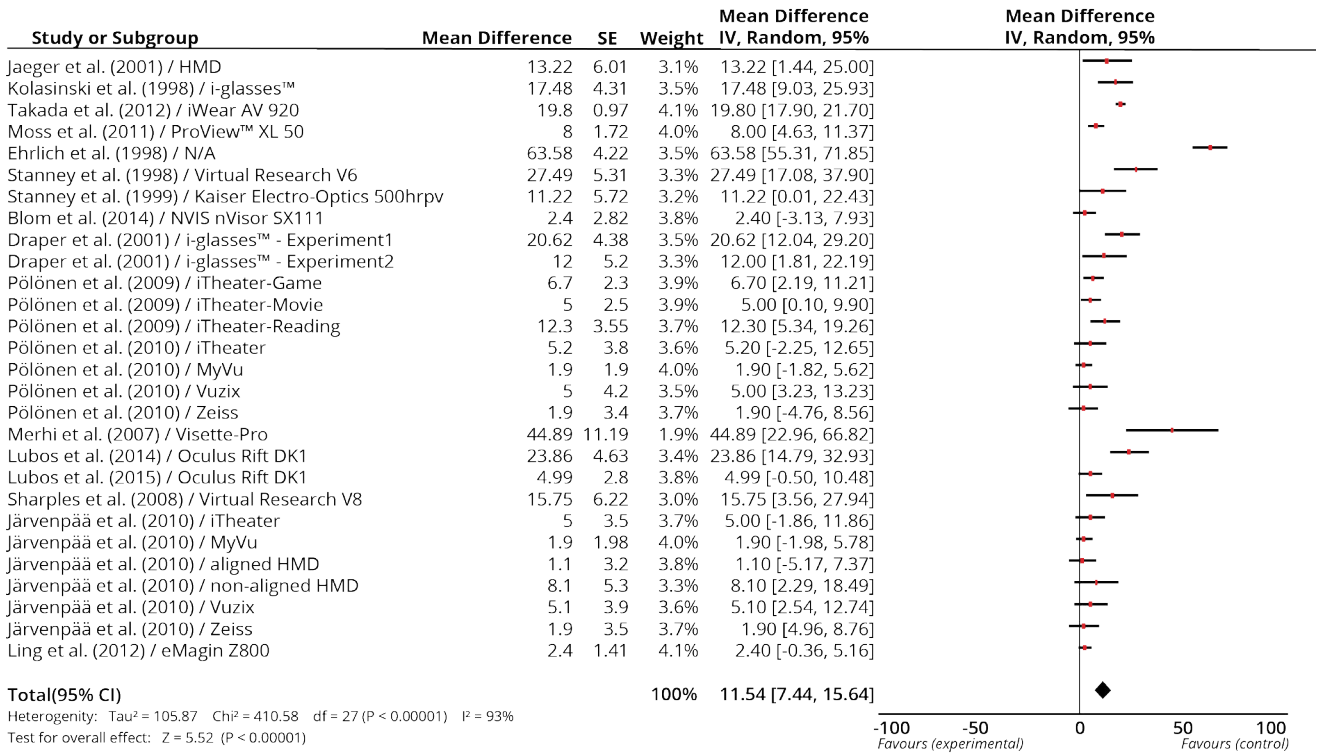

Figure 2: A forest plot diagram of mean change of the oculomotor scores of a simulator sickness questionnaire (SSQO) in pre- and post-HMDs exposure (abbreviations are the same as those in Figure 1).

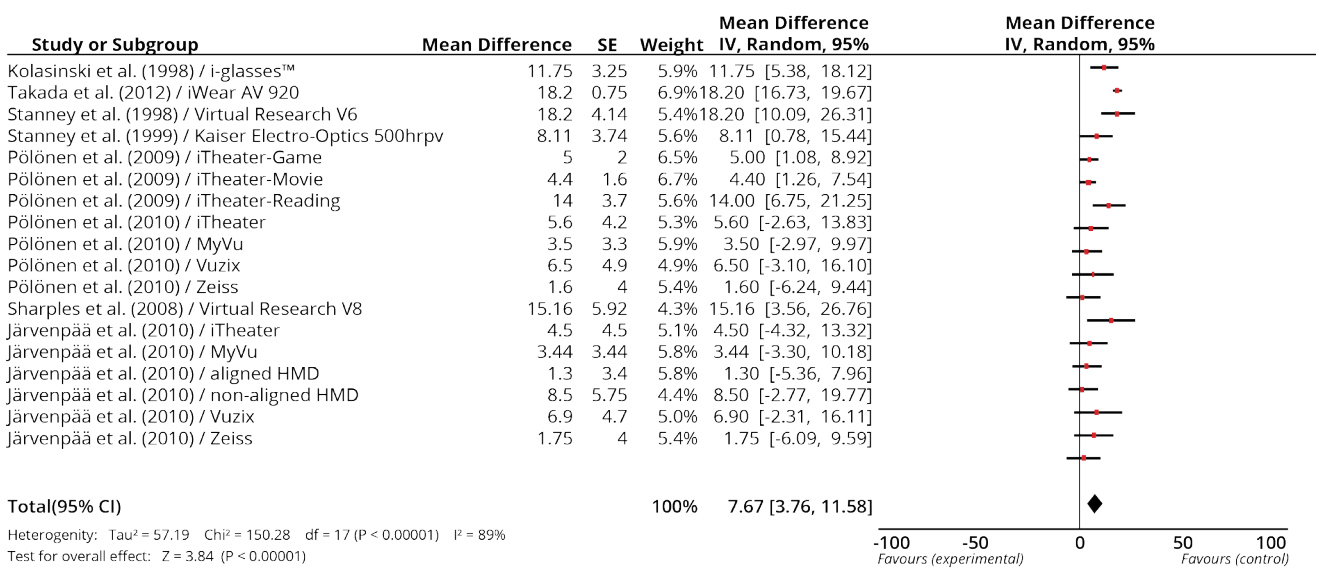

Figure 3: A forest plot diagram of mean change of the scores of visual strains questionnaire (VSQ) in pre- and post-HMDs exposure (abbreviations are the same as those in Figure 1).

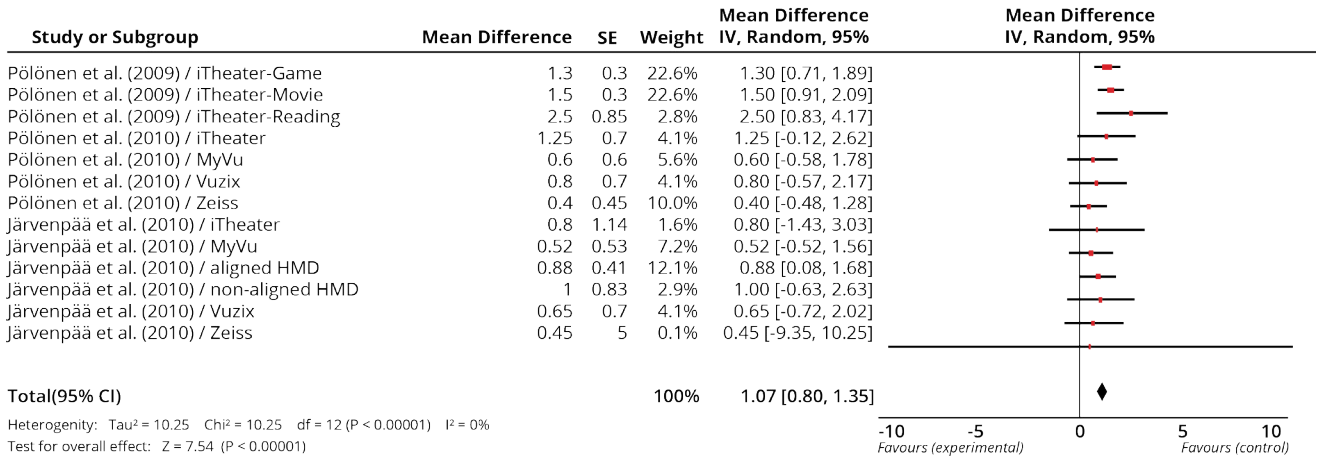

Figure 4: A forest plot diagram of sensitivity analyses of the mean change of the total severity score of SSQT in pre- and post-HMDs exposure (abbreviations are the same as those in Figure 1).

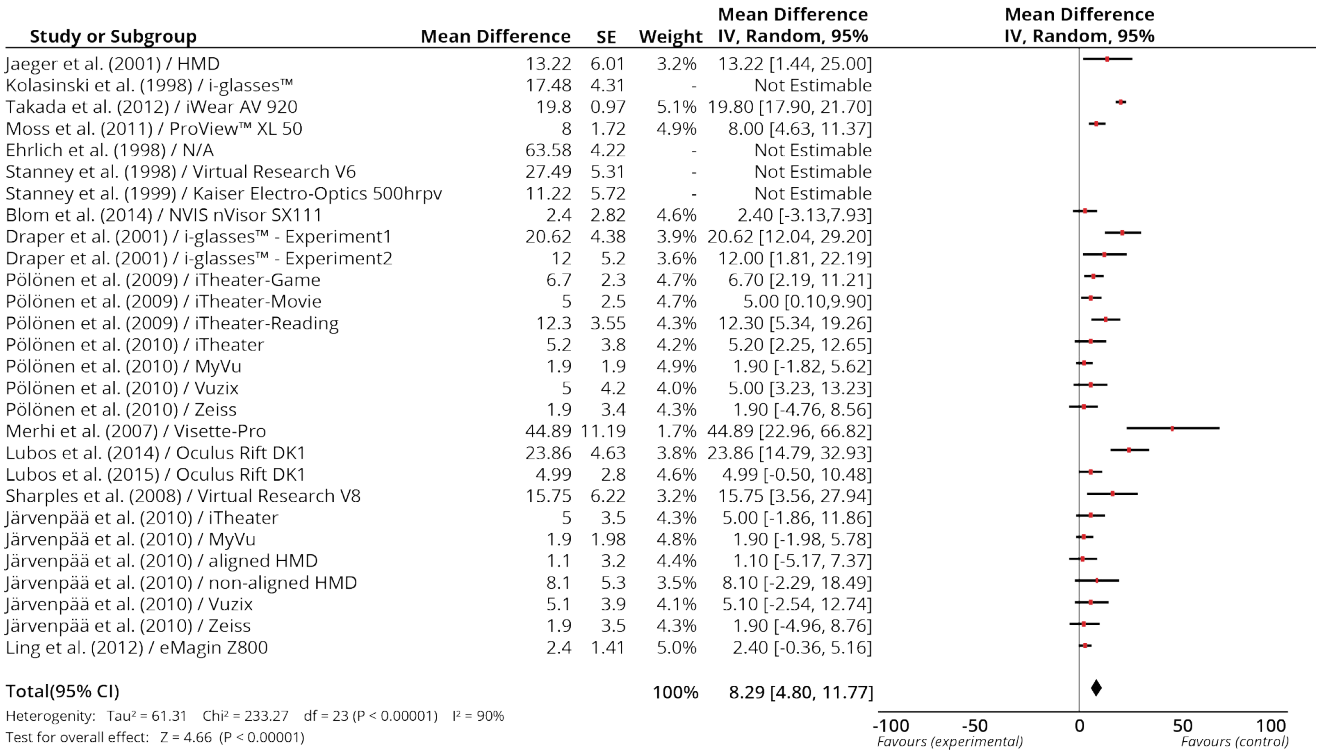

Figure 5: The flow chart of the process of article selection.

respectively between the various studies analyzed.

Procedure

The following variables listed below were used for primary outcomes. Mean change refers to the difference in SSQT scores between difference HMD devices (i.e. oculus rift versus FOVE).

(1) Mean change in symptom scores between different HMD-based VE.

(2) Comparison of mean change in symptom scores between HMDs and other traditional displays.

The visual impact of HMDs was used as the effect size in the meta-analysis. For multiple session VE exposure studies, we used only the data from the first VE exposure session in order to perform a between-group analysis. For studies with multiple measures of visual discomfort, we included only the SSQ and VSQ outcomes in the meta-analysis.

Statistical analysis

All statistical analyses were performed with Review Manager Version 5.3 (The Cochrane Collaboration, Oxford, England), using two-tailed p values and a 95% Confidence Interval (CI). For generic inverse variance outcomes, the mean difference was analyzed. Meta regression was performed, and heterogeneity was explored using the Q test with calculating I2, indicating the percentage of variability due to heterogeneity rather than to chance. I2 values of 50% or more were considered

substantial heterogeneity. The fixed-effects model was used to pool the data. A random-effects model was applied when P < 0.1 in the test for heterogeneity, and the fixed-effects model was used for other cases [62].

Results

Results of database search

Figure 5 shows the flow chart of the selection process for the reviewed studies. Of 69 potentially relevant studies identified through the electronic search, 34 publications met all the inclusion criteria. After excluding 17 articles because specific data for SSQ or VSQ were not provided, 17 studies with 1040 participants remained for inclusion in the meta-analysis. The smallest sample size in an included article was twelve [47], and the largest was 232 [39]. All 17 studies were published between 1998 and 2015. Eight were performed in the USA; three in Finland; two in Germany; and one each in the United Kingdom, Japan, Spain, and the Netherlands.

Characteristics and quality of trials

Table 2 provides a description of the pre- versus post-exposure mean score changes of SSQT, SSQO and VSQ. These were analyzed in seventeen, seven, and three studies, respectively. In three studies, the mean SSQT and SSQO score changes in exposure to HMDs and traditional displays also were included in the meta-analysis.

Effect of HMDs on VIMS and visual discomfort

The forest plots show that the visual discomfort was significantly different in pre- versus post-VR exposure (Figure 1, Figure 2, and Figure 3). The results show mean difference of 11.54 (95% CI 7.44 to 15.64; P < 0.00001), 7.67 (95% CI 3.76 to 11.58; P = 0.0001) and 1.07 (95% CI 0.8 to 1.35; P < 0.00001) for the SSQT, SSQO and VSQ, respectively.

In order to investigate the possible role of publication year, we undertook a sensitivity analysis by excluding the four studies published before 2000. Older publications assessed older HMDs; consequently, their results may have been skewed in favor of greater VIMS. This analysis showed a mean difference of 8.29 (95% CI 4.80 to 11.77; P < 0.00001) for SSQT in pre- versus post-VR exposure (Figure 4).

Comparison of HMD exposure versus traditional displays

Only four studies provided adequate information for meta-analysis of visual discomfort in HMDs compared to traditional displays (i.e., TV, desktop computer displays, or other 2D viewing condition) [37,39,43,54]. The forest plots show that the mean differences of SSQT and SSQO in HMDs versus traditional displays were 3.62 (95% CI 1.47 to 5.78; P = 0.001), and 4.78 (95% CI 1.51 to 8.05; P = 0.004) respectively; these results were statistically significant (Figure 6 and Figure 7).

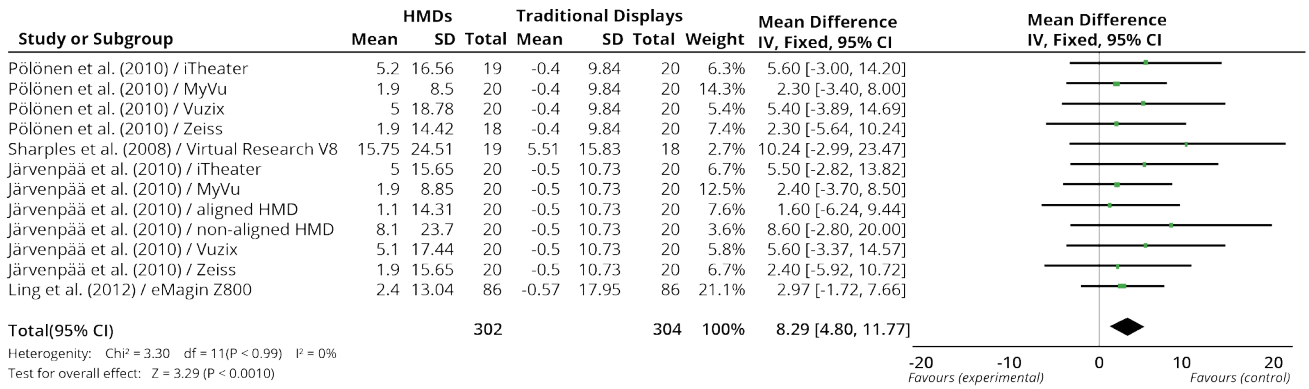

Figure 6: A forest plot diagram of HMDs versus the traditional displays (TV, desktop, or other 2D viewing condition) for the mean change of the total severity score of SSQT (abbreviations are the same as those in Figure 1).

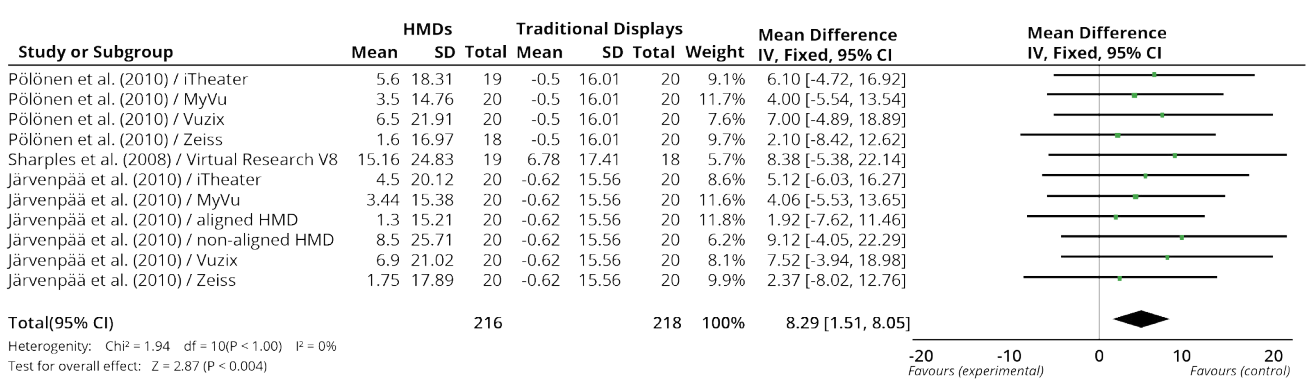

Figure 7: A forest plot diagram of HMDs versus the traditional displays (TV/desktop) for the mean change of the oculomotor scores of SSQO (abbreviations are the same as those in Figure 1).

Table 3: Experimental studies investigating causative factors of HMD-induced motion sicknes.

Number of Studies	Groups	Variables investigated	References
26	(1) Studies investigating variables related to systems	Display's field-of-view	Moss [34], Draper [51]
		System time delay	Moss [34], Draper [51], Nelson [64], St. Pierre [65]
		Optical characteristic	Aykent [66] 66 Peli [14], Kooi [67], Sheedy [18], Kuze [17], Moss [68], Ehrlich [69], Häkkinenl [70], Häkkinen [71] Moffitt [72], Kim [73], Pölönen [37], Pölönen [74], Pölönen [52], Howarth [20], Howarth [19], Kozulin [21], Vlad [75], Sharples [54], Nichols [22], Järvenpää [38], Järvenpää [39]
20	(2) Studies investigating variables related to individuals	Age, gender	Jaeger [48], Kolasinski [49], Häkkinen [69], Stanney [33], Kozulin [21], Mourant [76]
		Posture stability	Häkkinen [69], Smart [77], Owen [78], Cobb [79], Stoffregen [80]
		Habituation	Regan [81], Hill [82], Howarth [83], Kennedy [84]
		Personality traits	Takada [85], Ehrlich [50], Kotulak [86], Ehrlich [87], Kutsuna [88], Morse [89], Stoffregen [80]
28	(3) Studies investigating variables related to task characteristics	Dynamic or static stimuli	Jaeger [48], Ehrlich [50]
		Vection	Davis [90], Jang [91], Kuze [17], Smart [77], So [92], So [93], Mourant [76], Lo [94]
		Duration	Jaeger [48], Lampton [95], Kuze [17], Moss [34], Häkkinen [70], Stanney [32], Kozulin [21], Kennedy [84], Ames [25], Rushton [24], Steinicke [96], Järvenpää [39], Aaltonen [26]
		Viewing angle	Mon-Williams [30], Pölönen [97]
		Task content	Jaeger [48], Häkkinen [70], Pölönen [52], Nelson [64], Järvenpää [39]
		Sitting or standing	Merhi [53], Stoffregen [80], Nichols [22]

Table 4: Eye symptoms related to head mounted display exposure.

Author	Country	Subjects Male Female	Mean- age Age- range (years)	Head Mounted Displays	Evaluation methods	Results
Kooi [67]	Nether-lands	8	Not Given	Virtual I/O i-glasses™ Vision Sport monocular	Objective measurement	The scores of the accommodative facility after viewing the Vision Sport HMD[a] were reduced to nearly half their value, showing significant strain. The Virtual io HMD scores were intermediate, the monocular version being more straining than the binocular version. All subjects showed more eyestrain with the monocular systems.
Ehrlich [69]	USA	48 36M 12F	23.6 (18 - 50)	Virtual Research Fight Helmet	SSQ	The stereoscopic condition produced greater simulator sickness than the bi-ocular condition.
Howarth [19]	UK	20 16M 4F	28 (19 - 42)	Virtual I/O i-glasses™	Subjective questionnaire	The use of HMDs as personal viewing devices more readily induced the specific symptoms of virtual simulation sickness.
Peli [14]	USA	37 21M 16F	18 - 49	Virtual I/O i-glasses™	Subjective questionnaire Objective measurement	No functional differences were found between HMD and CRT[b]. Subjective comfort found a statistically significant difference in the impression of comfort between the CRT and the HMD in stereoscopic mode.
Nichols [22]	UK	9 6M 3F	25	Virtuality Visette 2, Virtual i/O i-glasses™ Division dVisor	Subjective questionnaire	Participants experienced different levels of discomfort in different systems. Ergonomics of HMDs were potential causes of discomfort.

Howarth [20]	UK	41 32M 9F	27 (19 - 56)	Virtual I/O i-glasses™ Virtuality Visette 2, Division dVisor	Objective measurement	The use of HMDs in immersive VR can lead to changes within the oculomotor system. The Virtual I-Glasses and Division systems induced exophoric changes (eyes turning outwards), Virtuality system induced esophoric changes (eyes turning inwards).
Sheedy [18]	USA	22	22 ± 5.9 (18 - 39)	Inviso eCase, Inviso eShades	Subjective questionnaire Objective measurement	Symptoms of eyestrain and blurry vision were significantly higher on monocular virtual than on other displays. No significant changes in visual acuity or heterophoria occurred with any of the displays. Motion-related symptoms with the head mounted near-eye display were not significantly different from those observed with other displays tested.
Häkki-Nen [70]	Finland	60 36M 24F	26.8 (18 - 41)	Olympus EyeTrek FMD-700	Simulator Sickness Questionnaire Visual Symptom Questionnaire	The stereoscopic condition produced slightly increased postural sway and sickness symptoms for 20-30 min after HMD use.
Häkki-nen [71]	Finland	60	27.8 (19 - 48)	Olympus EyeTrek FMD-700	Simulator Sickness Questionnaire	No significant differences in sickness symptoms compared to ordinary display and the virtual display in non-stereoscopic mode. In stereoscopic condition the eye strain and disorientation symptoms were significantly elevated compared to the ordinary display.
Kuze [17]	Japan	104	(17 - 32)	Sony Glasstron PLM-50	Subjective questionnaire	Viewing stereoscopic images caused visual fatigue.
Moss [68]	USA	10 2M 8F	20.6	ProView XL50	Simulator Sickness Questionnaire	Peak Simulator Sickness Questionnaire scores were significantly higher when wearing an HMD than when not wearing an HMD to view the laboratory.
Sharp-les [54]	UK	71 38M 33F	Not Given	Virtual research V8	Simulator Sickness Questionnaire	Higher reported symptoms in HMD compared with desktop viewing (nausea) and in HMD compared with reality theatre viewing (nausea, oculomotor and disorientation symptoms).
Kozulin [21]	Australia	60 29M 31F	11 (5 - 16)	Micro-Optical Binocular Viewer	Subjective questionnaire Objective measurent	In children aged 5 to 16 years, virtual imagery viewing with the Binocular Viewer had few additional adverse effects when compared to viewing a more conventional high definition television display.
Järven Pää [38]	Finland	120	Not Given	iTheater, MyVu, Vuzix, Zeiss	Simulator Sickness Questionnaire Visual Symptom Questionnaire	Small interocular differences in biocular NEDs are not easily detected by humans, but may still create visual fatigue.
Järven Pää [39]	Finland	232 123M 109F	34.5 (21 - 53)	Five unidentified Head Mounted Displays likely including HMDs from Järvenpää [38]	Simulator Sickness Questionnaire Visual Symptom Questionnaire	The determination of NED's characteristics helped to predict the subjective experiences, but the nature of the relation between subjective and objective findings was rather complex and depended on several NED-, user-, and task-related features.

Pölönen [37]	Finland	97 48M 49F	33.8 (23 - 45)	iTheater, MyVu, Vuzix, Zeiss Cinemizer Plus	Simulator Sickness Questionnaire Visual Symptom Questionnaire	In general sickness levels remained low after 40 min of immersion. Better headset fit, and light structure were related to lower total workload, frustration and effort levels, and to positive opinion change. Higher visual quality and positive opinion change were related to more pleasant task experiences, whereas sickness and high workload led to less pleasant outcomes.
Pölönen [74]	Finland	20 10M 10F	34.9 (23 - 53)	iTheater BP4L, Zeiss Cinemizer Plus, Vuzix Wrap 920	Simulator Sickness Questionnaire Visual Symptom Questionnaire	All near-to-eye displays induced eyestrain and sickness symptoms, but the magnitude of these symptoms varied according to the device. The adverse symptoms were related to problems with the display optics and design, text layout, headset fit, use context, and individual differences.
Vlad [75]	France	102 65M 37F	25	Prototype HMDs	Simulator Sickness Questionnaire	Different stereoscopic displays generated different symptoms.
Aykent [66]	France	14 12M 2F	24.4 ± 2	OCULUS Rift	Subjective questionnaire Objective measurement Modified Simulator Sickness Questionnaire	Oculus HMDs could cause more sickness in driving simulators, such as Eco2 driving simulator, than medium field of view systems. However, this type of HMD may have provided better immersive impressions than medium to large files of view display systems.

[a]HMD: Head-Mounted Display; [b]CRT: Cathode Ray Tube.

Table 5: Eye symptoms related to vection in a head mounted display environment.

Study	HMD	Vection	Immersion times (minutes)	Eye symptom
So [93]	Virtual Research VR4	3D VE[a] viewing, E1: visual scene oscillation in the yaw axis (angular velocity was 30°/second and the range of oscillation was ± 60°), E2: visual scene was stationary.	20	Total severity scores of SS[b] questionnaires and three SS Questionnaire sub-scores increased significantly after both conditions (with and without scene movement); with the absence of scene movement, these scores were significantly less.
Mourant [76]	Virtual Research VR8	3D VE: virtual driving simulator three types: highway (60 mph[c]), rural (60 mph), city (25 mph)		Participants in the highway (60 mph) or rural road (60 mph) virtual environments reported more symptoms than those in the city virtual environment (25 mph).
So [92]	Virtual Research VR4	3D VE: Speeds of 3.3, 4.3, 5.9, 7.9, 9.5, 23.6, 29.6, and 59.2 m/s[d] RMS[e] in the fore-and-aft axis	30	Vection sensation and sickness symptoms increased with increasing navigation speeds from 3 m/s to 10 m/s RMS. Beyond 10 m/s RMS, both vection and sickness stabilized and remained steady as speeds increased further to 59 m/s RMS.
Lo [94]	Virtual Research VR4	E1: Scene oscillations along different axes (pitch, yaw, roll or no oscillation), E2: Without scene oscillations	20	Nausea ratings and SS Questionnaire scores increased at higher rates in the presence of scene oscillations than with no oscillation. Overall effects of oscillations along different axes were not significant.
Kuze [17]	Glasstron PLM-50	E1: Shaky video, E2: Stabilized video	20	Change in eyestrain scores was higher when viewing shaky video.
Davis [90]	Oculus Rift DK 1	Two virtual roller coasters	14	The more realistic roller coaster with higher levels of visual flow had a significantly greater chance of inducing sickness.

[a]VE: Virtual Environment; [b]SS: Simulator Sickness; [c]mph: Miles Per Hour; [d]m/s: Meters Per Second; [e]RMS: Root Mean Square.

Systematic review of the different influence factors of HMD-induced visual discomfort

The previous studies highlighted a number of factors that have the potential to cause stress to the visual system in HMD-based VR. It seems that the stress on the visual system is multifactorial [63] (Table 3). We identified several studies that reported the effects of HMDs from different influence factors. Among these studies, HMDs' optical characteristics (system features), participants' gender (individual characteristics), duration, vection, and task content (task characteristics) were systematically reviewed respectively (Table 4, Table 5, Figure 8, Figure 9, and Figure 10).

Discussion

Advances in HMD technology have provided the potential for its widespread use in VR. However, VIMS, as an inherent problem, still remains an obstacle to public adoption and commercial development of this technology. HMD devices, such as Oculus Rift, HTC Vive, Samsung Gear, FOVE and Google DayDream have already entered the market, thus highlighting the importance of further research about VIMS. In our meta-analysis and systematic review, we have demonstrated through our data analysis the presence of significant visual discomfort after exposure to HMDs, when compared to traditional displays, and identified the potential moderating factors for this visual discomfort. To our knowledge, this is the first comprehensive summary and meta-analysis to address this issue.

Although the evaluation methods of HMD-induced visual problems varied between studies and in some studies the details were not provided, the results of this meta-analysis showed that regardless of the evaluation methods, the exposure to HMDs has been associated with significant visual discomfort. This meta-analysis of pre- and post-exposure questionnaires demonstrated significant associations between visual impact and the mean change scores of total severities of SS, oculomotor score of simulator sickness questionnaires scores

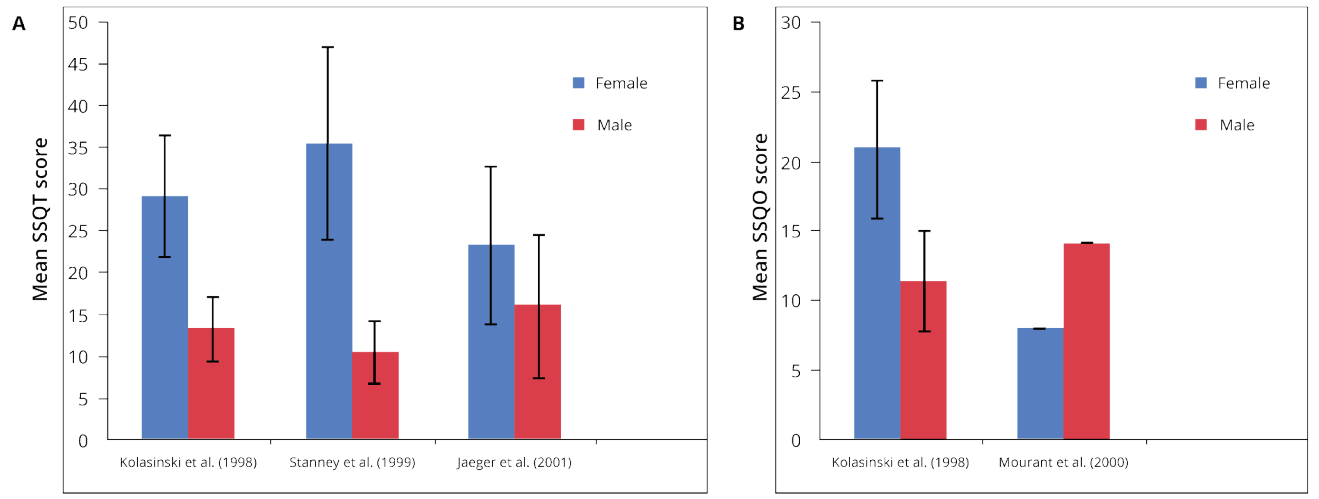

Figure 8: Mean SSQ scores by gender in different studies (higher scores = higher symptom severity). A: SSQT scores; B: SSQO scores. Error bars represent standard error of mean.

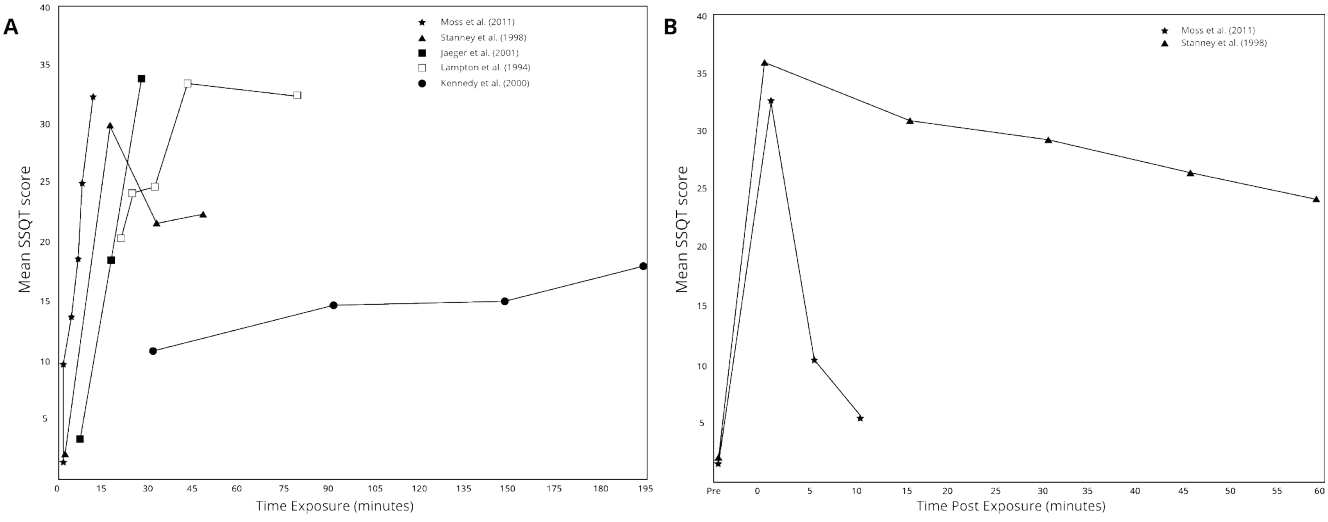

Figure 9: Mean SSQT scores by duration of exposure in different studies. A: SSQT score and exposure duration; B: SSQT score and post exposure duration.

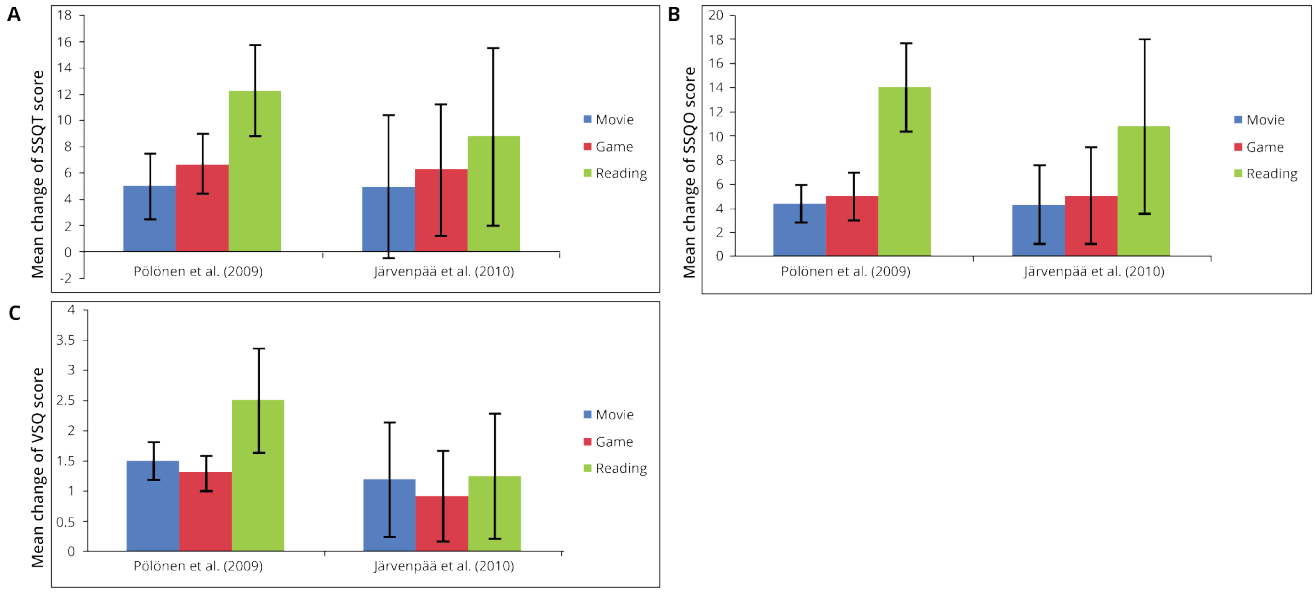

Figure 10: SSQ and VSQ Change (Post - Pre) are demonstrated after performing different tasks in two studies (higher scores = higher symptom severity). A: SSQT change; B: SSQO change; C: VSQ change. Vertical lines represent standard error of mean.

and visual strain questionnaires scores. Furthermore, HMD exposure was associated with higher scores of mean changes of SSQT and SSQO compared to other traditional displays, such as TV and desktop computer displays.

Theoretically, HMDs with sub-optimal designs were used in the earlier articles, i.e., those published before 2000. The visual discomfort reported in those papers might have been a result of their poor design, rather than valid observations. Therefore, the meta-analysis from those papers published before 2000 may have substantially overestimated the incidence of HMD-induced visual discomfort. For example, the Virtual Research V6 HMD used for Stanney's 1998 study was a mid-range display made by the US-based Virtual Research System Inc. and had a lower brightness and poorer color presentation compared to the updated Virtual Research V8 HMD used for Sharples' 2008 study [32,54]. These advancements in the manufacturer's HMD technology may have produced a higher mean change of the questionnaire score when compared to scores from participants who had used the older Virtual Research V6.

In order to rule out any significant influence from the papers published prior to 2000, (i.e., to assess the reliability of our meta-analysis), our sensitivity analysis excluded the four studies published before 2000. This exclusion did not change the outcome of our meta-analysis; i.e. the result after eliminating the old papers was statistically consistent with the result of original meta-analysis. Even though these questionnaires are self-reported subjective evaluation methods, they provide converging evidence that HMD-based VR causes visual discomfort. These findings are consistent with a cross-sectional survey of 953 questionnaires related to VIMS, in which almost 35% of the respondents reported tired eyes during 3D movies [98]. The results suggest a need for raising public awareness about the visual discomfort that individuals may suffer after exposure to HMDs. We recommend that the HMD industry and manufacturers address the visual discomfort issue before their products become commonly used.

To date, no controlled studies have evaluated the extent to which user subjective responses are determined by characteristics resulting from pre- and post-test measures. Young gave subjects SSQ's either pre- and post-VR immersion, or only post immersion. Participant reports of sickness after immersion in VR showed higher scores when both pre- and post-test questionnaires were given to the participants than when only a post-test questionnaire was used [23]. These results are notable because measurements of sickness by both pre- and post-self-report questionnaires are significantly biased due to demand characteristics, and may substantially overestimate the incidence of HMD-induced visual discomfort. We suggest that comparative studies of the visual effects of HMD-based VEs employ experimental designs that are not subject to such biases, or at least take measures to balance these biases. Alternatively, more objective measures could be used systematically in order to evaluate visual effects after HMD exposure.

User Settings Risk Factors

Our systematic review also shows that many factors impact HMD-induced VIMS. These factors include the characteristics of the device system, the participants in the studies we included, and the tasks they were asked to perform. Device system variables included viewing mode (e.g. monocular, binocular or dichoptic), headset design (e.g. fit, weight), optics (e.g. misalignment in the optics; contrast, luminance), Field Of View (FOV), and time lag (i.e. transport delay). HMD weight has been associated with the experience of visual discomfort and

injury [99]. A key consideration for HMD design must be that weight is within the level of human tolerance to minimize head and neck fatigue. With the decrease in cost of components, HMD design has moved to more ergonomic HMD systems, which has been reflected in the adoption of mobile systems, such as Samsung Gear and Google DayDream.

Symptoms of eyestrain and blurry vision were significantly higher in monocular mode than in other modes [18,67,72]. The use of HMDs in stereoscopic mode is less comfortable than in non-stereoscopic mode [14,17,69-71]. Spatial properties of the display, i.e., Field of View (FOV), may be implicated in producing visual discomfort symptoms [34,51]. The FOV studies show that narrow FOV (< 50 degrees) reduces the perception of self-motion and wide FOV (> 100 degrees) may increase the presence and level of simulator sickness. Patterson, et al. recommend a minimum 60° FOV to achieve a full sense of immersion [100].

Device Risk Factors

Resolution contributes to overall image quality but also directly affects the users' experience of VIMS. It is often uncomfortable to view low-quality images that are noisy or blurry. Anatomically, the central retinal fovea has the highest number of photoreceptors and the highest capacity for resolving an image [101]. While the limit of human visual resolution is 1 minute of arc at the central fovea, few HMDs can achieve this, primarily due to current technological limitations. The result can be a pixelated experience [101]. It is important to provide the highest possible resolution in the central field of view of the virtual environment to truly simulate a real-life experience and mimic the viewing characteristics of human vision. Some devices attempt to achieve this by creating a gradient of resolution with the highest resolution in the central field of view and the lowest resolution at the periphery [101,102]. The potential trade off of higher resolution is the overexposure of energy from the display, given the proximal distance of the display to the eyes.

Time lag between an individual's action and the system's reaction potentially could influence a user's experience of VIMS symptoms, as it affects human perception of visual and vestibular cues [33,51,64,65]. Therefore, reducing the sensor error of HMD systems may minimize the VIMS experience. HMD optical characteristics, such as eye relief (a fixed distance from the eyepiece lens to its exit pupil), convergence demand, horizontal disparity, vertical misalignment of displays, inter-ocular rotation difference, vertical-horizontal magnification differences, luminance, focus differences, temporal asynchrony, focal distance, field curvature difference and Inter-Pupillary Distance (IPD), are all potential factors that can induce visual discomfort and headache when they are poorly aligned or adjusted [37-39,66,68,73-75,100,103-106]. Another consideration is the type of optics used in HMD systems, single focus lens systems vs. multifocal lens systems, with the latter lending to more natural adaptive zones for multiple focal lengths typically encountered in VR environments, especially interactive experiences.

High rates of ocular symptoms may be associated with certain device characteristics (Table 1). For example, the VIMS experienced with the Vuzix may be attributable to the focal distance of the display (5 m/2.4 m), luminance level (24 cd/m^2), and vertical misalignment (0.8°). Conversely, the low ocular symptom rate in the MyVu may be explained by its luminance level (97 cd/m^2), lack of vertical misalignment (0°), physical design and assigned tasks. It is essential to note that technical advances have reduced obvious problems such as physical ergonomic issues including HMD weight, system time delay, and luminance.

It is also important to note that the conflict between visual and vestibular input remains a significant problem. In other words, the VIMS from HMD exposure is not simply a "technical problem" that will be resolved as the technology advances. The discomfort from the vestibular-visual mismatch will not resolve unless the mismatch itself resolves, which may involve a multifactorial process of synchronizing sensory inputs dependent on hardware specifications and software/content design.

User Individual Risk Factors

Individuals differ in their susceptibility to VIMS [107]. Age has been shown to have a significant relationship with HMD-related eyestrain symptoms [70]. Children 2-12 years of age have immature visual systems and binocular function that is worse than that of adults; this makes children more susceptible to both visual discomfort caused by HMDs and oculomotor side effects including reduced visual acuity, amblyopia, or strabismus [21,31,108,109]. Adults with limited fusional ranges experienced more visual discomfort, specifically with convergent eye movement in response to stimuli in VEs (Karpicka E, unpublished data). Therefore, age effect on HMDs needs to be further studied and taken into account in the design of future HMDs. In regard to gender, females reported more simulator sickness and more often withdrew from HMD-based VEs when compared to male participants [16,19,33,48,49,70]. This difference may be due to under-reporting of susceptibility on self-reports by males (so-called "macho effect") or hormonal effects [110]. Other possible explanation for this gender difference is that females generally have a wider FOV than males, which increases the likelihood of flicker perception and sickness susceptibility [111].

People with visual deficits may have an increased susceptibility to oculomotor side effects compared to those without such deficits, although this has yet to be verified experimentally. A past history of motion sickness has also been found to predict susceptibility to

sickness in HMD-based VEs [49]. Individuals also differ in their ability to habituate or adapt to HMD-based VEs (i.e. plasticity), with some individuals adapting much more readily than others after repeated exposures to stimuli [50,81-84,87].

It has been suggested that those with greater plasticity may be less susceptible to VIMS, although the time course to adapt may vary. Greater plasticity is associated with faster symptom reduction on repeated exposures rather than with reduction of initial symptoms [81-84]. Thus far, the characteristics of individuals with greater levels of plasticity have not been identified, and this will require further study.

Other Risk Factors

An individual's posture may also contribute to VIMS. The postural instability theory states that motion sickness occurs with a loss of postural control [112]. In a virtual environment setting, there is a sensory conflict between the virtual image and the real-world posture that increases the body's risk for motion sickness [70,77-80,112]. Postural stability relies on input from the visual, somatosensory, and vestibular systems. This input is processed and then controls two major reflexes, including the Vestibular Ocular Reflex (VOR) that maintains stability of visual objects on the retina as well as the vestibular spinal reflex that maintains body postural stability while an individual is in motion. Conflict between the visual and vestibular sensory inputs can give rise to postural instability (ataxia) as well as to VIMS [79]. Postural instability, which has been reported as a symptom of HMDs exposure, may last for several hours after exposure [70,77-80,85,88]. Special consideration for HMD user safety, as related to the risk of postural instability, must be kept in mind. For instance, HMD users should allow for adaptation and recovery time before engaging in potentially dangerous activities such as driving, or sports may be in order.

Task characteristics have been also identified as potentially affecting VIMS. The most important of these is the duration of exposure to VE. As shown in Figure 9, longer exposure to VE increases the incidence of VIMS. These symptoms may persist up to 60 minutes after exposure [17,21,24-26,32,34,39,48,70,84,95,96]. Another important factor shown to influence VIMS is vection (i.e. an illusion of self-motion; Table 5), with faster vection resulting in greater sickness symptoms [17,77,91,93] Viewing HMD-based VR in a sitting position may reduce symptoms, as sitting reduces the demands on postural control [22,53,78,113]. More complicated tasks, such as reading, may induce total symptom severity scores and oculomotor-related symptom scores that are significantly higher than those observed with movies or games (Figure 10) [39,52,64]. These findings imply that more demanding tasks probably will create some degree of eyestrain. Increased reading sensitivity, when compared to watching a movie or playing a game, might be due to activation of different areas of the brain, which may make reading more complex than other tasks. Alternatively, reading can affect attention and blink rate, which may also contribute to an increase in VIMS. Moreover, inappropriate vertical gaze angle may cause increased oculomotor changes and visual discomfort [30,97].

Conclusion

Our meta-analysis and systematic review confirms that visual discomfort occurs after exposure to current HMDs significantly more than after exposure to traditional displays. The visual discomfort induced by HMDs is influenced by the three categories of moderator factors, which indicates that the discomfort is multi-factorial and poly-symptomatic. It is conceivable that the visual discomfort induced by HMDs will diminish gradually as the quality of design of HMDs improves and the technology of the components increases; however, the discomfort may not resolve completely until the visual-vestibular mismatch is resolved. VIMS and visual discomfort continue to be obstacles for widespread acceptance of HMDs; this increases the importance of further research into VIMS. More research is needed to resolve visual-vestibular mismatch, and to develop objective methods of evaluating and quantifying VIMS symptoms such as visual/ocular changes (e.g. ocular movements), physiological changes (e.g. changes in heart rate, blink rate, EEG [electroencephalography]), and vestibular changes (e.g. perceived spatial velocity). More research focusing on the user experience is necessary, with recommended expansion of subjective assessment methods such as questionnaires (e.g. the SSQ and VSQ).

Furthermore, as the VR market expands from early consumer adoption, a burgeoning environment for VR-related software has developed. While the emphasis of our paper relates to the current hardware limitations of HMDs, the authors recommend future research also focus on the relationship of software implementation to simulation/VR sickness. For example, perceived motion in virtual environments is affected by how head motion or controls are mapped into the graphical representation of the virtual environment. To limit some of the effects of software-related VIMS, developers may limit movements in certain directions or provide a frame of reference. Recent advancements include the usage of eye tracking with foveal rendering to simulate real-world object focus in virtual environments [101].

We have proposed recommended guidelines below, in part for both hardware and software developers, to design accordingly to minimize VIMS. Although there are still hurdles related to creating seamless virtual environments, there is a lot of promise. Continued research and development of both hardware features and software implementation will continue to improve the VR experience.

Our meta-analysis has led us to propose a few key

observations and recommendations. Our observations are as follows:

1. Lighter HMDs are associated with a decrease in discomfort;
2. Monocular presentations should be avoided, as they are associated with more discomfort compared to binocular and dichoptic presentations;
3. Exposure to VR in sitting position may decrease VIMS;
4. Complex visual tasks and reading may increase VIMS severity;
5. Rapid vection results in an increase in VIMS symptoms.

Our recommendations are as follows:

1. Manufacturers need to be attentive to system characteristics of the devices they develop and market;
2. Users should be advised that children, women, users with visual field defects, postural instability, or past history of motion sickness may be especially prone to VIMS;
3. Inexperienced users are especially susceptible to developing VIMS, and users are different in their adaptation to HMDs;
4. Users should be warned to not use HMDs for a long period of time, and to take frequent breaks;
5. Users should avoid driving or operating heavy machinery after exposure to VR until VIMS and postural instability resolve.

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