Considering Ergonomic Aspects of Head-Mounted Displays for Applications in Industrial Manufacturing

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Abstract. In this paper, we apply a comprehensive approach to evaluate and analyze potential physiological and subjective workload effects of the application of head-mounted displays (HMDs) during a typical 3.5 hrs assembly operation. The approach refers to physical as well as cognitive workload associated with HMDs. The methods for capturing and determining physiological workload include an analysis of visual acuity, of visual field, electromyography (EMG), and general posture analysis (OWAS). Subjective ratings for overall workload (BLV, RSME) and simulator sickness (SSQ) are considered and analyzed in order to complete the analysis. Their feasibility and practical implementations are discussed based on the results of a pre-test with a smaller sample size in order to give recommendations for their practical use during on-going experiments and for future industrial applications.

Keywords: Head-mounted displays, ergonomics, physiological measures, strain, electromyography, visual field, BLV, SSQ.

1 Introduction

A rapidly advancing technological evolution of novel, small and bright displays has led to novel head-mounted displays (HMDs). In addition to specialized futuristic applications, present HMDs have become increasingly applicable for multiple industrial applications. They facilitate a context-specific integration of relevant instructional information within the primary field-of-view while the user is able to continue the primary task of manufacturing. This reduces the need for an active, spatial and thus disturbing shift between a manufacturing task on the one hand and work instructions on supplementary media (paper/screen) on the other. In addition to this, both hands are available for ambidextrous work and employees are not required to interact with supplementary paper or computer media. As a consequence, critical postures resulting in additional physiological workload, reduced performance and occupational diseases may also be reduced. Moreover, assembly or manufacturing personnel, for example, can be substantially relieved during their work.

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On the other hand, certain HMDs come along with negative side effects, which may result in poor task performance. They include technical design issues (e.g. peripheral obstructed view and muscle tension caused by inconvenient weight distribution) as well as perceptive/cognitive aspects of information representation on HMDs (e.g. information overload caused by comprehensive additional information). Several empirical studies have already investigated aspects for typical navigation and orientation tasks. In order to address practical aspects of HMD usage in a manufacturing context by giving recommendations which aim at a secure and strain optimal usage, it is required to investigate the interplay of measures which are able to capture substantial strain dimensions.

1.1 Head-Mounted Displays

Head-mounted displays generally consist of one or two displays and an optical module positioned in front of the eye(s) by a special head support or a helmet. By providing one screen per eye, binocular HMDs, as opposed to monocular HMDs, enable a stereoscopic, three-dimensional view. The optical modules shift the focus of the virtual image several meters in front of the users' eye. Hence, the virtual surface size increases [1]. HMDs can be classified by their transparency (See-through/Lookaround [2], [3]). A See-through HMD projects the image via a semitransparent mirror into the user's field of view, while a closed or Lookaround HMD excludes the real background. In some cases transparent HMDs are equipped with an opaque slider to close the semitransparent mirror in order to hide too bright or disturbing backgrounds.

In most cases the HMD reduces the natural human field of view to 20-40°. This is especially important for closed HMDs [4], [5]. Furthermore, display electronics of See-through HMDs are often fixed at the side, which likewise obstructs the field of view. Another restriction of See-Through HMDs consists in visual information that overlaps relevant real world objects [6], [7]. For the practical use limited luminosity (for white: max. 1.800 cd/m²) and low contrast (contrast: 300:1) of the screens, complicates outdoor (ca. 8.000 cd/m² overcast sky) usage of HMDs.

1.2 An Ergonomic Viewpoint

A comprehensive analysis of workload starts by defining the concept of stress and strain. Both are different from each other with respect to their relation to the human operator [8]. Strain is usually defined as objective, neutral dimension acting from the outside on the human. Stress describes the effect of this dimension on the human operator and can be observed at different levels: the physiological, verbal-subjective, and action level. [9] point out that several indicators for the different dimensions of strain are required. [10] e.g. suggest the following terms as ergonomic evaluation criteria for HMDs: human performance, strain, fatigue, and the occurrence symptoms of simulator sickness. Simulator sickness itself is often observed with closed HMDs [11]. Impairments of the visual system and headache during or after exposure were additionally observed for 92% of the examined sample. Further studies investigating physiological effects of HMD usage particularly focused on the visual system. Different types of perceptual disorders like i.e. wrong depth perception, defective estimations of height and inclination as well as incorrect movement perception were also observed. Similar deficits were found for helicopter pilots using HMDs [12]. These results were also supported by [13] when using binocular HMDs. Other implications of HMD usages are accommodation errors by accommodative spasms and current, instrument induced myopia [14]. It is unclear how these effects change during long-term use. Differences between a binocular HMD and conventional displays could not be identified by [15], the symptoms only appeared with monocular HMD. [16] considered the interplay of the eyes, the visual overlay, focus depth, position of the eyes as well as eye movement and dominance, related to the use of a monocular HMD. The interaction of both eyes (mono-/binocular) and visual overlay (dynamic / static background) affected task time to a greater extent. Transparent HMDs are consequently not suitable for dynamic and complex environments where visual attention is particularly important. [17] showed that navigation and orientation tasks conducted with HMDs produced higher values for the symptoms of the simulation sickness than with a handheld display, while the performance measured through task time was better. Similar experiments comparing a conventional display with a head-mounted display could not verify differences between displays, but also showed higher values for simulator sickness symptoms. Furthermore the subscales fatigue and strain of the BLV (Belastungsverlaufstest, test for temporal change of workload) increased if performed with an HMD [18]. Negative side effects of an HMD on strain, fatigue and simulator sickness were confirmed by [19]. Furthermore, they found that sight might be restricted by the HMDs display box and hence, stimuli within the peripheral field of view could easily be overlooked, so that the peripheral awareness decreases.

An application of HMDs for industrial manufacturing has only become possible for the last few years. Previously HMDs were predominantly utilized for futuristic applications in augmented or virtual reality implementations. Contemporary usage increasingly incorporates areas like assembly, maintenance, picking or system surveillance [20]. As a consequence users are wearing the HMD longer and more frequent and as part of demographic change a higher percentage of elderly becomes part of the user group [21]. Ergonomic approaches have to take this into account.

2 Method

The present work refers to a pretest analyzing the interrelationship between different physiological and subjective methods for determining workload. They are applied to test the occurrence of long-term effects of different types of HMD (See-through [HMD-ST] and Look Around [HMD-LA]) and a conventional flat screen during an experimental 3.5 hour manufacturing scenario (independent variable). The methods include measures and analysis of variables like task time, subjective workload, posture, symptoms of simulator sickness, muscle activity, visual acuity and perimetry (dependent variables).

In total, two female and four male subjects aged 22-54 years (M = 32 years, SD = 11.5) took part in the preliminary test. All of them had normal or corrected to normal sight. According to the Ishihara test [22] none of them suffered from dyschromatopsia, as well as none of them had any experience with HMDs.

Participants indicated their previous experience with assembly work on a 5-point scale (1 = no experience, 5 = long experience) with 2.33 (s = 1.21) on average, which is a medium experience level.

The experimental task consists of four working segments with duration of 48 minutes each during which the participants perform different maintenance tasks. After finishing each maintenance task segment they rate their mental effort and rest for 10 minutes. Tasks include assembly operations at an Opel Omega B X20SE engine, carburetor, starter and alternator. Instructions are sequentially displayed and illustrated by means of a virtual 3D engine model and photos. In addition textual guidance is given. The engine is mounted on a height-adjustable lifting table. Tools were handed to the participant to minimize distractions and reduce unwanted side effects.

3 Results

The results of the pre-test were used for a first evaluation and test of the experimental setup. It needs to be emphasized that they must be put into perspective of the small sample size.

3.1 Visual Acuity

Visual acuity did not change after performing the experimental task conducted with distinct display types. There were no differences found for the conventional screen (left eye: Mw = 1, right eye: Mw = 1), the HMD-ST (left eye: Mw = 0.8, right eye: Mw = 0.8) or the HMD-LA (left eye Mw = 1; right eye Mw = 1).

3.2 Visual Field

The mean defect on both eyes increases with the conventional screen and decreases with the HMD (see: fig. 1). Independent of exposure, the changes (positive as well as negative) appear to be stronger on the right than on the left eye. This might be explained by the order of examination or by the small sample size. The defect of the participant with the HMD-ST (left eye: -2.2 dB, right eye: -5.3) also increases stronger than the one with the HMD-LA (left eye: - 0.1 dB, right eye: - 0.5 dB).

Table 1. Mean value of the Mean Defect (MD) [dB] of the left and the right eye before and after the task depending on display type

	MD (dB) left eye (Mw)		MD (dB) right eye (Mw)	
Condition	before	after	before	after
S (n = 2)	2,6	3,3	1,5	4,7
HMD-ST (n = 1)	4,7	2,5	8,3	3
HMD-LA (n = 3)	2,7	2,7	2,6	2
Total (n = 6)	3	2,9	3,1	3

3.3 Performance

Apart from working segment two, where the participants with the conventional screen (S) completed the task faster than the other groups, the participant with the HMD-ST was the fastest.

Table 2. Mean value of task time (min.) depending on display type within working segments

Segment		n	mean
WS 1	S	2	34,74
	HMD-ST	1	31,93
	HMD-LA	2	35,12
	Total	5	34,33
WS 2	S	2	34,52
	HMD-ST	1	45,96
	HMD-LA	2	43,10
	Total	5	40,24
WS 3	S	2	19,45
	HMD-ST	1	19,15
	HMD-LA	2	21,26
	Total	5	20,11
WS 4	S	2	36,15
	HMD-ST	1	26,55
	HMD-LA	2	34,69
	Total	5	33,64

3.4 Posture Analysis

The items "head tilted to one side" and "head tilted back" did not occur during the video based posture analysis OWAS (Ovako Working Posture Analysis System). HMD a slightly smaller proportion (Mw = 70.5%) of all head positions is classified as "free" than with the screen (Mw = 72.5%). A slightly larger proportion of the head of the group with HMD (Mw = 28.75%) falls into the category "tilted forward". The results follow a presumed track that unfavorable head positions may happen during HMD use. If this is a relevant effect will be shown by the analysis of a larger sample in the course of the main study.

3.5 Muscle Activity

Fig. 1 shows the normalized, bilateral muscle activity (%MVE, %RVE) of the neck muscles M. Trapezius pars descendens (LTRAP [left], RTRAP [right]), M. Sternocleidomastoideus (LSCM, RSCM) and M. splenius capitis (LSPLN, RSPLN), depending on display type and working segments. At the M. splenius capitis the highest

Table 3. Data sets (n) per muscle within working segments depending on display type

Muscle	RSPLN				LSPLN				RTRAP				LTRAP				RSCM				LSCM			
Segment	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
HMD	4	4	3	3	4	4	3	3	4	4	4	4	4	4	4	4	4	4	3	3	4	4	3	3
Screen	2	2	2	1	2	2	2	1	2	2	2	1	2	2	2	1	2	2	2	1	2	2	2	1
Sum	6	6	5	4	6	6	5	4	6	6	6	5	6	6	6	5	6	6	5	4	6	6	5	4

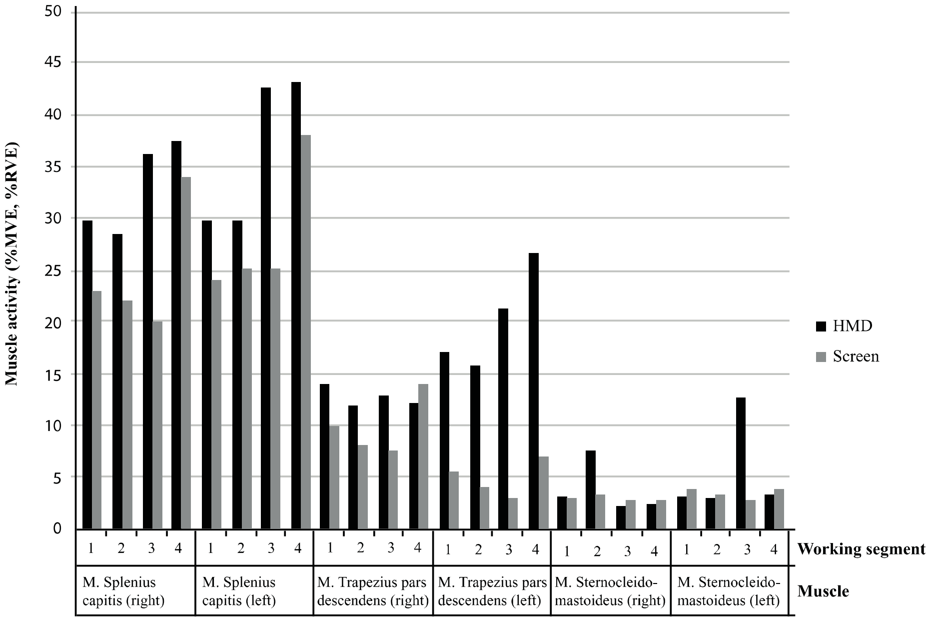

Fig. 1. Muscle activity (%MVE, %RVE) within working segments depending on display type

muscle activity is observed independent from display and working segment. The biggest difference between HMD and screen can be observed at the left side of the M. Trapezius pars descendens and on both sides of the M. splenius capitis. Muscle activity of the LSPN, RSPLN and LTRAP considerably goes up towards the end of the entire experimental task passed with the HMD.

3.6 Mental Effort

The RSME value describes subjective perceived mental effort on a scale from 0 to 150. It was surveyed as a starting point before the experimental task and during the individual working segments. As a result there are five evaluation points for all display types, which show an increase from the initial value to the second one. This demonstrates that the RSME is sensitive towards the stress. During all remaining four segments no interpretable trend or further increase revealed. The striking difference between HMD-LA and the other conditions are likely due to individual rating differences, since they also occur at the beginning.

3.7 Simulator Sickness

Comparing the simulator sickness scores measured before and after the task, interesting tendencies show up. Nausea values increase for all display types but slightly more under HMD-ST exposure (n=1; BS: 0 to 9,54; HMD-ST 0 to 19,08; HMD-LA 9,54 auf 28,62). Values of the oculomotor and disorientation scale go up within the HMD group while the ones of the screen group go down, so the results indicate the expected direction, even if to a limited extend. Further interpretation is not appropriate given the small sample size.

3.8 Subjective Perceived Strain

The BLV scores appear to be controversial and difficult to interpret. In general, all scores are on a low level. Achievement motivation values before (1,67) and after (2,67) the task only increased for the HMD-LA, which could be interpreted as a decrease in motivation caused by the experimental task. Fatigue shows across all groups a slight increase, while the rating of the performance item increases less intense with conventional screen and HMD-ST than with the HMD-LA (screen: 2,0 to 2,5; HMD-ST: 1 to 1,5; HMD-LA: 1,67 to 3,83). Mental strain shows a decrease in the screen condition at the end of the experiment (1.5 to 1.0), while the HMD-LA emerges a moderate increase (1.0 to 1.83).

4 Discussion

Conducted pre-tests were aimed at evaluating the interplay and applicability of a set of subjective and objective methods towards a comprehensive view of industrial long-term usage of HMDs. During a 3.5 h manufacturing task different physiological methods were applied. Questionnaires examined simulator sickness and workload. They all were, as expected, sensitive towards capturing workload parameters. The results provide a first impression of what might be expected from the main experiment data. Yet, results have to be evaluated in view of the fact that in total n=6 took part in the experiments, which lead to a group size of n=1 for the HMD See-through group, n=3 for the HMD Lookaround and n=2 for the conventional screen group. Certainly we are not interpreting the data to derive conclusions about strain caused by HMD usage; instead we want to learn which measures are worthwhile for further considerations or which need improvement for their application.

The experimental task consisting of 3.5 hours manufacturing assignments was easily conducted by manufacturing experts and novices. Some minor changes in the 3D engine model had to be implemented in order to prevent misunderstandings. Few textual instructions had to be formulated more precisely and subtasks had to be shortened so as to avoid mental underload.

Subjective and objective methods plus experimental task smoothly pooled into the entire experimental procedure, even if the sum of all inquiries prolongs the total test time. Some participants reported dwindling motivation during the tests and it cannot be precluded that this does not influence results; so before further experiments, load caused by the experiment itself needs to be minimized.

With respect to objective strain measures, visual acuity, mean defect of the visual field, task time and head-posture were analyzed. Alterations of visual acuity were not found. However, the measurement is based on law requirements for capturing visual acuity to determine whether a person is able to operate machinery or vehicles. It might be possible that very small changes cannot be detected in this way, but it is questionable how relevant these changes would be for a practitioner. This research focuses on a practically relevant approach.

The muscle activity was captured by electromyographic data acquisition of the M. Trapezius pars descendens, M. Sternocleidomastoideus und M. Splenius capitis on the left and right side. Until now, little was known about which muscles are strongly affected or causing headache by HMD usage during manufacturing work. Since muscle activity highly depends on hardware and work task, initially all neck muscles accessible by surface electromyography were measured in order to determine a focus based on pre-test results. Neck muscles are characterized by superposition of individual muscle layers. Usually muscle activities in those areas are gathered by fine wire electrodes to enhance signal quality, but in order to relieve participants and due to ethical reasons, this approach was disregarded. Results suggest that the M. Trapezius pars descendens and M. Splenius capitis are relevant to consider. Their activity increases towards the end of the task and increasing muscle activity might indicate muscular fatigue. Additionally a clear difference between the HMD group and the conventional display group showed up. One explanation for this could be the M. Splenius capitis' attempt to antagonize the main weight on the front part of the head (HMD). Unfortunately EMG measurements require high compliance of the participants and require some additional steps for preparation. The need to shave the neck could discourage participants to take part in the experiments. In addition EMG requires controlled temperature conditions and adequate clothing to prevent transpiration, because it makes electrodes break loose from the skin. The results concerning the visual field of the participants are also relevant. While the mean defect (dB) increases within the conventional screen group, it increases within the HMD-group. The fact that even very young participants show a defect prior to the experimental task, suggests that the method and its execution (cooperation/ concentrativeness of the participant) have a strong influence on the data. It is well worth considering if the method can be categorized as an objective one.

All methods proved to be suitable for this specific application of long-term strain evaluation during the use of HMDs. In terms of total experiment time and the participants motivation during the tests one can advise against the inflationary use of tests before and after the experimental task. It is deeply interesting if findings of ongoing main experiments are going to reflect pre-test results, and how they compare to similar experiments about workload during long-term HMD usage [23].

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