A head-mounted display as a personal viewing device: Dimensions of subjective experiences

Monika Pölönen

Institute of Behavioural Sciences
University of Helsinki, Finland

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University of Helsinki
Institute of Behavioural Sciences
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Supervisors:  
Professor Göte Nyman  
Department of Behavioural Sciences  
Faculty of Behavioural Sciences  
University of Helsinki, Finland

Adjunct Professor Jukka Häkkinen  
Department of Media Technology  
Faculty of Information and Natural Sciences  
Aalto University School of Science and Technology, Finland

Reviewers:  
Professor Sari Kujala  
Institute of Human-Centered Technology  
Tampere University of Technology, Finland

Senior Research Scientist Jari Laarni  
Human Activity and Systems Usability  
Technical Research Centre of Finland, Finland

Opponent:  
Professor Takashi Kawai  
Graduate School of Global Information and Telecommunication Studies  
Waseda University, Japan

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Abstract

The use of head-mounted displays (HMDs) can produce both positive and negative experiences. In an effort increase positive experiences and avoid negative ones, researchers have identified a number of variables that may cause sickness and eyestrain, although the exact nature of the relationship to HMDs may vary, depending on the tasks and the environments. Other non-sickness-related aspects of HMDs, such as users’ opinions and future decisions associated with task enjoyment and interest, have attracted little attention in the research community.

In this thesis, user experiences associated with the use of monocular and bi-ocular HMDs were studied. These include eyestrain and sickness caused by current HMDs, the advantages and disadvantages of adjustable HMDs, HMDs as accessories for small multimedia devices, and the impact of individual characteristics and evaluated experiences on reported outcomes and opinions.

The results indicate that today’s commercial HMDs do not induce serious sickness or eyestrain. Reported adverse symptoms have some influence on HMD-related opinions, but the nature of the impact depends on the tasks and the devices used.

As an accessory to handheld devices and as a personal viewing device, HMDs may increase use duration and enable users to perform tasks not suitable for small screens. Well-designed and functional, adjustable HMDs, especially monocular HMDs, increase viewing comfort and usability, which in turn may have a positive effect on product-related satisfaction.

The role of individual characteristics in understanding HMD-related experiences has not changed significantly. Explaining other HMD-related experiences, especially forward-looking interests, also requires understanding more stable individual traits and motivations.

Tässä väitöskirjassa tutkittiin markkinoilla olevien erilaisten päässä pidettävien näyttöjen käyttökokemuksia. Yksityiskohtaisemmin tarkasteltiin päässä pidettävien näyttöjen käyttöön liittyvää silmärasitusta ja pahoinvointia sekä näytön sääтомahdollisuuden hyötyjä ja haittoja käyttäjän näkökulmasta. Lisäksi tutkittiin laitteiden käyttöä lisälaitteena muille pienille multimedialaitteille sekä sitä, miten erilaiset taustamuuttujat ja laitteen käyttöön liittyvät kokemukset auttavat meitä ymmärtämään laitteen tulevaan käyttöön liittyviä mielipiteitä.

Tässä väitöskirjassa esitettyjen tutkimustulosten mukaan päässä pidettävät näytöt voivat aiheuttaa lievää silmärasitusta ja pahoinvointia, mutta erot muihin näyttöihin ovat selvästi pienentyneet. Päässä pidettävän näytön säätomahdollisuus parantaa katselukokemusta etenkin monokulaarisen päässä pidettävän näytön tapauksessa, mutta näytöjen säädettävyys voi hyödyttää myös bi-okulaaristen näyttöjen käyttäjiä.

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List of publications

This thesis is based on the following original publications, referred to in the text by the roman numerals I-IV.


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Abbreviations

HMD    head-mounted display
mHMD   monocular head-mounted display
NED    near-to-eye display
VE     virtual environment
VR     virtual reality
VET    virtual environment technology
2D     two dimensional
S3D    stereoscopic three dimensional
IPD    interpupillary distance
FOV    field of view
QVS    qualified viewing space (exit pupil)
VIMS   visually-induced motion sickness
D      disorientation
O      oculomotor disturbance
N      nausea
SSQ    Simulator Sickness Questionnaire
VSQ    Visual Strain Questionnaire
NASA-TLX NASA Task Load Index
DSI    Domain Specific Innovativeness
1 Introduction

The research and development of wearable displays began more than forty years ago when an American researcher Ivan Sutherland published his first paper on the subject (Sutherland, 1965 & 1967). Through the years there have been many breakthroughs in the optics and technology of displays; however, head-mounted displays (HMDs) are still relatively unfamiliar in consumer markets. In the following sections, some historically important HMD user experience-related publications are reviewed, and thereafter the results from our subjective studies are presented.

1.1 A general overview of head-mounted displays

1.1.1 The structure of head-mounted displays

Various terms have been used to refer to wearable head-mounted visual displays, including head-mounted displays (HMD), near-to-eye displays (NED), head-coupled displays, helmet-mounted, wearable, and virtual displays. On the basis of the modes of the image presentation, HMDs have been classified into three categories. A monocular HMD (mHMD) (Peli, 1990; Patterson, Winterbottom & Pierce, 2006; Häkkinen, Takatalo, Havukumpu, Komulainen, Särkelä & Nyman, 2004) has one display, which can (usually) be placed at a suitable viewing angle in front of either the right or the left eye. In a binocular mode two disparate images are presented on two displays and the picture is seen as stereoscopic (S3D; for a review, see Ukai & Howarth, 2008), while in a bi-ocular mode, the same image is presented on two displays, and therefore the image is perceived as two dimensional (2D). The nature of the information displayed on an HMD could vary from simple static symbols to complex, dynamically changing scenes, depending on the task and/or the purpose of the use. Some HMDs occlude external vision completely (non-see-through), while with others it is possible to see the outside world along with the information on the display (a semitransparent see-through display).

The first wearable displays were integrated into massive helmets, which could weigh up to three kilograms and cost tens of thousands of dollars. The current commercial HMDs resemble goggles or eyeglasses; they are much cheaper and lighter (e.g., MyVu 70 grams, iT heater 78 grams; see Figure 4) and because of progress in microdisplays,
diffractive optics, and electronics, they are superior technologically (e.g., Velger, 1998; Järvenpää & Pölönen, 2009; for an HMD optical engineering overview, see Cakmakci & Rolland, 2006).

Because of the variability in users (individuals interacting with the system, ISO 9241-10:1996) physical structure (e.g., distance between the centers of the pupils, for an overview, see Dodgson, 2004), and visual functioning (e.g., stereo acuity, near and far acuity, sensitivity to temporal stimulation, brightness and contrast), some HMDs are self-adjustable (Task, 1997; Moffitt, 1997; ISO/FDIS 9241-303:2008(E); Peli, 1990; Howarth, 1999), while others do not have these properties.

In addition to displays and image generators, a typical HMD system includes loudspeakers, battery chargers, and different input/output cables. Because of the small size and light weight, commercial HMDs as accessories of wearable technology can be used in various contexts (users, tasks, equipment, and the physical and social environments in which a product is used; ISO 9241-11:1998).

1.1.2 HMD and the contexts of use

The potential benefits of HMDs were first recognized in military and aviation contexts, and the benefits to numerous other areas in life, such as medicine, therapy, training, and entertainment soon followed (e.g., Kennedy, Lane, Berbaum & Lilienthal, 1993; Hettinger & Riccio, 1992; Riva, 2002 & 2005; Velger, 1998; Melzer & Moffitt, 1997; Hoffman, Patterson & Carrougher, 2000; Hoffman, Patterson, Carrougher & Sharar, 2001; Jang, Kim, Nam, Wiederhold, Wiederhold & Kim, 2002; Rash, Russo, Letowski & Schmeisser, 2009). Irrespective of the purpose of the device, users in both at work and leisure contexts may benefit from wearable displays in several different ways (e.g., Loomis, Blascovich & Beall, 1999; Riva, 2002, 2005).

In an air force, one of the HMD-related goals is to increase functionality and safety, which may lower pilots’ workload by providing necessary or/and valuable information not otherwise accessible or requiring extra effort (Kennedy, 1987; Brooks, 1987; Hiatt & Rash, 2005; Rash, Russo, Letowski & Schmeisser, 2009). In the entertainment field, features such as the large field of view (FOV) and good image quality may increase the users’ sense of being present and involved and thus make the experience more enjoyable and fun (Pölönen, Salmimaa, Aaltonen, Häkkinen & Takatalo 2009; Lombard

1.2 HMDs and virtual environments

Terms, definitions, and features associated with virtual reality (VR, including mixed reality applications) and virtual environments (VE) vary across studies (e.g., Wilson, 1999; Wann & Mon-Williams, 1996; Durlach & Mavor, 1995; Stanney, 2002; Burdea & Coiffet, 2003). Carr (1995) summarized the different views connected with definitions and concepts of virtual reality with a single common factor and concluded that all the constructs simulate human perceptual experience by creating an impression of something that is not really there. Wann and Mon-Williams (1996) described virtual reality in more detail as a computer-generated three-dimensional interactive environment, while Stanney, Mourant, and Kennedy (1998) defined VE as a system that enhances the communication between humans and computers. Many researchers have connected or reviewed virtual reality vis-à-vis simulations. Ellis (1995), for example, described VEs as personal simulators, whereas Foster and Meech (1995) viewed VR as a high-fidelity simulation of a model world or environment, which could simulate both existing and totally artificial environments.

Because HMDs may contain features valued in the context of VEs, such as bi(n)ocular mode and large FOV in addition to small size and transferability, HMDs are often exploited as visual output devices in VE systems (e.g., Sharples, Cobb, Moody & Wilson, 2008; Burdea & Coiffet, 2003). Thus, a great number of HMD-related user studies (i.e., an individual interacting with the system; ISO 9241-10:1996), especially sickness and eyestrain-related, have been carried out in simulators and/or VEs. Partly for this reason and because many of those studies have used experimental setups comparable to the setups used in our tests, namely, bi-ocular HMD mode and similar tasks, many of those results will be used as background references in here. Results from some binocular HMDs studies will be also used as references, even though it is known
that the same problems with binocular display characteristics may cause much stronger sensations of sickness and eyestrain than with bi-ocular HMDs (ISO/FDIS 9241-303:2008(E); Peli, 1998; Self, 1986; Mon-Williams & Wann, 1998). The concept of VE will be used in this dissertation as a general term to refer to different virtual environments, simulators, and other augmented and mixed reality applications, irrespective of how well they correspond to the current definitions of VEs (Stanney, Mollaghasemi, Reeves, Breaux & Graeber, 2003).

1.3 Theories of motion sickness

Motion sickness is a general term for a group of symptoms and adverse signs, such as drowsiness, dizziness, nausea, postural changes, sweating, salivation, and vomiting, evoked by exposure to abrupt, periodic, or unnatural accelerations (e.g., Kennedy, 1985; Money, 1970; Benson, 1978). There is a wide variety of stimuli that can provoke motion sickness, and the physical intensity of the stimulus is not necessarily related to the degree of nauseogenicity (e.g., Hettinger & Riccio, 1992; Hettinger, Berbaum, Kennedy, Dunlap & Nolan, 1990; Golding, 2006, 1998; Andersen & Braunstein, 1985; Crampton & Young, 1953; Turner & Griffin, 1995 & 1999; Reason & Brand, 1975; Kennedy, Lanham, Massey & Drexler, 1995).

1.3.1 Models of motion sickness

Because of the variability in symptoms and stimuli that can evoke adverse signs, several models of motion sickness have been presented (for reviews, see Money, 1970; Kennedy, 1985; Reason & Brand, 1975). An evolutionary hypothesis (Treisman, 1977) suggests that when the body vomits in response to motion sickness, the body is interpreting the stimulus as if it were a poison and thus assures the survival of the species. An ecological theory of motion sickness (Riccio & Stoffregen, 1991) connects postural stability with motion sickness. According to the theory, prolonged postural instability causes symptoms of motion sickness.

The most accepted theories of motion sickness are the so-called sensory conflict theories (see also the sensory rearrangement theory; Reason, 1978) (Oman, 1982, 1984, 1990, 1998; Reason, 1970; Duh, Parker, Philips & Furness, 2004; Lackner & DiZio,
The theories assume that motion sickness arises owing to conflicting sensory information in the ongoing motion of the body, or the expected sensory feedback from intended movements does not correspond with the movement actually generated. In addition, it has been hypothesized that the magnitude of the conflict is a major determinant of the latency and intensity of the symptoms.

Even though the motion sickness theories provide different explanations for the reasons and causes of motion sickness, they have been criticized for their lack of specificity, necessary for making solid, testable predictions (e.g., Draper, Viirre, Gawron & Furness, 2001; Stoffregen & Riccio, 1991; Warwick-Evans & Beaumont, 1995).

1.3.2 VE-related sickness

Similar to motion sickness susceptibility, VE-related sickness susceptibility is multifactorial with variability in symptoms and causes. For that reason, the definitions of VE-related sickness and the concepts used to describe the state of sickness vary among systems and contexts of use (e.g., Kennedy, Lane, Berbaum & Lilienthal, 1993; Patterson, Winterbottom & Pierce, 2006; Hettinger, Berbaum, Kennedy, Dunlap & Nolan, 1990; Kennedy & Fowlkes, 1992).

The majority of VE-related sickness definitions describe it as a type of motion sickness. According to Burdea and Coiffet (2003), cyber sickness is a form of motion sickness that results from interaction with or immersion in VEs (e.g., eyestrain, disorientation, postural instability, sweating, pallor, drowsiness, nausea, vomiting). Hettinger, Berbaum, Kennedy, Dunlap, and Nolan (1990) also defined simulator sickness as a form of motion sickness, but with a dominance of oculomotor symptoms and with fewer sickness symptoms than in the case of motion sickness (in some publications simulator sickness refers to the simulators, while in others, it is used as a more general term for VE-related sickness). Biocca (1992) viewed simulator sickness as a kind of motion sickness with varied symptoms without a need for real physical motion (Hettinger & Riccio, 1992; Kennedy, Hettinger, Harm, Ordy & Dunlap, 1996; McCauley & Sharkey, 1992). Similarly, visually-induced motion sickness (VIMS) refers to sickness experiences evoked by immersion in computer-generated virtual environments without the use of mechanical simulators (i.e., without real motion).
Because of the lack of real motion in VIMS, it has been suggested that stimuli-related features such as vection (see section 1.6.1), lag, and image quality are the main contributors to VIMS symptoms (Stanney, Mourant & Kennedy, 1998; Nichols & Patel, 2002). Because of the similarities between VIMS causes and the experimental setups used in Publications I, II, III, and IV, the sickness levels measured and discussed in this thesis correspond to the VIMS symptoms (also referred to as sickness in this thesis).

### 1.3.3 VE sickness subgroups and profiles

In 1993, Kennedy, Lane, Berbaum, and Lilienthal classified the most common adverse effects connected with VE exposure into three subgroups. The first subgroup includes gastrointestinal distress (nausea, N; see Appendix 1); the second subgroup contains visuomotor or oculomotor symptoms (O) (cf. section 1.4.2); and the last group incorporates the symptoms of vestibular disturbances (disorientation, D). Since simulator sickness may be caused by several factors (equipment features, usage, or user fitness), which may induce or cause different symptoms and no single symptom predominates in all users, Kennedy and Fowlkes (1992) defined simulator sickness as polygenic (i.e., different causes) and polysymptomatic (i.e., symptoms variability).

Howarth and Costello (1997) associated specific sickness symptoms with specific causal factors. According to the authors, a sensory conflict will most probably lead to nausea and stomach awareness; motion stimuli (including head movement) will induce feelings of disorientation, and problems with optical design can evoke eyestrain and other ocular symptoms. In addition, multiple causal factors could lead to VE-related sickness, but not all factors need to be present for the symptoms to occur (see also Pöllönen, Järvenpää & Häkkinen, in press).

Stanney and Kennedy (1997) separated VE exposures and other disorienting environments from each other by using profiles from Simulator Sickness Questionnaires (SSQ, see Appendix 1) (Kennedy, Lane, Berbaum & Lilienthal, 1993). According to Stanney and Kennedy (1997), VEs tend to produce more disorientation than nausea symptoms and fewer oculomotor disturbances (D>N>O profile), but VE profiles differ from the profiles of other provocative environments; space sickness (O>D>N profile) and simulator sickness (O>N>D profile) cause the most oculomotor symptoms, while
seasickness and airsickness induce the most nausea symptoms and the fewest oculomotor symptoms (N>D>O profiles).

1.4 Discomfort and aftereffects

Several books and papers published on VEs have stressed the importance of system ergonomics (Wilson, 1999; Nichols, 1999; Melzer & Moffitt, 1997; Howarth, 1999; Kalawsky, 1999; Wann & Mon-Williams, 2002). Parameters connected with HMD’s optics (e.g., misalignments in optics; contrast, illumination), headset design (e.g., fit, weight), a viewing mode (monocular, bi-ocular, binocular), and an FOV have been shown to have an influence on comfort (the extent to which the user is satisfied with physical comfort; Bevan, 2008) and/or visual ergonomics (eyestrain and ocular discomfort) (e.g., Nichols, 1999; Howarth, 1999; Peli, 1998).

1.4.1 Physiological changes

Because of unnatural viewing conditions, the use of HMDs in different VE environments can lead to measurable physiological changes in the human body (Wann & Mon-Williams, 1996; Rushton, Mon-Williams & Wann, 1994; Shibata, 2002; Ukai & Howarth, 2008; Rushton & Riddell, 1999).

For instance, the goal of the vergence-accommodation interaction is to ensure that vision is both clear (the accommodation process) and single (the vergence process). Conflicting information in the cues presented on HMD displays (especially in the binocular mode) for accommodation and vergence may cause change in heterophoria\(^1\) values (e.g., Mon-Williams, Wann & Ruston, 1993; Hasebe, Nonaka & Ohtsuki, 2005; for review, see Edgar, 2007). Because several HMD optics-related characteristics may potentially affect user visual functioning, different explanations for the same outcome have been offered. Howarth (1999) suggested that changes in heterophoria may be caused by the mismatch between the instrument lenses (the inter-ocular distance) and the screens (inter-screen distance), while Mon-Williams, Plooy, Burgess-Limerick, and

\(^1\) Heterophoria is the tendency of the lines of sight (visual axes) to deviate from the relative positions
Wann (1998) explained changes in heterophoria values through different vertical gaze angles.

Some researchers have associated changes in visual functioning with a specific HMD mode (binocular and bi-ocular e.g., Ruston, Mon-Williams & Wann, 1994), whereas others have shown that similar outcomes are possible regardless of the mode (Howarth, 1999) or the devices used (Peli, 1998). Peli (1998), for example, compared bi-ocular and binocular HMDs with a cathode ray tube (CRT) desktop display. Because no changes in measured visual variables (accommodative status by refraction, binocular visual acuity at a distance, fixation disparity at a distance, stereo acuity at near, phoria at a distance and near, vergence at a distance and near, accommodative reserve by fuse cross cylinder, convergence, contrast sensitivity at a distance and TBU time) between devices were found, Peli concluded that the functional visual changes that have been reported following short-term use of HMDs are not specific to stereoscopic presentation and do not differ from those caused by desk-top CRT display. However, the use of the HMD in stereoscopic mode may otherwise be less comfortable than the use of the CRT. Moreover, Peli (1998) emphasized that the statistical significance of the results should always be examined from other points of view as well, i.e., how clinically meaningful the changes are and whether the findings give reasons to be concerned because many changes in visual functioning following HMD use are not necessarily harmful, even though they are statistically significant.

1.4.2 Eyestrain

It is well documented that the use of computers or prolonged near-sighted work may cause eyestrain (i.e., asthenopia, a term generally used to designate any subjective symptoms or distress arising from use of the eyes; Schapero & Hofstetter, 1968) (e.g., Tyrrell & Leibowitz, 1990; Patel, Henderson & Bradley, 1991; Tsubota & Nakamori, 1993). Typical symptoms connected with eyestrain are eye fatigue, discomfort, burning, irritation, ache, sore eyes, tired eyes, headache, photophobia, blur, double vision, itching, tearing, dryness, and foreign-body sensations. Over the years many conditions (such as glare from lighting, problems in image quality, a non-optimal gaze angle, flickering, dry eyes, and other vision-related problems) have been identified as causing

On the basis of symptom descriptions and locations, Sheedy and colleagues (2003; Sheedy, 2007) distinguished two different afferent pathways for symptoms of asthenopia. According to these authors, external symptoms such as burning, irritation, tearing, and dryness located in the front and bottom of the eye are most likely caused by such factors as holding the eyelid open, glare, up gaze, small font, and flickering, which are related to dry-eye symptoms common in computer work (Tsubota & Nakamori, 1993; Donnenfeld & Thimons, 1999; Patel, Henderson & Bradley, 1991; Toda, Fujishima & Tsubota, 1993). Internal symptoms such as ache, strain, and headache located behind the eyes were associated with accommodative and/or binocular vision problems, which are common complaints associated with prolonged near-work conditions, but also possible when bi-ocular or binocular HMDs are used (e.g., Tyrrell & Leibowitz, 1990; Mon-Williams, Plooy, Burgess-Limerick & Wann, 1998).

1.4.3 Eyestrain, changes in visual functioning, and HMDs

As discussed in section 1.4.1, changes measured in visual functioning while wearing an HMD might be caused by problems in vergence-accommodation interactions, which in turn could be seen as image blur and/or double images (cf. internal symptoms, Sheedy, 2007; Patterson, Winterbottom & Pierce, 2006). Because HMDs are specific types of displays, it is clear that they might have problems in image quality, and/or with a gaze angle similar to other displays, and these problems may, for example, cause external symptoms of eyestrain.

Comparison between HMDs and non-wearable displays has shown that the use of HMDs may cause sickness symptoms, but also increase eyestrain symptom levels (e.g., Kennedy, Lane, Berbaum & Lilienthal, 1993; Nichols & Patel, 2002; Howarth, 2008; Howarth & Hodder, 2008; Hääkkinen, Vuori & Puhakka, 2002; Howarth, 1999). For example, Howarth and Costello (1997) reported that the use of an HMD configured as a personal viewing system produced a greater frequency of sickness and eyestrain symptoms than when the same task was performed on a desktop computer display. Similarly, Sharples and colleagues (2008) reported an increase in symptom levels when HMD was compared with a desktop display and reality theatre (7.5 meters horizontally*
2.5 meters vertically) (cf. section 1.3.3), while Sheedy and Bergström (2002) found no significant differences between binocular wearable and flat panel displays when eye-, motion-, and musculoskeletal-related symptoms with static stimuli were evaluated (a reading task, a letter-counting task, a word-search task) (cf. Häkkinen, 2004; Rushton, MonWilliams & Wann, 1994; Peli, 1998).

1.4.4 Aftereffects

In addition to reported sickness, visual discomfort, and physiological changes, immersion in VEs may cause aftereffects\(^2\) after exposure to VEs. For example, problems in hand-eye coordination, postural and visual disturbances, and malaise have been associated with adapting\(^3\) to VEs (DiZio & Lackner, 2002; Champney, Stanney, Hash, Malone, Kennedy & Compton, 2007; Kennedy & Stanney, 1996; Kennedy, Lane, Lilienthal, Berbaum & Hettinger, 1992; Hettinger, Berbaum, Kennedy, & Westra, 1987; Biocca & Rolland, 1998). Some of these aftereffects can be connected with VE-related sickness and may last from a few minutes to days or even longer (Stanney, Mourant & Kennedy, 1998; Stanney, Salvendy, Deisinger, DiZio, Ellis, Ellison, et al., 1998).

1.5 Recommendations and frameworks

User experiences are defined as person's perceptions and responses that result from the use or anticipated use of a product, system or service (also referred to as subjective experiences) (ISO DIS 9241-210:2008, see also Law, Roto, Hassenzahl, Vermeeren & Kort, 2009; Hassenzahl, 2003, 2008). Identifying parameters affecting user experiences and offering new solutions to the existing problems and preventing other problems in the future, are the most important subjects in product research and development process of HMDs. Over the years several frameworks and integrated models on human characteristics (such as gender, experience level, personality, cognitive abilities, age), task-related features (such as motion and interaction), characteristics of the system used

\(^2\) Any effect that is observed once a participant has returned to the physical world (Stanney, Mollaghasemi, Reeves, Breaux & Graeber, 2003).

\(^3\) A semi-permanent change of perception and/or perceptual–motor coordination that serves to reduce or eliminate a registered discrepancy between, or within, sensory modalities, or the errors in behavior induced by this discrepancy (Welch, 1978).
(display size, field of view, brightness, usability of input and output devices, and headset physical features), and context of use have been published (e.g., Kennedy & Fowlkes, 1992; Kolasinski, 1996; Wann & Mon-Williams, 1996; Mon-Williams & Wann, 1998; Stanney, Mollaghasemi, Reeves, Breaux & Graeber, 2003;).

In 1999, Kalawasky introduced a computer-based diagnostic tool for the usability\(^4\) of virtual/synthetic environment systems. In addition to the question of ten usability factors (interface functionality, user input, system output, user guidance and help, consistency, flexibility, simulation fidelity, error correction, sense of immersion and presence, overall system usability), Kalawasky recommended fast screening (before the test), including visual-acuity measures and experience-level evaluations among the VE research tools.

In 1999 Loomis, Blascovich and Beall (1999; see also Blascovich, Loomis, Beall, Swinth, Hoyt & Bailenson, 2002) reviewed virtual environment technology (VET) as a tool for psychology research. These researchers believe that VET offers increased ecological validity through more complex, but controlled simulation. VET increases the power of experimental research by increasing the impact of manipulations on participants (e.g., acrophobia); it enables execution and planning experimental setups that are otherwise impossible; it can be an easier, faster, and less expensive way to arrange new experimental setups, and it might provide new and practical data sources that would be automatically available for data analysis (see Lampton, Bliss & Morris, 2002). However, there are potential VET-related shortcomings that should be taken into accounts, such as the likelihood of artifacts contaminating the research findings (limitations to the visual display, a slow graphics update rate, and significant lags between head tracking and visual display), the difficulty of setting up high-quality VE laboratories, and aftereffects (such as sickness, eyestrain, disturbance of balance and eye-hand coordination, drowsiness) (e.g., Kennedy, Lane, Berbaum & Lilienthal, 1993). According to Loomis, Blascovich and Beall (1999), improving the selection of participants and excusing participants from the experiment at the onset of the earliest discernible symptoms are the best ways to avoid or mitigate any side effects.

Nichols and Patel’s (2002) literature review of the health and safety implications of VR divided individual parameters associated with sickness into two main categories:

\(^{4}\) Extent to which a product can be used by specified users to achieve specified goals with effectiveness, efficiency and satisfaction in a specified context of use (ISO 9241-11:1998).
dynamic characteristics, meaning features that can be changed through training or by using other kinds of support (such as experience level, education, and the state of health); and static characteristics, meaning more permanent features that are not sensitive to training or education (such as age, gender, and personality). Since the characteristics in each group behave differently, they create different demands for VE system development. According to Nichols and Patel, system improvements may help to avoid the discomfort associated with static features. In contrast, dynamic features do not necessarily demand manipulation of the system, but supportive actions could lead to more positive outcomes. Among other aspects related to VE research, the authors emphasized the importance of methodological demands; empirical trials should reflect the likely context of VR use; in other words, the trails should be ecologically valid. Researchers should consider interactions between effects and discuss the ways in which the effects could be managed.

1.6 What and how to measure?

In 1999 Cobb, Nichols, Ramsey, and Wilson examined several problems associated with VE and HMD research setups. They listed as critical the large number of potential influencing or causative factors and overlapping categories of potential effects, unknown interactions between these factors, a wide range of candidate methods and measures (applied from different research fields), and possible interference between these methods. According to the authors, methods for measuring VR/VE effects should be able to identify whether such effects exist, measure the degree of effects experienced, and aid the understanding of any causative factors (see also Nichols, Cobb, & Wilson, 1997; Nichols & Patel, 2002).

Similarly, according to Cobb and colleagues (1999), selecting appropriate methods and measures is still a demanding process; in addition to explaining the variables recognized earlier, experimental setups should include possible new variables that may help to us understand product usability and user experiences from other non-sickness-related viewpoints.

According to some researchers, simulator sickness is a technical problem, and for that reason, it could be eliminated through the development of technology. Others believe that user-related features and experiences have an influence on perceived
sickness intensity (Kennedy, Stanney & Dunlap, 2000; Menozzi, 2000). Owing to the different viewpoints, several user-, system-, and task-related parameters have been recognized and connected with HMD-related sickness and eyestrain.

### 1.6.1 Task characteristics

#### 1.6.1.1 Vection

The majority of VE researchers believe that vection (an illusory feeling of self-motion; Biocca, 1992) is a necessary precursor to simulator sickness, and for that reason, it is the most examined task-related feature in the context of VEs (Hettinger, Berbaum, Kennedy, Dunlap & Nolan, 1990; Howarth & Costello, 1997; Häkkinen, Takatalo, Komulainen, Särkelä, Havukumpu & Nyman, 2005).

Lo and So (2001) examined the effects of scene oscillations along different axes. On the basis of the results, the authors concluded that the presence of scene oscillations for a period longer than five minutes will increase nausea ratings, while a stationary scene viewed for up to 15 minutes will probably cause no significant change in the nausea levels of the viewer (cf. Howarth & Costello, 1997).

Merhi, Faugloire, Flanagan, and Stoffregen (2007) asked participants to play games with optic flow simulating complex patterns of self motion via an HMD, either standing or sitting. Both setups induced sickness, but the sickness rates were significantly higher in a standing position. To eliminate the possible nauseogenic influence of an HMD and to increase the ecological validity of the game setup, Stoffregen, Faugloire, Yoshida, Flanagan, and Merhi (2008) repeated the experiment above by using a video monitor. The authors found that motion sickness can occur among the players of console video games under a variety of conditions even when games are viewed on a video monitor from a comfortable distance. Moreover, the postural instability theory of motion sickness was supported by their findings; they found significant differences in postural activity between sick and well participants prior to the onset of subjective symptoms of motion sickness (Riccio & Stoffregen, 1991). A comparison between the test arrangements revealed that an HMD most likely contributes to motion sickness when the users are standing. Jaeger and Mournat (2001) also reported more severe sickness when subjects performed a task in a standing position compared with a walking
simulator; static simulator-related symptoms resembled a visually-dependent immersive virtual environments syndrome, whereas the dynamic simulator-related sickness symptoms were comparable to motion-based physiological effects.

1.6.1.2 Other task-related features

Other task-related features similar to vection may have an influence on user experiences. For example, Howarth and Costello (1997) and Pölönen, Järvenpää, and Häkkinen (in press) demonstrated that in addition to dynamic stimuli, the use of static stimuli may induce nausea and discomfort. Also the degree of user-initiated control provided the users in VEs, immersion duration, and repeated exposures to VE may either decrease or increase the occurrence and severity of sickness and eyestrain symptoms (Stanney & Hash, 1998; Reason & Benson, 1978; Sharples, Cobb, Moody, & Wilson, 2008; Lampton, Kolasinski, Knerr, Bliss, Bailey & Witmer, 1994; Kennedy, Stanney, & Dunlap, 2000; Kennedy, Stanney & Dunlap, 2000).

1.6.2 System and context features

1.6.2.1 HMD optical characteristics

Because even small optical misalignment and distortions may cause sickness and eyestrain, several recommendations and thresholds for system characteristics have been published (e.g., McCauley & Sharkey, 1992; Rushton, Mon-Williams, & Wann, 1994; Patterson, Winterbottom & Pierce, 2006; Self, 1986; Task, 1997; Nichols, 1999).

For example, ISO recommendations for non-see-through binocular and bi-ocular displays provide a set of ergonomics-related performance objectives for helping achieve a comfortable user experience with virtual displays (ISO/FDIS 9241-303:2008(E). HMD optical characteristics such as, eye relief, convergence demand, horizontal

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5 A distance from the last physical surface of the virtual display optics to the exit pupil where the pupil of the eye is placed. Eye relief is constrained by two factors: the eye must be near enough to the lens that the whole display is visible, but far enough away from the display so that spectacles can be worn (ISO/FDIS 9241-303:2008(E).

6
disparity, the vertical misalignment of displays, interocular rotation difference, vertical and horizontal magnification difference, luminance and focus difference, as well as temporal asynchrony, focal distance, field curvature difference and IPD, are reviewed as potential factors that can induce eyestrain, headaches, and discomfort when they are poorly aligned or adjusted (see Draper, Viirre, Gawron & Furness, 2001; Patterson, Winterbottom & Pierce, 2006; Self, 1986). Also low screen contrast and luminance levels, geometric distortions, poor legibility, and poor readability may decrease viewing experiences and performance efficiency (e.g., ISO/FDIS 9241-303:2008(E); Patterson, Winterbottom & Pierce, 2006).

1.6.2.2 Headset features

Even though it is known that problems in HMD physical ergonomics, especially in headset ergonomics, may decrease viewing comfort, and thereby shorten the time spent with the system, only a few research results have been published on the subject.

Nichols (1999) identified several parameters in headset physical ergonomics that may cause pain or discomfort. According to her results, a headset’s weight, pressure points (weight distribution), fit, and shape may all decrease headset usability, but may also have a negative influence on future HMD-related opinions (see also Davis, 1989; Nichols, 1999). In addition, some authors have assumed that problems in headset ergonomics explain certain reported symptoms; for example, headset weight has been connected with headaches and fatigue (e.g., Lo & So, 2001; Howarth & Costello, 1997).

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6 The convergence position of the eyes that is required for binocular fusion is the convergence demand of the binocular virtual display system. The system should not cause a convergence demand that is in the divergent direction from the parallel visual axes.

7 Horizontal disparity is the difference in the relative position of the visual images along the horizontal axis/meridian of an object on the two retinas.

8 Vertical misalignment refers to the vertical position of the two displays relative to each other.
1.6.2.3 Context of use

As with all displays, the context of use affects the user’s experiences and task performance. For example, reflections of ambient light sources (lamps, windows, etc.), the viewing distance, and the viewing angle may reduce a display’s contrast level and thus decrease the legibility of the information (e.g., Hill & Kroemer, 1986; Jaschinski, Heuer & Kylian, 1988; Burgess-Limerick, Plooy & Ankrum, 1998; Burgess-Limerick, Mon-Williams & Coppar, 2000; Whitestone & Robinette, 1997, Patterson, Winterbottom & Pierce, 2006).

Also the test arrangement used may affect the user’s experiences and thus decrease the ecological validity of the results, meaning the relationship between real-world phenomena and the investigation of these phenomena in experimental contexts (Schmuckler, 2001). Because one of our goals was to evaluate users’ opinions and experiences as they might be in real-life scenarios, all the measures, stimuli, and laboratory settings used were kept as close as possible to characteristics usage situations.

1.6.3 Individual characteristics

In many publications associated with HMDs, it has been shown that information about the differences between users may help us understand the experiences associated with VE sickness and performance outcomes (Egan, 1988; Stoffregen & Riccio, 1991; Cobb, Nichols, Ramsey & Wilson, 1999; Kennedy & Fowlkes, 1992; Stanney, 2002). Among others factors, parameters such as the health state of a user before immersion (Kennedy & Frank, 1983), prior experience with HMDs (Pausch, Crea & Conway, 1992), susceptibility to motion sickness (Kennedy, Lane, Berbaum & Lilienthal, 1993; Hettinger & Riccio, 1992), gender (Dobie, May, MsBride, & Dobie, 2001; Cheung & Hofer, 2003; Kolasinski, 1996), migraine history (Nichols, Ramsey, Cobb, Neale, D’Cruz & Wilson, 2000; Golding, 1998; Drummon, 2002), age (Kolasinski, 1996 & 1995), mental rotation ability (Kolasinski, 1996), and postural stability (Kolasinski 1996; Marcus & Furman, 2007; Owen, Leadbetter & Yardley, 1998) may be associated with side effects, aftereffects and discomfort.
The importance of other individual characteristics such as personality traits, user motives, and cognitive abilities has also been recognized, but only a few HMD-related subjective studies have been carried out on such topics (Biocca, 1992; Nichols & Patel, 2002, Kolasinski, 1995). Turner and Love (2003) examined relationships between psychological factors, side-effects, and task difficulty that may influence the ease of use of head-mounted display systems. The authors found clear differences between users in spatial attention as a function of personality type (neuroticism) and as a function of the symptoms of sickness experienced. Some earlier studies connected a user’s perceptual style with a susceptibility to motion sickness (e.g., Barrett & Thornton, 1968 & 1969; Barrett, Thornton & Cabe, 1970). Because of the variability in the results, it is assumed that if the relationship between motion sickness and perceptual style exists, then it is not an obvious one (Kolasinski, 1995).

1.6.4 The process of technology acceptance

1.6.4.1 The unified theory of acceptance and use of technology

The unified theory of acceptance and use of technology (Viswanath, Morris, Davis & Davis, 2003) posits that three direct determinants of intention to use (performance expectancy, effort expectancy, and social influence) and two direct determinants of usage behavior (intention and facilitating conditions) interact with experience, voluntariness, gender, and age. According to the theory, effort expectancy describes the degree of ease associated with the use of the system (also referred to as the perceived ease of use, Davis, 1989; Davis, Bagozzi & Warshaw, 1989; Moore & Benbasat 1991 and complexity of technology use (opposite of ease of use), Thompson, Higgins & Howell, 1991). Social influence focuses on the degree to which an individual perceives that important others believe he or she should use the new system. Performance expectancy describes the degree to which an individual believes that using the system will help him or her to attain gains in job performance and refers to constructs such as perceived usefulness (Davis 1989; Davis, Bagozzi & Warshaw, 1989), extrinsic motivation (Davis, Bagozzi & Warshaw, 1992), job-fit (Thompson, Higgins & Howell, 1991), outcome expectations (Compeau & Higgins, 1995; Compeau, Higgins & Huff, 1999), and relative advantage (Moore & Benbasat, 1991). Facilitating conditions reflect
individual beliefs that an organizational and technical infrastructure exists to support the use of the system, while an attitude toward technology consists of concepts such as attitude toward behavior, intrinsic motivation, and affect toward use. According to Viswanath, Morris, Davis, and Davis, all the constructs affect an individual’s likes, enjoyment, joy, and pleasure associated with technology use, and thus, the theory might inform further inquiry into the short- and long-term effects of information technology implementation on such job-related outcomes as productivity, job satisfaction, organizational commitment, and other performance-oriented constructs.

1.6.4.2 Model of user experience

Whereas Viswanath and his colleagues’ (2003) theory of acceptance and use of technology focuses primarily on the ease of use and the perceived usefulness of technology in a work context, a different approach to user experiences is presented by Hassenzahl and colleagues (Hassenzahl, Burmester & Beu, 2001; Hassenzahl, 2002, 2003, 2004, 2008). According to their model of user experience, when individuals use a product they take note of the product’s features and, on the basis of these, create a personal version of the apparent product character (Hassenzahl, 2003). The product character integrates product features, users’ standards (other objects the product can be compared to) and expectations, but it might change over time due to increasing numbers of experiences with the product. The product features include user attributes associated with product manipulation effectiveness and with person’s psychological well-being (i.e., stimulation, identification, and evocation), which in turn have an influence on users’ emotional responses (i.e. consequences) and on the general evaluation of the products, but their importance may vary in different situations (Hassenzahl & Roto, 2007). Consequences such as product-related satisfaction (freedom from discomfort and positive attitudes to the use of the product; ISO 9241-11:1998), pleasure, and appealingness are viewed as outcomes of experience with or through technology; when someone uses a product and his experience differs positively from what he expected, then the user will probably be pleased, while an appealing product is associated with positive emotional reactions (i.e., a product is good, pleasant, attractive, and desirable). Because product appealingness takes the context of use into account, it may vary among individuals and contexts.
1.6.4.3 HMDs and user satisfaction

It has been shown that the process of technology acceptance integrates different parts of user experiences. Yet only few publications have connected user experiences other than non-sickness related ones with using wearable displays (e.g., Nichols, 1999; Cobb, Nichols, Ramsey & Wilson, 1999). Gulliver, Serif, and Ghinea (2004) evaluated the level of enjoyment and the perceived level of quality separately in order to distinguish between participants’ subjective satisfaction with the content of a video clip and the ability to assess the quality of the video clip objectively (Gulliver & Ghinea, 2009). In the authors’ view, the subjective level of enjoyment was significantly affected by the type of video, while the quality of the video and type of video adaptation were less important when the level of enjoyment was measured. Nichols (1999) connected a decrease in the ergonomics and usability of HMDs with the outcomes such as pain, discomfort, and lack of satisfaction, while problems of visual displays were associated with lowered effectiveness of VE and lack of satisfaction with VR use.

1.6.5 Subjective measures

Despite the fact that different methods could be used to study VEs and HMDs, the majority of published papers have used subjective measures (questionnaires, rating scales, and interviews), either alone or together with objective measures (physical and physiological measures, visual functioning, performance outcome through the error rates, or reaction times) (e.g., Cobb, Nichols, Ramsey & Wilson, 1999; Nichols, Cobb & Wilson, 1997; Lo & So, 2001; Mon-Williams, Wann & Rushton, 1993).

According to some authors, the use of different methods is considered extremely valuable because it helps developers and experts to focus on various technological attributes that cannot easily be investigated through single technical verification tests (Karaseitanidis, Amditis, Patel, Sharples, Bekiaris, Bullinger & Tromp, 2006). However, it is not always possible or even reasonable to use several different methods; there is often a lack of time, money, or resources, while obtrusive techniques may lower ecological validity. According to Pugnetti, Meehan, and Mendoza’s (2001), data from physiological measures may reflect individual response styles and help clinicians
understand, classify, and predict outcomes, yet measures demand resources and knowledge and may affect participants’ ability to concentrate on their tasks, limit their movements, reduce the feeling of presence, and increase their awareness of the external world. According to Wilson and Nichols (2002), in many VE-related issues the use of subjective measures might be the only method that offers the validity, flexibility, applicability, and practicability needed to assess the concepts (see Wilson & Nichols, 2002; McKenna, 2002; Annett, 2002).

1.7 Current knowledge of HMD-related user experiences

Several individual, system, and task-related parameters may cause sickness, eyestrain, and discomfort, even though the exact impact of single parameters may vary among individuals, tasks, and use contexts. The same task with the same HMD may cause sickness and eyestrain in person A, who often suffers from headaches, while the same setup does not necessarily cause any of these symptoms in person B, who also suffers from headaches, but has used HMDs before (Cobb, Nichols, Ramsey & Wilson, 1999; Kennedy & Fowlkes, 1992; Stanney, 2002). To avoid the symptoms associated with HMD use, several recommendations and design guidelines have been published and several of those recommendations have been implemented in devices that benefit from progress in technology and optics. As a result, today’s HMDs are much smaller in size and lighter than before, and they also have better display characteristics with superior data transfer options. Thus, it could be expected that the systems cause fewer adverse symptoms in the users, and for that reason, the importance of other user experiences becomes more relevant. However, because the majority of papers published have examined HMD-related sickness and eyestrain using older HMD models, it is difficult to interpret how much the current devices differ from their forerunners or how experiences other than non-sickness-related experiences influence a user’s current and future device-related opinions. In the following sections results from commercial biocular and monocular HMD studies will be presented.
2 Aims of the study

The study addresses the following questions:

1. How much do current commercial HMDs cause sickness and eyestrain? (Publications I, II, III, IV)

2. What are the most perceptible benefits when HMDs are used as accessories for handheld devices? (Publication III)

3. What are the benefits and shortcomings when adjustable versus non-adjustable HMDs are used? (Publications I, II, III, IV)

4. How do individual characteristics and task- and device-related demands affect the evaluated visual quality, headset fit, task pleasantness, user’s opinions, and forward-looking product-related interests? (Publications I, II, III, IV)
3 Methods and results

3.1 General methods

In a total of thirteen different test setups were carried out to study the ergonomics of HMDs and user experiences (see Table 1, Appendix 1). The comparisons were as follows: the comparison of two display positions by using a monocular HMD (I); the comparison of three different tasks by using a HMD-mobile system (III); the comparison of four different bi-ocular HMDs (II); the comparison of adjustable and non-adjustable HMDs (IV): film viewing on TV screen (II), and playing with mobile phone (III). Each volunteer participated in one test session, which lasted from 1.5 to 2.0 hours, depending on the experimental settings used. All participants were workers in Finnish technology company, but their assignments varied. Approximately half were women. All the participants were volunteers and were rewarded with cinema tickets.

![Figure 1. Experimental course](image)

Each test session began with visual screening (visual acuity, near and far; IPD; stereo acuity, color vision, phoria, the near point of accommodation) and an Optometric Symptom Questionnaire (Blaskey, Scheiman, Parisi, Ciner, Gallaway & Selznick, 1990) in order to ascertain that participants were not prone to eyestrain and that visual functions were normal (see Figures 1 and 2). The participants then completed several questionnaires in addition to background questions and were introduced to the tasks and
the equipment. Thereafter, participants viewed a film, read a text, played games, or viewed animation along with the letter detection task for at least 40 minutes. Afterwards the participants once again completed several questionnaires on their viewing experiences and answered a few interview questions. During the tasks, the participants sat on an adjustable TV chair in a dimly lighted room and were allowed to change sitting positions.

Because one of the goals was cross-comparison of different experimental setups, a core set of self-reported evaluation tools (e.g., self-reported scales, questionnaires, single questions) was used in Publications II, III, IV (see Table 1, partly also in I). In Publication I changes in visual functioning were also measured.

Table 1. Goals, tasks, and measures for different experiments

<table>
<thead>
<tr>
<th>Publication</th>
<th>Goals</th>
<th>Task</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>mHMD’s position influence on visual functioning and user experiences (I)</td>
<td>Which position is more comfortable?</td>
<td>Animation/letter (A/B) detection task</td>
<td>Phoria Nearpoint of accommodation User experiences</td>
</tr>
<tr>
<td>Comparison of HMDs (II)</td>
<td>Comparison of bi-ocular HMDs and TV</td>
<td>Film viewing</td>
<td>User experiences (see Appendix 1)</td>
</tr>
<tr>
<td>HMDs as accessories of hand-held devices (III)</td>
<td>Task influence on user experiences and symptom levels</td>
<td>Film viewing</td>
<td>User experiences (see Appendix 1)</td>
</tr>
<tr>
<td></td>
<td>Compare of HMD-mobile phone system, mobile phone, and TV</td>
<td>Game playing</td>
<td></td>
</tr>
<tr>
<td>Comparison of adjustable and non-adjustable HMDs (IV)</td>
<td>Comparison of user experiences with adjustable and non-adjustable HMDs</td>
<td>Film viewing</td>
<td>User experiences (see Appendix 1)</td>
</tr>
</tbody>
</table>
3.2 Equipment

Altogether six HMDs in addition to a TV and mobile telephone were used as viewing devices for different tasks. All binocular displays were used in a bi-ocular mode even though some of the HMDs used support S3D (for details, see Table 2; Publications II, III, and IV). MicroOptical’s SV-6 PC Viewer (Publication I) attached to plastic frames was used to study the monocular display’s position influence on user experience and visual functioning. A direct-view LG 42” LF66 LCD-TV (Publications II, IV) and a N95 8GB (III, IV) mobile phone were used as reference devices with bi-ocular HMD setups. In Publication I, the animation was viewed on a ViewSonic 20.1-inch MVA color TFT active-matrix display. In Publications II and IV a source-composite video signal was taken from a Toshiba DVD video player SD-350E. In Publication III a mobile phone and the HMD phone system setups, the source-composite video signal was taken from an N95 phone. External loudspeakers (GENELEC) were used for hygienic reasons in all Publications.
Table 2. Characteristics of HMDs (adapted from Järvenpää & Pölönen, 2010).

<table>
<thead>
<tr>
<th></th>
<th>iTheater (II, III, IV)</th>
<th>MyVu (II, IV)</th>
<th>Vuzix (II, IV)</th>
<th>Zeiss (II, IV)</th>
<th>eMagin adj. (IV)</th>
<th>eMagin non-adj. (IV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Panel resolution</td>
<td>QVGA</td>
<td>QVGA</td>
<td>VGA</td>
<td>VGA</td>
<td>SVGA</td>
<td>SVGA</td>
</tr>
<tr>
<td>Luminance (cd/m²)</td>
<td>136</td>
<td>97</td>
<td>24</td>
<td>72</td>
<td>153</td>
<td>153</td>
</tr>
<tr>
<td>Contrast ratio</td>
<td>62:1</td>
<td>38:1</td>
<td>37:1</td>
<td>41:1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Focal distance left (m)</td>
<td>2.2</td>
<td>1.6</td>
<td>5.0</td>
<td>0.26-∞</td>
<td>0.51</td>
<td>0.51</td>
</tr>
<tr>
<td>Focal distance right (m)</td>
<td>2.0</td>
<td>2.7</td>
<td>2.4</td>
<td>0.26-∞</td>
<td>1.25</td>
<td>1.25</td>
</tr>
<tr>
<td>Convergence distance (m)</td>
<td>1.7</td>
<td>0.9</td>
<td>1.6</td>
<td>1.6</td>
<td>1.29</td>
<td>1.57</td>
</tr>
<tr>
<td>FOV horizontal (°)</td>
<td>23.2</td>
<td>12</td>
<td>22.7</td>
<td>20.8</td>
<td>30.6/31.5</td>
<td>30.6/31.5</td>
</tr>
<tr>
<td>FOV vertical (°)</td>
<td>17.4</td>
<td>8.8</td>
<td>17.6</td>
<td>15.4</td>
<td>23.6/24.2</td>
<td>23.6/24.2</td>
</tr>
<tr>
<td>FOV diagonal (°)</td>
<td>29.0</td>
<td>14.9</td>
<td>28.7</td>
<td>25.9</td>
<td>38.6/39.7</td>
<td>38.6/39.7</td>
</tr>
<tr>
<td>QVS horizontal (mm)</td>
<td>15</td>
<td>10</td>
<td>14</td>
<td>12</td>
<td>(38)</td>
<td>(38)</td>
</tr>
<tr>
<td>QVS vertical (mm)</td>
<td>15</td>
<td>10</td>
<td>14</td>
<td>10</td>
<td>(18)</td>
<td>(18)</td>
</tr>
<tr>
<td>Interocular distance (mm)</td>
<td>63</td>
<td>62</td>
<td>63</td>
<td>62</td>
<td>63 (adj.)</td>
<td>62</td>
</tr>
<tr>
<td>Luminance difference</td>
<td>22%</td>
<td>5%</td>
<td>3%</td>
<td>14%</td>
<td>3.2%</td>
<td>3.2%</td>
</tr>
<tr>
<td>Vertical misalignment (°)</td>
<td>0.5</td>
<td>0.0</td>
<td>0.8</td>
<td>0.1</td>
<td>1.3</td>
<td>0.0 - 0.2</td>
</tr>
</tbody>
</table>

3.3 Publication I

Several context and individual-related parameters, such as head posture, target distance, and individual differences in a visual and musculoskeletal subsystem, have been shown to have an influence on how people select their preferred line of sight (Hill & Kroemer, 1986; Jaschinski, Heuer & Kylian, 1988; Burgess-Limerick, Plooy & Ankrum, 1998; Burgess-Limerick, Mon-Williams & Coppard, 2000; Whitestone & Robinette, 1997). In addition it is assumed that a relaxed eye position exists and that when this position is used, ocular muscles become less tired, and thus users may experience less visual and musculoskeletal discomfort (see Peli, 1990, cf. Sheedy, 2007). Since, commercial mHMDs can be used with many tasks in different contexts, optimal performance may demand the use of different display positions. In this paper, eyestrain (also referred to as visual strain), VIMS, and other user experiences were evaluated when different mHMD positions, below or above the line of sight, were used.
3.3.1 Methods

Altogether 43 participants viewed the computer-animated movie called *Shrek* while simultaneously performing a letter detection task for 40 minutes. Twenty-one of the subjects tested display positions below the ViewSonic display, and 22 subjects tested positions above the display. Each test session started with visual screening and question answering. After the task, once again the near point of accommodation and phoria were measured and the SSQ completed, in addition to other viewing experience-related questions (Kennedy, Lane, Berbaum & Lilienthal, 1993, see Appendix 1) and VSQ (Howarth & Istance, 1985).

3.3.2 Results

The above position induced more oculomotor symptoms (SSQ) than below position, and total symptom severity level (SSQ) was higher than with the below position setup (see Figure 3). Both display positions caused some changes in phoria values, and the participants from both setups reported some eyestrain. The experiment as a whole was more pleasant\(^9\) when the mHMD’s display was below eye level than above, but participants’ opinions on wearable displays changed\(^10\) in the same way in both user groups (see Figure 4, above). The majority of the participants enjoyed the animation, even though they had to perform the second task simultaneously.

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\(^9\) Task pleasantness or the viewing experience, which took into account both the use of an HMD and a task (see Appendix 1).

\(^10\) Opinion change (i.e. change in user’s opinions associated with HMDs (see Appendix 1).
Figure 3. Change in sickness (i.e., post values – pre values); (the weighted means for SSQ are above, see Appendix 1 and for visual strain are below) (1. iTheater phone system reading, 2. iTheater phone system game, 3. iTheater phone system movie, 4. iTheater, 5. Zeiss, 6. MyVu, 7. eMagin alined, 8. eMagin non-alinged, 9. Vuzix, 10. Vuzix 95 min., 11. mHMD below, 12. mHMD above, 13. TV, and 14. phone).
Figure 4. Above: The mean scores for headset fit, visual quality, task pleasantness, and opinion change (1 iTTheater phone system reading, 2 iTTheater phone system game, 3 iTTheater phone system movie, 4 iTTheater, 5 Zeiss, 6 MyVu, 7 eMagin aligned, 8 eMagin non-aligned, 9 Vuzix, 10 Vuzix 95 min., 11 mHMD below, and 12 mHMD above) (see Appendix 1 for details). A scale from poor (1) to excellent (5) was used. Below: The mean scores for physical demand, effort and frustration (NASA TLX) (1. iTTheater phone system reading, 2. iTTheater phone system game, 3. iTTheater phone system movie, 4. iTTheater, 5. Zeiss, 6. MyVu, 7. eMagin alinged, 8. eMagin non-alinged, 9. Vuzix, 10. Vuzix 95 min., 11. TV, and 12. mobile phone). A scale from 5 to 100 was used, where 100 is the highest demand score.
3.4 Publication II

Because many HMD-related studies have used older models, it is difficult to predict how much more user friendly and comfortable are HMDs today and in what way user experiences affect future device-related interest. In Publication II, different HMDs were evaluated and compared from the viewpoint of the user’s experience.

3.4.1 Methods

Altogether 106 participants viewed *The Queen* either by using one of the HMDs or on a television screen for 40 minutes. Each test session started with a short introduction followed by visual screening (see Figure 1). We asked participants to complete the SSQ (Kennedy, Lane, Berbaum & Lilienthal, 1993) and VSQ (Howarth & Istance, 1985) questionnaires and to answer several individual experience-related questions (see Appendix 1). After the film, the participants again completed the SSQ and VSQ questionnaires in addition to the NASA TLX questionnaire (Hart & Staveland, 1988) together with questions on the viewing experience and headset ergonomics.

3.4.2 Results

Several differences among the HMDs and, between the HMDs and TV were found. All the screens induced some changes in eyestrain and/or oculomotor symptoms, but the symptom levels remained low (see Figure 3). Unlike other devices, the use of the Zeiss HMD caused no significant change in SSQ and VSQ scores. The iTheater HMD users reported mild nausea symptoms (SSQ), but no one mentioned the symptoms of disorientation (vestibular disturbances, SSQ). Likewise, evaluated task pleasantness, visual quality, and opinion change scores varied among the displays; some HMDs were more pleasant to use than others, while headset fit also varied with different HMDs (see Figure 4). Film viewing with iTheater HMD was clearly a more frustrating experience than when MyVu HMD (NASA TLX) was used (see Figure 4). A comparison between TV and HMD-related experiences showed that viewing the film on the TV screen was physically less demanding and required less effort than using an HMD, which suggest problems in headset design and ergonomics.
3.4.2.1 Connections between the measured parameters

The correlation analysis revealed that better visual quality and higher task pleasantness were connected with positive opinion change, whereas increased workload levels, task demands, and symptom severity had a negative influence on opinion change and future interest (also referred to as forward-looking interest/decisions) in HMDs (cf. Figure 6).

Participants having previous HMD and VE experiences were more critical than participants with less experience: they scored headset fit and visual quality lower, their opinions on HMDs changed in a less positive direction, and they also reported a higher level of frustration, effort, and total workload. Despite the shortcomings, participants were positively surprised because the devices used were better than they had expected (cf. Figure 7). Headset weight (weight distribution, pressure on the nose), size (loose, tight), sharp edges, and poor fit when personal glasses were used, were mentioned as important parameters that may decrease the usability and comfort of wearable devices.

3.5 Publication III

The idea of using an HMD as a personal viewing device is not a new one, but few studies have been conducted on the subject (e.g., Howarth & Costello, 1997; Häkkinen, 2004). Among the papers that have been published, no one has used a multimedia phone as a source of composite video signals for HMDs. The main goal of this experiment was to use a real HMD phone system with typical handheld device-related tasks and to evaluate setup-related user experiences.

3.5.1 Methods

Fifty-eight participants used an HMD phone system with three different applications: film viewing, game playing and reading. In the reading task, people read a Finnish version of Uncle Bernac: A Memory of the Empire, by Sir Arthur Conan Doyle. In the game-playing task, participants were asked to play more than one game among six N-Gage game alternatives, and in the movie group participants viewed The Queen for 40 minutes. Contrary to other experiment setups in which each attendee participated in
only one test session, people who played games participated in two sessions: in the first
session they used an HMD phone system, and in the second session they played games
on a mobile screen. The same questionnaires, self-reported scales, and questions were
used in Publication II (see Table 1).

3.5.2 Results

All the systems and tasks caused some oculomotor symptoms (SSQ) and eyestrain
(VSQ). Total symptom severity levels (SSQ) were higher with an HMD phone system
than with a phone setup (see Figure 3). However, the symptom levels were on average
low and partly depended on the task. Game playing induced some disorientation,
especially when games with strong motion scenes were played, and participants in the
reading group reported some nausea-related symptoms. Regardless of the tasks
performed, participants’ opinions about wearable displays changed in a positive
direction, while the ergonomics (fit, pressure, weight) and image quality were scored
similarly in all tasks (see Figure 4).

3.5.2.1 HMD comparison with TV and phone setups

Comparison between a mobile phone and an HMD-phone system revealed a significant
difference in disorientation values. The participants graded using a scale of 1 to 10 the
playing experience higher with the HMD system (6.7) than with the mobile phone (5.9).
The estimated duration of a playing session with the HMD system in the future was on
average 36 minutes, while the estimated duration of the mobile phone game session was
around 20 minutes.

Similar to the results reported in Publication II the movie viewing on the television
screen differed in many ways from the viewing experiences when an HMD-phone
system was used: TV viewing was physically less demanding and the participants were
less frustrated; there were fewer oculomotor symptoms, and the total symptom severity
level was lower (see Figures 3 and 4).
3.5.2.2 Connections between measured outcomes

Low symptom and demand levels were associated with a positive outcome and vice versa. Among other things, the total symptom severity correlated negatively with task pleasantness and opinion change. Participants with greater interest in technology were more accustomed to playing than were others, and those who played more experienced fewer symptoms of nausea than those who played less. The majority of participants were positively impressed by HMDs, regardless of whether they had used displays before.

3.6 Publication IV

Whitestone and Robinette (1997) defined the quality of fit as the degree to which a head-mounted system can accommodate any individual in a population. They cite four different ways to maximize the quality of a fit: a good proportion and shape of a single size; design features that broaden the accommodation range in a single size; having a range of adding sizes; and adding the ability to custom-make the system for individuals (cf. Task, 1997). However, it is also well known that the more adjustments that can be made, the more moving parts are required, which increases chance for component failure. Still, it has been recommended that some individual adjustments should be available to users, especially when binocular or binocular HMDs are used (ISO/FDIS 9241-303:2008(E). One of the main goals of Publication IV was to compare user experiences when aligned and non-aligned HMDs were used and try to connect the subjective outcomes with objective measures.

3.6.1 Methods

The same experimental setup and questionnaires were used as in Publications II and III (see Table 1). Participants viewed The Queen for 40 minutes, using either an aligned or a non-aligned eMagin HMD.
3.6.2 Results

Data analysis showed that the participants reported more severe nausea and an increase in total symptom severity levels when the non-aligned (adjustable) HMD was used (see Figure 3). Because vertical misalignment is almost nonexistent in the natural world, people have limited binocular ability to fuse slightly misaligned images (see Moffitt, 1997; Self, 1986). Large degrees of vertical misalignment have been connected with visual fatigue, eyestrain, diplopia, and monocular suppression. According to some authors, even small degrees of a display’s vertical misalignment may lead to visual fatigue and eyestrain, especially if the device is used for long periods. Since the most remarkable difference between setups was in the values of vertical misalignment (non-aligned, adjustable=1.3°; aligned, non-adjustable=0.0-0.2°), it seems plausible that differences between symptom levels were at least partly caused by differences in a display’s vertical misalignments.

In addition, participants from both test setups referred to the poor image resolution and unclear contours, and thus described the viewing experience as annoying. We therefore expected poor image quality to have some influence on reported eyestrain and/or oculomotor symptoms (e.g., Howarth, 1999; Howarth & Costello, 1997). However, comparisons of the tested HMDs (Publications II, III, IV, and Figure 3) did not reveal any significant differences in symptom levels, which could clearly be connected with blurred image quality. It might be that the questionnaires used in this study were not sensitive enough to detect small changes in symptom levels or that quality-related features do not necessarily induce symptoms, but do have an impact on the subjective viewing experience.
4 Discussion

4.1 Visually-induced motion sickness and eyestrain

As could be expected on the basis of earlier published results (e.g., ISO, 2008; Patterson, Winterbottom & Pierce, 2006; Howarth, 1999; Mon-Williams, Plooy, Burgess-Limerick & Wann, 1998; Aaltonen & Pölönen, 2009; Nichols, 1999; Merhi, Faugloire, Flanagan & Stoffregen, 2007; Howarth & Costello, 1997), a headset’s design, user- and task-related factors as well as problems with the optics in HMDs had an influence on HMD-related user experiences and outcomes (Publications I, II, III, IV).

All the viewing devices used in the tests induced either some eyestrain and/or sickness-related symptoms (see Figure 3). For example, reading for 40 minutes caused more sickness-related symptoms than playing or movie viewing when the same HMD was used. On the other hand, film viewing with some HMD models induced as many or even more symptoms than reading or game playing with other devices, while symptom levels from some setups were comparable to TV and phone outcomes.

Both mHMD positions caused eyestrain, but the position above the line of sight also increased oculomotor symptom levels. Thus, if we assume that the SSQ oculomotor symptom subgroup refers to the strain of ocular muscles, then it seems that the above position causes external symptoms in addition to the internal symptoms associated with accommodation and vergence systems and binocular vision (cf. Sheedy, Hayes & Engle, 2003; Sheedy, 2007).

Mean changes in symptom levels were low on average; the average increase in total symptom severity level was 1.2 symptoms (mean = 4.7, 1 symptom = 3.73), while the change in eyestrain levels was 0.9 symptoms (mean = 0.91, 1 symptom = 1) (SSQ profile for the data O>D>N; cf. section 1.3.2.1) (see Figure 5). On the basis of symptom level changes, it seems that using commercial binocular HMDs for up to 40 minutes is a comfortable experience for most of the users. A few people may have clear signs of visually-induced motion sickness and/or eyestrain, especially when applications with strong motion scenes are viewed. Thus, the symptom levels depend on the task, the HMD model, and the display’s position, but because of the variability between individual
Figure 5. Distributions of the changes of symptoms levels when before and after scores were compared (top = eyestrain, middle = oculomotor symptoms, bottom = total symptom severity). Negative values refer to a decrease in symptom levels; 0 means no change and a positive value increase in symptom levels.
symptom levels, it seems to be difficult to predict any symptom levels for single users even though the tasks, HMD model, and display positions are known.

Because the studies presented included no repetitions, generalization of the results to long-term continuous usage should be carefully considered (cf. Aaltonen & Pölönen, 2009; Stanney, Hale, Nahmens & Kennedy, 2003; Kennedy, Stanney & Dunlap, 2000). However, it is most probable that repeated use of the system will reduce the prevalence and severity of the symptoms through the process of habituation (e.g., Kennedy, Stanney & Dunlap, 2000; Howarth & Hodder, 2008; Howarth & Hill, 1999). It is likely that positions other than sitting will increase the reported symptom levels, but it is relatively unlikely that non-see-through commercial HMDs will be used in positions other than sitting (e.g., Jaeger & Mournat, 2001; Stoffregen, Faugloire, Yoshida, Flanagan & Merhi, 2008).

4.2 An HMD as an accessory to a handheld device

The use of HMDs as personal viewing displays and as accessories for small handheld multimedia devices affects user experiences and reported outcomes in various ways (Publication III; see Figures 3, 4, and 5). Playing games with an HMD phone system induced such symptoms as nausea, dizziness, and vertigo, which may also appear when other typical console games are played (cf. Biocca 1992; McCauley & Sharkey, 1992; Stoffregen, Faugloire, Yoshida, Flanagan & Merhi, 2008; Merhi, Faugloire, Flanagan & Stoffregen, 2007; Stanney, Kingdon, Graeber & Kennedy, 2002). Thus, when related game-playing symptoms were interpreted as part of the game’s nature, the participants reported an increase in the sense of presence compared with console-playing experiences, and they were more interested in the system use in the future. On the other hand, when no connections between playing and symptom levels were found, the participants were not interested in using the system, even though there were other possible uses for the system being tested.

In addition to more realistic playing experiences, the use of the HMD phone system may extend the duration of use. For example, according to subjective opinions, a suitable duration for playing on an HMD phone was almost twice as long compared with playing on a mobile phone display. Text reading from a small display for as long
as 40 minutes was an extremely demanding task, while using an HMD phone system up to 40 minutes was acceptable for most users. As might have been expected, the experiences reported varied according to the task: reading from an HMD display was more demanding and less pleasurable than film viewing or game playing. However, users’ opinions about HMDs changed in a more positive direction irrespective of the task or the workload level (see Figure 4).

In sum, an HMD phone system enables longer sessions and facilitates tasks that can be demanding to perform on small screens.

4.3 Adjustable versus non-adjustable HMDs

4.3.1 Bi-ocular HMDs

Self-adjustability may improve viewing experiences and/or increase headset physical ergonomics (cf. Nichols, 1999; Melzer & Moffitt, 1997). On the other hand, the same feature may unintentionally move other parts of the system and cause optical misalignments, which can degrade image quality and/or cause eyestrain and headaches (cf. Patterson, Winterbottom & Pierce, 2006; Self, 1986; Moffitt, 1997). Because most of the publications and recommendations concerning HMD adjustability are theoretical reviews, one of the goals was to find connections that in practice associate specific optical characteristics with specific subjective outcomes and experiences.

Comparison between non-aligned (adjustable) and aligned (non-adjustable) HMD setups (In Publication IV, see Figure 3) showed that the use of a non-aligned HMD increased the level of nausea and total symptom severity. Because the optical measurement of HMDs also revealed that along with IPD adjustment, the level of vertical misalignment increased, it seems credible that symptom levels were caused at least in part by changes in optical misalignment. In addition to increased symptom levels, participants evaluated the use of a non-aligned HMD as physically more demanding and frustrating compared with the use of an aligned HMD. Interestingly, the blurred image quality in both setups did not have any clear influence on reported eyestrain or sickness levels, even though it was described as annoying. The image quality of both setups was clearly scored lower than the image quality of other HMDs.
(see Figure 4) (cf. Lambooij, Ilsselsteijn, Fortuin & Heynderickx, 2009; Mon-Williams, Wann & Ruston, 1993; Howarth, 1999).

By contrast, the use of the diopter adjustable HMD\textsuperscript{11} did not cause any significant increase in eyestrain or sickness levels (see Figure 3) (Publication II). According to the optical measures, no optical mismatches between displays were found (see Table 2). As could be expected on the basis of symptom levels and optical measures, subjective opinions on visual quality and task pleasantness were also positive and supported the view that well designed and functional self-adjustable features may have a positive influence on user experiences.

User experiences with non-adjustable bi-ocular HMDs were in many ways comparable with the experiences of adjustable HMD setups (Publications II, III, IV): non-adjustable HMDs may have problems in display optics, which in turn may affect viewing comfort and users’opinions (see Table 2) (Publications II and IV; Aaltonen & Pöllönen, 2009).

Because we did not use any stereoscopic 3D presentations in our tests, it is probable that the same optical problems found in our tests, may have a much stronger influence on symptom levels when binocular HMDs are used (Patterson, Winterbottom & Pierce, 2006; Self, 1986; Moffitt, 1997; Ukai & Howarth, 2008; Kooi & Toet, 2004). On the other hand, benefits connected with an optical adjustability might be superior because of the sharper stereoscopic image quality.

4.3.2 Monocular HMDs

As with bi-ocular HMDs, a properly adjusted mHMD may increase viewing comfort and positive experiences (see Peli, 1990; Sheedy & Bergström, 2002; Sheedy, 2007) (Publications I and IV). Both display positions, that is, below and above the eye, induced some changes in phoria values, but because the changes between measures were small, they seem to have no clinical meaning (Publication I).

The position below the eye clearly caused fewer symptoms than the above positions. For example, increase in eyestrain symptom levels for the position below was on average 0.5 symptoms, while for the position above it was 1.5 symptoms; total

\textsuperscript{11} No need for personal glasses if glasses diopters are between +3.5D to –3.5D
symptom severity for the below position was negative, which means that on average participants reported fewer symptoms after the test than before, while for an above position there was on average an increase of 1.18 symptoms (cf. Sheedy, Hayes & Engle, 2003; Burgess-Limerick, Mon-Williams & Coppard, 2000). Interestingly, changes in symptom levels did not have an effect on the evaluated subjective opinions or task pleasantness. According to the participants’ comments, the task was easy, and it was possible to concentrate on animation, even though the dual task setup was used. It seems that on a general level, the use of an adjustable mHMD as a secondary information display in a peripheral position does not interrupt the performance of a primary task or decrease the viewing experiences when the presented stimuli are clearly visible and simple. Because changes in eyestrain and sickness levels are possible, the use of the below position should be favored if the position of the display can be adjusted and the position is reasonable for the context of use (cf. Peli, 1990).

In sum, the users of monocular as well as bi-ocular HMDs could benefit from display-related self-adjustable possibilities, especially when those features are well designed and functional. On the other, the benefits connected with bi-ocular HMDs are not always superior when compared with experiences from non-adjustable HMD setups. From the consumer’s point of view this means that bi-ocular HMD adjustability versus non-adjustability features alone do not define the quality of a device, but the significance of other HMD design factors should also be considered. With monocular HMDs the below the eye display position should be preferred whenever possible, but also the positions above the eye can be used if needed.

4.3.3 Headset fit

Despite the fact that a headset’s adjustability might improve the viewing experiences, most of the HMDs used were goggles without the possibility of headset fit adjustment (cf. Nichols, 1999). Only in one model was it possible to adjust the headset fit by tightening the tapes of the headband. However, according to the participants, the adjustment of the band was difficult and easily became too tight. Because of the nature of the HMDs used, it was not surprising to find that almost all the headsets had some fitting problems (see Figure 49. For example, some models were too tight, while some others were too loose, and all the models except the one with
adjustable glasses diopters were difficult to wear with personal eye glasses. A typical symptom associated with tight goggles was a “fullness of head,” which is a part of the disorientation subscale that refers to symptoms of vestibular disturbances.

4.4 Relationships between background factors and user experiences

All the individual background parameters and user experiences evaluated in Publications I, II, III, and IV were chosen because they have been shown to have some influence on user experiences (e.g., Kolasinski, 1995; Cobb, Nichols, Ramsey & Wilson, 1999; Nichols, 1999; Kennedy, Lane, Berbaum & Lilienthal, 1993; Howarth & Costello, 1997; Häkkinen, 2004; Lo & So, 2001; Viswanath, Morris, Davis & Davis, 2003; Hassenzahl, 2003; Hassenzahl & Roto, 2007). One of the goals in this thesis was to view different HMD experiences at a more comprehensive level: how different user experiences are connected with each other and which parameters are most useful in explaining variables if we want to understand experiences other than non-sickness-related ones (cf. Nichols, 1999; Cobb, Nichols, Ramsey & Wilson, 1999).

4.4.1 How task and device-related outcomes affect HMD-related opinions and decisions

As expected on the basis of the results in Publications I, II, III, and IV, several relationships among the evaluated user experiences were found: the lower the symptom and demand levels (frustration, effort, and physical demand), the higher the scores given to headset fit, visual quality, and task pleasantness (see Figure 6 and Appendix 2). In addition, users’ opinions changed into a more positive direction, and users were more interested in HMD use in the future (cf. Nichols, 1999; Viswanath, Morris, Davis & Davis, 2003; Hassenzahl, 2003).

At more detailed level, the good visual quality of the bi-ocular HMD seems to be connected with a positive change of opinion, increased task pleasantness, and better headset fit. The positive relationships between visual quality and headset fit probably refers to the situation where poor headset fit might cause the display to be misaligned
with the eye, which in turn may reduce image quality near the edges of the display and thus influence overall visual quality.

In addition to visual quality, better headset fit has a positive influence on task pleasantness and opinion change, but no connection with future interest was found. Thus, when someone use an HMD with good ergonomics and usability (light, no sharp edges) and the task as a whole is relatively easy and fun (task pleasantness), person’s options about an HMD will probably change positively, and the experiences will have some influence on device-related future decisions. However, we cannot say which relationships, parameters, or parameter combinations are more important if we try to predict future experiences.

### 4.4.2 How individual characteristics affect HMD-related experiences

Because commercial HMDs are in many ways more user friendly than ever, it could be expected that the significance of individual features as explanatory variables for HMD-related experiences, especially for eyestrain and visually induced motion sickness, has changed. To find out which individual characteristics are connected with evaluated
HMD use-related experiences, the data from bi-ocular HMD setups were examined (in Publications II, III, and IV).

The correlation analysis brought out many weak, but significant relationships between individual characteristics and the experiences evaluated (see Figure 7 and Appendix 2) (cf. Publications II, III). For example, the use of personal glasses with an HMD was described as annoying and connected with decreased headset fit (Publications II and III). No relationships between eye glasses and eyestrain or sickness symptoms were found; however, the use of eye glasses with an HMD seems to have a positive relationship on opinion change: a user’s opinions changed into a more positive direction when the user wore glasses during the task (cf. Nichols, 1999). This means that users will probably face some problems in the headset fit and ergonomics of HMD when eye glasses must be worn, but these experiences do not necessarily have a significant influence on other evaluated experiences.

As in earlier publications, here too gender and motion sickness susceptibility were found to have some effect on reported sickness symptom levels: women reported higher levels of oculomotor symptoms and nausea, while increased susceptibility to motion sickness was connected with increased total symptom severity (Kolasinski, 1995, 1996; Kennedy & Fowlkes, 1992; Hettinger & Riccio, 1992; Dobie, May, MsBride & Dobie Jr, 2001; Cheung & Hofer, 2003; Regan & Ramsey, 1994).

Because all the tasks were entertaining in nature and the participants were asked to perform only the tasks in the way they usually do them, negative relationships were found between, before, and after the task scores in nausea, disorientation, and oculomotor symptoms. On the basis of these relationships, we can assume that the use of HMDs as personal viewing devices does not necessarily interrupt the task performance significantly, and, similar to experiences with other displays, the viewing experience can be relaxing (see Figure 5). Older participants reported an increase in eyestrain levels and they were less interested in HMD use in the future as were participants who reported some nausea before the test. The participants who were used to playing games more often reported fewer oculomotor symptoms, disorientation, and total symptom severity. This is logical because frequent console game players are used to sessions of long durations and scenes containing strong motion scenes are often connected with increased
Previous experience with HMDs and VEas was found to have the most effect on evaluated HMD-related experiences. Similar to other studies, participants with more technology experience were more critical in their evaluations (cf. Jumisko-Pyykkö & Häkkinen, 2008). For example, users who had used both HMDs and VE systems before reported a significant increase in effort and physical demand levels; they were more frustrated, and their eyestrain, nausea, and oculomotor symptoms levels were higher compared with less experienced participants. In addition, their opinions changed less to a positive direction, which was also seen in the scores of task pleasantness, headset fit, and visual quality. One of the reasons why people with more experience were more
critical is probably that the HMD usage situation was compared with earlier experiences; if the expected change did not correspond to the advance expectations, it lowered the evaluation and vice versa (cf. Hassenzahl, 2003).

Similar to earlier results, our results support the view that several individual characteristics are important for explaining the variables for eyestrain, but especially for sickness (Kolasinski, 1995, 1996; Hettinger & Riccio, 1992; Regan & Ramsey, 1994; Nichols & Patel 2002; Kennedy & Fowlkes, 1992). However, the majority of relationships between individual characteristics and user experiences were weak, which at least partly indicates to strong variations between users’ experiences, especially in symptom levels (see Figures 3 and 5).

4.4.3 Task pleasantness, opinion change, and future interest: a more comprehensive approach

According to the results presented in sections 4.4.1 and 4.4.2, most of the experiences evaluated seem to have some connection with other experiences or with specific individual characteristics. However, it is difficult to say which parameters or parameter combinations are the most useful explanatory variables when a certain experience is being evaluated.

It is known that the eyestrain, SSQ, and NASA TLX are either task and/or system dependent questionnaires in a way similar to questions of headset fit and visual quality. Because we did not separate HMDs or tasks on the basis of different features (see sections 4.1 and 4.3), the models of those parameters will not be presented in this thesis. However, because one of our goals was to obtain a better understanding of how different experiences could be connected, task pleasantness, opinion change and future interest were modeled (for detailed results, see Appendix 3).
As Figure 8 shows, 38.6% of task pleasantness could be explained by frustration level, visual quality, total symptom severity, and physical demand levels. If we assume that pleasantness can be defined as a positive outcome triggered by positive emotional reactions that are related to a product’s appeal (e.g., Hassenzahl, 2003), then the same trend can be seen in our model: better visual quality (display characteristics) along with lower levels of frustration (headset fit), physical demand (headset fit) and oculomotor symptoms (display characteristics) predict a pleasanter outcome (cf. Figures 6 and 7).
According to the data, task pleasantness, HMD/VE experience, and visual quality explain 45.6% of HMD-related opinion change (see Figure 8). The model shows that participants’ opinions clearly changed to a more positive direction when the experience was thought to be pleasant and the visual quality of the stimuli was high. On the other hand, the previous experience level seems to have a negative influence on opinion change (cf. section 4.4.2). Because the test setups did not trigger strong negative reactions and the tasks used were entertaining, participants with no previous experience or only some previous experience were pleased as a result of the immersion, while the initial expectations of more experienced users were not realized because of the relatively small improvements in HMD technology and optics. This disappointment was seen in opinion change scores.

The explanatory variables used to model task pleasantness and opinion change were not useful in explaining HMD use-related, forward-looking interest; only opinion change seems to have had some influence on future interest, yet it explains only 3.9 percent of the forward-looking interest (see Figure 8).

Thus, it seems that most of the parameters used in this study have some impact on a user’s experiences when HMDs are used as personal viewing devices (cf. Hassenzahl, 2003; Hassenzahl & Roto, 2007). As in earlier publications, here too many single, user-related characteristics are still important parameters if we want to understand the vulnerability to sickness and eyestrain, even at relatively low symptom levels (Kolasinski, 1995, 1996; Kennedy & Fowlkers, 1992). But if we want to understand HMD use-related opinion change and future interest, the importance of other parameters must be emphasized.

However, it is possible that the importance of different explanatory variables may change relative to user experiences. For example, binocular HMDs may increase symptom levels; thus, the importance of a symptom level as an explanatory variable may also become important also in explaining variables such as future interest or opinion change.

Even though several HMD-related background factors and user experiences were employed to model future interest, it is clear that some important explanatory factors were missing from the setups. Because it is known that different personality traits, features, and motivations have an influence on psychological well-being, physical
health, people’s opinions, decisions, and behavior, based on our results, it appears that such variables will necessarily be added to a research framework if the goal is a more comprehensive examination of experiences (e.g., Deci, 1975; Ryan & Connell, 1989; Deci & Ryan, 1985; Ryan & Deci, 2000; Ryan & Deci, 2002; Deci & Ryan, 2008; Goldberg, 1990; Lindfors & Lundberg, 2002; Viswanath, Morris, Davis, & Davis, 2003).

4.5 Limitations of the results presented

Because one of our targets was to keep all the experimental setups used comparable to real-life situations, the data collected came mostly from self-reported measures. Such measures may be influenced by social desirability biases, but according to our previous results, self-reported measures can be reliable and can provide even more information than some complex measurement systems (cf., Häkkinen, 2004; Häkkinen, Puhakka, & Vuori, 2002; Pölönen, Salmimaa, Aaltonen, Häkkinen, & Takatalo, 2009; Young, Adelstein, & Ellis, 2006). Additionally, the use of validated questionnaires is a reliable, fast, comfortable, and inexpensive way to gather information. The method can be used in different contexts with different user groups by people representing different professions, yet who are working with the same topic. Some user experiences were studied although the answers from single questions. It is clear that the use of validated questionnaires would have been a more appropriate way to get information, but because of participants’ time limits, it was better to use simple single questions rather than to have no knowledge of the subject.

Since we used only bi-oocular and monocular systems with relatively easy tasks, it is possible that user experiences are different when more demanding tasks or binocular HMDs are used. However, the measured user experiences and individual characteristics are also useful variables if we want to study other HMD modes and tasks.

Because external loudspeakers were used for hygienic reasons, we cannot say how much the different audio options affect HMD-related experiences and outcomes. Even though it is rather certain that the use of advanced audio options may increase the sense of presence and task pleasantness (Turku, Vilermo, Seppälä, Pölönen, Kirkeby, Kärkkäinen, & Kärkkäinen, 2008).
Finally, all the participants were workers in technology company in Finland, although they represented very different positions. Further studies using different age groups, people from different cultural contexts, and setups with long-term repeated usage may increase the validity of the presented results and add new perspectives to the current knowledge.
5 Conclusions

Over the years, several factors have been shown to have an influence on the usability of HMDs and the experience of sickness. Some of these factors have been studied in depth, while others have been connected with HMD user-related experiences only on the basis of theoretical considerations. Moreover, because of the variability in the setups and the parameters studied, it has been difficult to generalize results to other setups or predict future outcomes based on them.

All the commercial HMDs tested induced some eyestrain and sickness-related symptoms, but the symptom levels were low, and viewing experiences with some HMDs are already comparable to experiences connected with other displays. A few users may feel disoriented or nauseous, but when the experience is interpreted as part of the characteristic outcome associated with a specific task, it may have a positive influence on a user’s opinions and on his forward-looking interest. An HMD as an accessory for a small handheld device may increase viewing comfort, the sense of presence, and the realism of the context of use, which in turn may afford longer durations in the use and performance of tasks, which are demanding and difficult to carry out on small-size displays.

Self-adjustable HMDs may increase viewing comfort, especially when monocular devices are used. Benefits connected with bi-ocular HMD adjustability are less unambiguous, but when the device adjustability is well designed and functional they probably increase users’ experiences.

As in earlier publications, our results too showed that single individual features are useful in explaining variables if we want to understand the experiences related to eyestrain and sickness, even when the reported symptom levels are low. On the other hand, a more comprehensive examination of HMD-related experiences also requires knowledge of user motivations, personality, and other more stable features.

In summary, the present commercial monocular and bi-ocular HMDs are comfortable displays, which can be used for many tasks in various contexts. Playing games, watching movies, reading documents, surfing the Internet, or participating in video meetings are just some example of the uses for which HMDs are suitable, in contexts such as trains, buses, or airplanes. As with other displays, frequent breaks and avoiding
long viewing sessions help to assure comfortable, positive, and enjoyable user experiences.
References


Appendix 1

Questions that were examined in more detail Publications I, II, III, and IV.

Background information:
- Gender
- Age
- Previous experience with HMDs and VE systems (yes, no)
- Weekly computer use (in hours)
- Playing frequency (never, rarely, sometimes, often)
- Close work done before the test (in hours)
- Vulnerability to motion sickness (never, rarely, sometimes, often)
- Eye glasses (yes, no)
- Diagnosed migraine (yes, no)
- Headache susceptibility (never, rarely, sometimes, often)
- Health state before the test (normal, good, flu, stomach trouble, tired, allergy symptoms, stressed, something else)
- Domain specific innovativeness (DSI; Goldsmith & Hofacker, 1991). A scale for measuring consumer innovativeness directly or to gauge the tendency of consumers to be among the first to try new items in a specific product field after the products have appeared on the market.

Eyestrain questionnaire (VSQ; adapted from Howarth & Istance, 1985) (scale: none, slight, moderate, severe):
- Tired eyes
- Sore or aching eyes
- Irritated eyes
- Watering or runny eyes
- Dry eyes
- Hot or burning eyes
- Blurred vision
- Double vision
- General visual discomfort

Simulator sickness questionnaire (SSQ; Kennedy, Lane, Berbaum & Lilienthal, 1993) (scale: none, slight, moderate, severe)
Nausea (N, weight 9.54), disorientation (D, weight 7.58), oculomotor symptoms (O, weight 13.92). Subscales provide more specific information about the nature of the sickness. Total symptom severity score is a sum of N, O, and D (weight 3.74) and reflects the overall discomfort level.
- General discomfort: N O
- Fatigue: O
- Headache: O
- Eye strain: O
- Difficulty focusing: O D
- Increased salivation: N
- Sweating: N
- Nausea: N D
- Difficulty concentrating: N O
- "Fullness of the head": D
- Blurred vision: O D
- Dizzy (eyes open): D
- Dizzy (eyes closed): D
- Vertigo: D
- Stomach awareness: N
- Burping: N

NASA Task Load Index (NASA TLX; Hart & Staveland, 1988) (scale: 0-100)
A scale for assessing subjective workload (i.e., a collection of attributes that may or may not be relevant in controlling assessments and behavior). The questionnaire measures the level of six different task load factors (performance, effort and frustration, mental, physical, and temporal). Because of the nature of the test setups used, only three workload factors (associated with HMD use) were used in the final analysis.

- Effort (How hard did you have to work [mentally and physically] to achieve your level of performance?)
- Frustration level (How insecure, discouraged, irritated, stressed, annoyed versus secure, gratified, content, relaxed, complacent did you feel during the task?)
- Physical demand (How much physical activity was required?)

User experience questions:
- Opinion change after the use of an HMD (1/Clearly more negative, 2/Somewhat more negative, 3/No change, 4/Somewhat more positive, 5/Clearly more positive)
- Evaluated task pleasantness (i.e. task performance with HMD X) (5/Very pleasant, 4/Quite pleasant, 3/Neither pleasant nor unpleasant, 2/Quite unpleasant, 1/Very unpleasant)
- Visual quality (1/Very poor, 2/Rather poor, 3/Moderate, 4/Rather good, 5/Very good)
- Overall headset fit (1/Very poor, 2/Rather poor, 3/Moderate, 4/Rather good, 5/Very good)
### Appendix 2

Significant correlations (Kendall’s tau-b) between visual quality, pleasantness, opinion change, effort, frustration, physical demand, total symptom severity, eyestrain, and future interest. * \( p<0.05 \), ** \( p<0.01 \)

<table>
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<tr>
<th></th>
<th>Pleasantness</th>
<th>Visual quality</th>
<th>Opinion change</th>
<th>Physical demand</th>
<th>Effort</th>
<th>Frustration</th>
<th>Total symptom severity</th>
<th>Visual strain</th>
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<td>Opinion change</td>
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<td>-0.232**</td>
<td>-0.298**</td>
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<td>-0.554**</td>
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<tr>
<td>Physical demand</td>
<td>-0.301**</td>
<td>-0.462**</td>
<td>-0.594**</td>
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<td>-0.145**</td>
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<tr>
<td>Effort</td>
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<td>-0.594**</td>
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<tr>
<td>Frustration</td>
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<td>-0.594**</td>
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<tr>
<td>Total symptom severity</td>
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<td>-0.462**</td>
<td>-0.594**</td>
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<td>-0.145**</td>
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<td>Visual strain</td>
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<td>Future interest</td>
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Significant correlations between background parameters and user experiences. * \( p<0.05 \), ** \( p<0.01 \)
Appendix 3

A linear regression stepwise method was used to analyze the parameter sets.
LN LOG transformation was used for frustration, effort, and physical demand scores.
LN LOG transformation (total symptom severity+20) was used for total symptom severity scores.

**Pleasantness**
Parameters used in stepwise analysis: LOG frustration, LOG effort, LOG physical demand, experience level, eyestrain level, visual quality, headset fit, eye glasses, motion sickness, playing, DSI, age, LOG total symptom severity, and gender.

Task pleasantness=5.963–LOG frustration×0.227+Visual quality×0.024–LOG total symptom severity×0.607–LOG physical demand×0.132
($R^2=0.386$, Adjusted $R^2=0.373$, $p<0.001$, $F(4;186)=28.64$)

<table>
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<td>4.229</td>
<td>1</td>
<td>182</td>
<td>.042</td>
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</tbody>
</table>

a. Predictors: (Constant), LOG frustration
b. Predictors: (Constant), LOG frustration, Visual quality
c. Predictors: (Constant), LOG frustration, Visual quality, LOG total symptom severity
d. Predictors: (Constant), LOG frustration, Visual quality, LOG total symptom severity, LOG physical demand
e. Dependent Variable: Pleasantness

**Opinion change**
Parameters used in stepwise analysis: LOG frustration, LOG effort, LOG physical demand, experience level, eyestrain level, visual quality, headset fit, eye glasses, motion sickness, playing, DSI, age, LOG total symptom severity, gender, and pleasantness.

Opinion change=0.907+Pleasantness×0.470+ Visual quality×0.337–Experience×0.184
($R^2=0.456$, Adjusted $R^2=0.447$, $p<0.001$, $F(3;186)=51.205$)
Future interest

Parameters used in stepwise analysis: LOG frustration, LOG effort, LOG physical demand, experience level, eyestrain level, visual quality, headset fit, eye glasses, motion sickness, playing, DSI, age, LOG total symptom severity, gender, pleasantness, and opinion change.

Future interest = 3.904 + Opinion change * 0.376

\( R^2=0.039, \text{ Adjusted } R^2=0.034, \ p<0.01, \ F(1;185)=7.47 \)