Development of a Multimodal, Universal Human-Machine-Interface for Hypovigilance-Management-Systems

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Geleitwort der Herausgeber

Über den Erfolg und das Bestehen von Unternehmen in einer marktwirtschaftlichen Ordnung entscheidet letztendlich der Absatzmarkt. Das bedeutet, möglichst frühzeitig absatzmarktorientierte Anforderungen sowie deren Veränderungen zu erkennen und darauf zu reagieren.

Neue Technologien und Werkstoffe ermöglichen neue Produkte und eröffnen neue Märkte. Die neuen Produktions- und Informationstechnologien verwandeln signifikant und nachhaltig unsere industrielle Arbeitswelt. Politische und gesellschaftliche Veränderungen signalisieren und begleiten dabei einen Wertewandel, der auch in unseren Industriebetrieben deutlichen Niederschlag findet.

Die Aufgaben des Produktionsmanagements sind vielfältiger und anspruchsvoller geworden. Die Integration des europäischen Marktes, die Globalisierung vieler Industrien, die zunehmende Innovationsgeschwindigkeit, die Entwicklung zur Freizeitgesellschaft und die übergreifenden ökologischen und sozialen Probleme, zu deren Lösung die Wirtschaft ihren Beitrag leisten muss, erfordern von den Führungskräften erweiterte Perspektiven und Antworten, die über den Fokus traditionellen Produktionsmanagements deutlich hinausgehen.

Neue Formen der Arbeitsorganisation im indirekten und direkten Bereich sind heute schon feste Bestandteile innovativer Unternehmen. Die Entkopplung der Arbeitszeit von der Betriebszeit, integrierte Planungsansätze sowie der Aufbau dezentraler Strukturen sind nur einige der Konzepte, welche die aktuellen Entwicklungsrichtungen kennzeichnen. Erfreulich ist der Trend, immer mehr den Menschen in den Mittelpunkt der Arbeitsgestaltung zu stellen – die traditionell eher technokratisch akzentuierten Ansätze weichen einer stärkeren Human- und Organisationsorientierung. Qualifizierungsprogramme, Training und andere Formen der Mitarbeiterentwicklung gewinnen als Differenzierungsmerkmal und als Zukunftsinvestition in Human Resources an strategischer Bedeutung.

Von wissenschaftlicher Seite muss dieses Bemühen durch die Entwicklung von Methoden und Vorgehensweisen zur systematischen Analyse und Verbesserung des Systems Produktionsbetrieb einschließlich der erforderlichen Dienstleistungsfunktionen unterstützt werden. Die Ingenieure sind hier gefordert, in enger Zusammenarbeit mit anderen Disziplinen, z. B. der Informatik, der Wirtschaftswissenschaften und der Arbeitswissenschaft, Lösungen zu erarbeiten, die den veränderten Randbedingungen Rechnung tragen.

Die von den Herausgebern langjährig geleiteten Institute, das

- Fraunhofer-Institut für Produktionstechnik und Automatisierung (IPA),
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- Institut für Industrielle Fertigung und Fabrikbetrieb (IFF), Universität Stuttgart,
- Institut für Arbeitswissenschaft und Technologiemanagement (IAT), Universität Stuttgart

arbeiten in grundlegender und angewandter Forschung intensiv an den oben aufgezeigten Entwicklungen mit. Die Ausstattung der Labors und die Qualifikation der Mitarbeiter haben bereits in der Vergangenheit zu Forschungsergebnissen geführt, die für die Praxis von großem Wert waren. Zur Umsetzung gewonnener Erkenntnisse wird die Schriftenreihe „IPA-IAO – Forschung und Praxis“ herausgegeben. Der vorliegende Band setzt diese Reihe fort. Eine Übersicht über bisher erschienene Titel wird am Schluss dieses Buches gegeben.

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Engelbert Westkämper   Hans-Jörg Bullinger   Dieter Spath

Vorwort

Die vorliegende Arbeit entstand während meiner Tätigkeit als wissenschaftlicher Mitarbeiter am Institut für Arbeitswissenschaft und Technologiemanagement der Universität Stuttgart (IAT) und am Fraunhofer-Institut für Arbeitswirtschaft und Organisation (IAO).

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Stuttgart, August 2007 Lorenz Hagenmeyer

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Abbreviations

Abbreviation	Description
A	Ampère (electrical current unit)
ABM	Advanced Brain Monitoring Incorporation
ACARP	Australian Coal Association Research Program
AG	Arbeitsgruppe [Engl.: *work group* or *unit*]
a.m.	after midnight, before noon [latin: *ante meridiem*]
ARRB	Australian Road Research Board
ASTiD	Advisory System for Tired Drivers
ATIS	Advanced Traveler Information Systems
AWAKE	System for Effective Assessment of Driver Vigilance and Warning According to Traffic Risk Estimation
BAN	Body Area Network
bzw.	beziehungsweise [Engl.: *respectively*]
CEPA	Centre d'Etudes de Physiologie Appliquée [Engl.: *Center for Studies of Applied Physiology*]
CERTH	Centre of Research and Technology Hellas
CNC	Computerized Numerical Control
CNRS	Centre National de la Recherche Scientifique [Engl.: *National Centre for Scientific Research*]
COAT	Center of Applied Technologies in Neuroscience
CSIRO	The Commonwealth Scientific and Industrial Research Organisation
ctd.	continued
CVO	Commercial Vehicle Operations
DC	DaimlerChrysler
DGSM	Deutsche Gesellschaft für Schlafforschung und Schlafmedizin [Engl.: *German Society for Sleep Research and Sleep Medicine*]
DIM	Driver Information Module
DIN	Deutsche Industrie Norm [Engl.: *German Industrial Norm*]
DMD	Drowsiness Monitoring Device
DVI	Driver Vehicle Interface
EC	European Communion
EDA	Electrodermal Activity
EDR	Electrodermal Reaction
EDVTCS	Engine Driver Vigilance Telemetric Control System
EEPROM	Electrically Erasable Programmable Read-Only Memory
EN	Euro Norm
Engl.	English
ESoP	European Statement of Principles

Abbreviation	Description
ESS	Epworth Sleepiness Scale
ESP	Electronic Stability Program
EUR	Euro
EEG	Electro Encephalogram
e.g.	for example [Latin: *exempli gratia*]
FP	Frame Program
GAU	Größter Anzunehmender Unfall [Engl.: *worst case scenario*]
GDV	Gesamtverband der Deutschen Versicherungswirtschaft [Engl.: *Association of German Insurers*]
ggf.	gegebenenfalls [Engl.: *as the case may be*]
GSR	Galvanic Skin Resistance
H	Kruskal-Wallis-H
HCI	Human Computer Interaction
HDM	Hypovigilance Detection Module
HF	Human Factors
HIT	Hellenic Institute of Transportation
HM	Hierarchical Manager
HMC	Human Machine Communication
HMI	Human Machine Interface
HVMS	Hypovigilance-Management-System
IAO	Institut für Arbeitswirtschaft und Organisation [Engl.: *Insitiute for Industrial Engineering*]
IAT	Institut für Arbeitswissenschaft und Technologiemanagement [Engl.: *Institute for Human Factors and Technology Management*]
IFT	Institut für Fertigungstechnik [Engl.: *Institute of Production Engineering*]
INESC	Instituto de Engenharia de Sistemas e Computadores [Engl.: *Institute of System and Computer Engineering*]
IP	Internet Protokoll/Integrated Project
IR	infrared
ISO	International Organisation for Standardization
i.a.	amongst other things [Latin: *inter alia*]
i.e.	that is [Latin: *id est*]
Inc.	Incorporated
IT	Information Technology
KSS	Karolinska Sleepiness Scale
LAN	Local Area Network
LED	Light Emitting Diode
M	mean
max.	maximum
MEQ	Morningness-Eveningness-Questionnaire
min.	minimum/minute
MINDS™	MicroNod Detection System
mm	millimeter

Abbreviation	Description
MMS	Mensch-Maschine-Schnittstelle [Engl.: *Human Machine Interface; HMI*]
MWT	Maintenance of Wakefulness Test
msec	millisecond
MSLT	Multiple Sleep Latency Test
N	sample size
NASA	National Space Agency
no.	number
n.s.	not significant
NTSB	National Transportation Safety Board
OEM	Original Entity Manufacturer
p	error probability
pdf	portable data format
PDPU	Personal Data Processing Unit
PERCLOS	Percentage of Closure
p.m.	after noon, before midnight [Latin: *post meridiem*]
PPE	Personal Protective Equipment
PTC	Parametric Technology Corporation
PVC	Polyvinylchlorid
qty.	quantity
SCM	Sensor Communication Module
SD	Standard Deviation
SDA	Safety Drive Advisor
sec	second; seconds
SENSATION	Advanced Sensor Development for Attention, Stress, Vigilance, and Sleep/Wakefulness Monitoring
sog.	sogenannt [Engl.: so-called]
SSS	Stanford Sleepiness Scale
SWAI	Sleep-Wake Activity Inventory
TAP	Test of Attentional Performance
TCP	Transmission Control Protocol
t_r	repetition time
TRE	Traffic Risk Estimation [Module]
U	Mann-Whitney U
u.a.	unter Anderem [Engl.: *amongst other things; i.a.*]
UI	User Interface
UK	United Kingdom
US	United States [of America]
USPTO	United States Patent Office
V	Volt (electrical voltage unit)
VBA	Value Benefit Analysis
VDADA	Vehicle Driver's Anti-Dozing Aid
VDI	Verein Deutscher Ingenieure [Engl.: *Association of German Engineers*]
vs.	versus

Abbreviation	Description
VTI	väg-och transportforskningsinstitut [Engl.: *Road and Transport Research Institute*]
VW	Volkswagen
wrn.	warning
z.B.	zum Beispiel [Engl.: *for example*]

0. Zusammenfassung

In der vorliegenden Arbeit wird die Entwicklung und Evaluation einer multimodalen, universellen Mensch-Maschine-Schnittstelle (MMS) für Hypovigilanz-Management-Systeme beschrieben. Die Grundfunktion solcher Systeme besteht darin, den Vigilanz-Zustand eines Nutzers zu messen und bei kritischen Vigilanz-Zuständen den Nutzer zunächst situationsspezifisch vor dem erhöhten Risiko zu warnen und ggf. zu versuchen, ihn kurzfristig wach zu halten, bis er seine gefährliche Tätigkeit unterbrechen kann.

Als Hintergrund sei dargestellt, dass Hypovigilanz oder Schläfrigkeit in Arbeitssituationen in den westlichen Nationen stetig zunimmt. Hierzu tragen verschiedene Faktoren bei. Ein entsprechendes Beispiel ist die aus der Globalisierung resultierende „24h-Gesellschaft“, die viele Menschen veranlasst, Schlaf zugunsten anderer Aktivitäten zu opfern. Ein weiteres Beispiel ist die Schichtarbeit. So erfordern dort konkurrenzfähige, hocheffiziente Produktionsprozesse durch ihren hohen und kapitalintensiven Automatisierungsgrad einen „rund um die Uhr“-Betrieb. Weiterhin ist der starke Anstieg von Schlafstörungen in der westlichen Gesellschaft zu nennen. Alle diese Faktoren erzeugen Schlafdefizite und damit Hypovigilanz.

Hypovigilanz ist u.a. von Einschränkungen der Aufmerksamkeit sowie der Konzentrationsfähigkeit begleitet. In der Folge sind die Fähigkeiten aufmerksamkeitsbasierte Tätigkeiten effektiv zu verrichten, die Geschwindigkeit der Informationsverarbeitung sowie die Qualität von Entscheidungsprozessen beeinträchtigt. Damit führt Hypovigilanz zu einem stark erhöhten Unfallrisiko.

Hypovigilanz ist eine der Hauptunfallursachen in verschiedenen Arbeitsumfeldern, wie z.B. im Verkehr oder in Produktionsbetrieben mit Schichtarbeit. Angemessene Gegenmaßnahmen können das Unfallrisiko senken. Zunächst sollten primäre Maßnahmen ergriffen werden, die die Entstehung von Hypovigilanz grundsätzlich vermeiden. Hierzu gehören u.a. die Gestaltung von Schichtarbeitsplänen nach arbeitswissenschaftlichen bzw. chronobiologischen Gesichtspunkten und die Behandlung von Schlafstörungen. Trotz solcher primärer Maßnahmen kann die Entstehung von Hypovigilanz jedoch nicht immer ausgeschlossen werden. In diesen Fällen können Hypovigilanz-Management-Systeme maßgeblich zur Senkung des Unfallrisikos beitragen.

Um ein solches System zu gestalten wurden daher zunächst die der Hypovigilanz zugrunde liegenden Mechanismen untersucht. Es wurde dargestellt, dass in der aktuellen Literatur die entsprechenden Begrifflichkeiten inkonsistent verwendet werden. Daher wurden diese für die vorliegende Arbeit konsistent definiert und ein neuer, holistischer Vigilanzbegriff eingeführt, welcher für die Ausführung arbeitswissenschaftlich relevanter Aufgaben notwendige kognitive Sub-Konstrukte zusammenfasst. Auf der Basis des Schlafmodells von Borbély (1982) wurde ein einfaches Modell entwickelt, das den Hypovigilanz-Zustand einer Person als Funktion zweier vom circadianen Rhythmus moderierter, gegenläufiger Kräfte, dem *Schlafdruck* und dem *Wachdruck*, beschreibt. Die Haupteinflussfaktoren für Schlaf- und Wachdruck wurden beschrieben. Dabei wurde betont, dass die einzig langfristig effektive Gegenmaßnahme zu Hypovigilanz das Schlafen ist, woraus

geschlossen wurde, dass Hypovigilanz-Management-Systeme darauf abzielen müssen, den Nutzer zu einer Unterbrechung seiner risikoreichen Tätigkeit zu bewegen und zu schlafen oder zumindest einen sog. *Powernap* zu machen. Weiterhin wurde abgeleitet, dass einzelne, akut wirkende Gegenmaßnahmen evtl. zur kurzfristigen Unterstützung des Nutzers sinnvoll sein können.

Es wurde eine Analyse der Produktanforderungen von Hypovigilanz-Management-Systemen durchgeführt. Hierzu wurden zunächst die potentiellen Nutzer solcher Systeme nach ihrem Mobilitätsgrad und der Systemdynamik ihres Arbeitssystems kategorisiert und Charakteristika von Privatpersonen im Vergleich zu professionellen Nutzern aufgezeigt. Die Analyse ergab, dass ein universelles Hypovigilanz-Management-System mobil sein, prädiktive Warnfähigkeiten aufweisen und auf inhaltliche Überzeugung des Nutzers abzielen sollte. Die Grundstruktur der Systeminteraktion wurde erarbeitet: Um effektiv zu sein, muss eine Warnung zunächst Aufmerksamkeit erregen, dann Detailinformationen über den Grund der Warnung und Handlungsempfehlungen darstellen und schließlich eine Quittierung einfordern. Ein effektives Hypovigilanz-Management-System muss also grundsätzlich MMS-Elemente beinhalten, die diese Funktionen bereitstellen. Ebenso wurde aufgezeigt, dass eine kontinuierliche Anzeige des Vigilanz-Status sowie eine Funktion zur kurzfristigen Wacherhaltung des Nutzers integriert werden sollte. Grundsätzliche Gestaltungsrichtlinien für diese Funktionen wie auch für ihre physische Implementierung wurden aus der wahrnehmungspsychologischen und arbeitswissenschaftlichen Literatur abgeleitet. Ebenso wurden relevante Usability-Aspekte diskutiert und Vorteile eines universellen Systems dargestellt.

Auf der Basis der oben genannten Anforderungen an ein effektives Hypovigilanz-Management-System wurden bestehende Lösungen zum Hypovigilanz-Management untersucht. Es zeigte sich, dass keines der 18 besprochenen Systeme allen Anforderungen entspricht, woraus direkt weiterer Forschungsbedarf folgt. Es wurde daher im Sinne einer Forschungshypothese behauptet, dass es prinzipiell möglich ist, ein System zu generieren, dass allen genannten Anforderungen gerecht wird. Weiterhin wurde behauptet, dass ein solches System effektiv sei, gemessen an einer Reduktion von Fehlern und einer möglichen Steigerung der Produktivität von hypovigilanten Nutzern. Dabei ist zu betonen, dass sowohl die Entwicklung eines entsprechenden Systems als auch eine entsprechende Validierung bisher fehlen.

Die oben genannten Anforderungen wurden für eine detaillierte Konstruktion nicht als ausreichende Basis betrachtet, sie mussten daher durch praktische Anforderungen von den Anwendungsfeldern ergänzt werden. Das Problem, zu einem frühen Zeitpunkt detaillierte Systemanforderungen von den Anwendungsfeldern zu extrahieren, wurde diskutiert. Zur Lösung wurde ein hybrider Entwicklungsansatz dargestellt.

In diesem wurde zunächst auf der Basis der bekannten Anforderungen eine basale Interaktions- bzw. Warnstrategie entwickelt und von dieser wurden Grundanforderungen an die physischen MMS-Elemente abgeleitet. Auf der Basis der Ergebnisse dieser zunächst rein theoriegetriebenen Entwicklung konnte nun ein hinreichend detaillierter Fragebogen zur Anforderungsextraktion aus den Anwendungsfeldern entwickelt werden. Hierfür wurde eine repräsentative Gruppe an Anwendungsfeldern ausgewählt, in denen die spezifischen Anforderungen erhoben wurden. Die Daten wurden mit dem Ziel analysiert, Anforderungs-Cluster zu identifizieren und solchermaßen eine möglichst universelle HMI-Konfiguration zu entwickeln. Es konnte eine Konfiguration bestimmt werden, die in allen Anwendungsfeldern einsetzbar ist.

Auf der Grundlage dieser detaillierten Anforderungen wurden die endgültige Warnstrategie sowie die zugehörigen physischen MMS-Elemente methodisch konstruiert. Dazu wurden zunächst in einem interdisziplinären Brainstorming-Workshop Wirkprinzipien sowohl für die Warnstrategie als auch für die MMS-Elemente generiert. Diese wurden in morphologischen Kästen systematisiert dargestellt und Lösungsvarianten abgeleitet. Letztere wurden in Nutzwertanalysen verglichen, die jeweils beste Lösung wurde ausgewählt:

Für die Warn- und Kommunikationsstrategie beinhaltet diese eine kontinuierliche Vigilanz-Statusanzeige. Im Falle einer Warnung wird zunächst durch die Kombination eines vibrotaktilen und eines auditiven Signals die Aufmerksamkeit des Nutzers erregt. Für akute Warnungen werden diese durch erhöhte Vibrations-Pulsfrequenz und höhere Lautstärke sowie ein zusätzliches Blinklicht intensiviert. Anschließend werden durch eine Sprachmitteilung die Gefahr und mögliche Gegenmaßnahmen erläutert sowie eine Quittierung der Warnung durch Drücken eines Tasters eingefordert. Nach einer akuten Warnung wird das Vigilanz-Erhaltungssystem aktiviert, welches den Nutzer durch sog. *Landströmsounds* kurzfristig aktiviert. Daten für die Personalisierung des Systems werden dabei extern gespeichert.

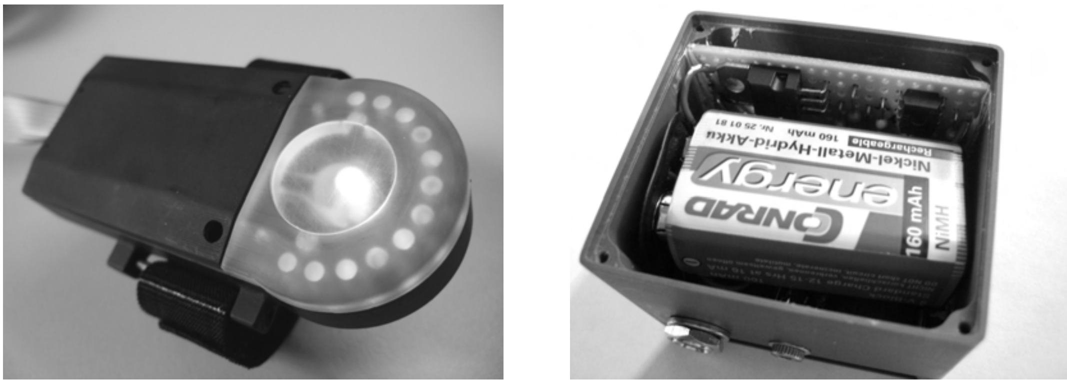
Die beste Lösung für die MMS-Elemente definiert LEDs für die visuellen Anzeigen. Alle Einstellungen werden durch Taster vorgenommen. Zur Wiedergabe von auditiven Signalen wird ein Ohrhörer eingesetzt, eine Vibrationseinheit wird in die Kleidung integriert. Personenbezogene Informationen werden auf einer Smart-Card gespeichert.

Auf der Basis der solchermaßen detaillierten Anforderungen wurde die Warnstrategie konstruiert. Für die Warnstrategie wurden drei Warnmodi definiert: Der *Normmodus*, in welchem der aktuelle Vigilanzstatus angezeigt wird, der *Vorwarnmodus*, in welchem frühzeitig auf eine Vigilanzdegradation hingewiesen wird und der *Akutmodus*, in welchem der Nutzer intensiv über ein stark erhöhtes Unfallrisiko informiert wird und aufgefordert wird, sofort eine Pause zu machen. Weiterhin wird in diesem letzten Modus das Vigilanz-Erhaltungssystem aktiviert. Die Warnstrategie berücksichtigt dabei die Vigilanz-Historie des Nutzers; so reagiert das System z.B. sensibler, wenn der Nutzer bereits gewarnt worden ist. Die Warnstrategie wurde mittels des Softwaresystem *SwitchBoard* implementiert.

Ebenso wurden die physischen MMS-Elemente konstruiert. Zentrum der MMS ist ein Gerät, das wie eine Armbanduhr getragen wird. Um das „Ziffernblatt“ herum sind die Status-LEDs angeordnet. Das gesamte „Ziffernblatt“ ist als Taster ausgebildet, welcher zur Quittierung von Warnmeldungen dient. In diesen ist mittig eine ultra-helle, weiße LED als Blinklicht integriert. Taster zur Lautstärkeeinstellung befinden sich auf der Oberseite, ein Taster für die Repetition von Sprachmitteilungen an der Seite des Geräts „bei zwei Uhr“. Weiterhin wurde eine Vibrationseinheit konstruiert. Eine Usability-Studie zeigte, dass dieses am besten auf dem Hüftknochen getragen wird. Daher wurde die Vibrationseinheit entsprechend an einem Gürtel installiert. Ein Standard-Ohrhörer, der hohen Tragekomfort mit sicherem Halt am Ohr verbindet, wurde zur Darstellung von Audiosignalen ausgewählt. Alle Elemente der MMS kommunizieren über ein Body und Local Area Network (BAN/LAN) mit der Implementierung der Warnstrategie.

Die Teile wurden prototypisch gefertigt. Sie sind in den Abbildungen 0.1a und 0.1b dargestellt.

Aufgrund der gewählten Konstruktionsweise erfüllt das konstruierte Hypovigilanz-Management-System inhärent die erste Forschungshypothese und zeigt, dass es möglich ist, ein Hypovigilanz-Management-System zu konstruieren, das allen definierten Anforderungen entspricht.



(a) „Armbanduhr“ (b) Vibrationseinheit

Abbildung 0.1.: Prototypen der MMS-Elemente

Eine Usability-Studie hat darüber hinaus gezeigt, dass das System auch aus Nutzersicht gut gestaltet wurde: Es war einfach anzuwenden, die Bedienung des Systems war einfach zu erlernen. Das System störte nicht bei der eigentlichen Arbeitsaufgabe der Nutzer, was als Voraussetzung für eine Anwendung in der Praxis anzusehen ist. Die Nutzer passten ihr Verhalten dem System an, was weiter oben als wichtiges Bewertungskriterium für Hypovigilanz-Management-Systeme hervorgehoben wurde.

Nach der gelungenen Entwicklung war der zweite Teil der Forschungshypothese zu überprüfen, die erwartete Steigerung der Sicherheit und ggf. der Arbeitsleistung von hypovigilanten Nutzern. Hierfür wurde die Arbeitsaufgabe eines Schichtarbeiters analysiert und auf eine standardisierte Laboraufgabe übertragen, welche die Kontrolle von äußeren Einflussfaktoren erlaubte. Diese bestand aus einer monotonen Positionierungsaufgabe, welche mit einem Test zur geteilten Aufmerksamkeit kombiniert wurde. Diese praxisnahe Arbeitsaufgabe wurde durch eine subjektive Schläfrigkeitsskala sowie ausgewählte Sub-Tests einer neuro-psychologischen Testbatterie ergänzt. Eine homogene Probandengruppe wurde angeworben und randomisiert auf die drei Versuchsgruppen aufgeteilt: Eine *Kontrollgruppe*, welche keine Intervention erfuhr, eine *Treatment-Gruppe*, welche das entwickelte System nutzte sowie eine *Positivkontrollgruppe*, welche ein System mit randomisierten Warnungen nutzte. Alle Gruppen wurden zunächst einem Training unterzogen, um Lerneffekte in den Messdaten zu vermeiden. Sie absolvierten dann eine Baseline-Messung am Abend und, nach einer Nacht kontrollierten Schlafentzugs, eine Messung am frühen Morgen.

Es konnte gezeigt werden, dass die abhängigen Variablen sensitiv für Vigilanzänderungen sind und damit sinnvoll gewählt wurden. Ebenso konnte gezeigt werden, dass der Versuchsaufbau als solcher anhand der abhängigen Variablen einen validen Vergleich der Versuchsgruppen erlaubte.

Dennoch konnte die Forschungshypothese nicht bestätigt werden. Anders als erwartet zeigte sich kein signifikanter Unterschied zwischen den Versuchsgruppen in den Daten der morgendlichen Messung. Es konnten also keine kurzfristigen Effekte des Hypovigilanz-Management-Systems nachgewiesen werden. Verschiedene Einflussfaktoren, die zu diesem Ergebnis geführt haben könnten, wurden diskutiert. Es wurde gefolgert, dass Hypovigilanz-Management-Systeme mehr dem Risikomanagement als dem direkten Leistungs-Management zuzuordnen sind und sich damit ihre Effekte eher über lange

Zeiträume hinweg zeigen. Es konnte jedoch gezeigt werden, dass das System u.a. zu einer Risikominimierung beitragen kann, indem es dem Nutzer ermöglicht, durch objektive Rückmeldung langfristig seinen eigenen Hypovigilanz-Zustand besser einzuschätzen und somit möglichst effiziente Pausen planen zu können.

Weiterer Forschungsbedarf wurde abgeleitet. Es wurde vorgeschlagen, das entwickelte Hypovigilanz-Management-System in einer Langzeitstudie im Feld zu evaluieren. Weiterhin wurde vorgeschlagen, andere Anwendungsfelder mit einzubeziehen und Effekte einer Anpassung der vom System empfohlenen Pausendauer an den tatsächlichen Erholungsverlauf des Nutzers zu untersuchen.

Schließlich wurde auf die ethische Implikation der Einführung von Hypovigilanz-Management-Systemen in der Praxis hingewiesen. Abschließend kann festgehalten werden, dass diese anzunehmenderweise einen entscheidenden Beitrag zur Risikominimierung leisten können, es jedoch möglich ist, sie auch zur personenspezifischen Überwachung einzusetzen.

1. Introduction

Human beings need to sleep. Sleep is not a matter of choice, it is essential and inevitable. The longer someone remains awake, the greater the need to sleep and the more difficult it is to resist falling asleep. Sleep will eventually overpower the strongest intentions and efforts to stay awake (NCSDR/NHTSA, 1998).

Today's "24 hour society" seems to pressure many individuals to sacrifice sleep in favor of other activities (Rajaratnam and Arendt, 2001). As an example, the process of industrialization was adjoint by important innovations. The introduction of electric light, the installation and improvements of ground and air transportation as well as digital collaboration by means of Internet have created a global work community which runs 24 hours on seven days in a track. Often, individuals fail to realize the negative effects the resulting sleepiness has on their health and their ability to perform a wide range of tasks.

Moreover, as much as 10% of the general population suffer to some degree from sleep disorders, such as hypersomnia, narcolepsy, and sleep apnea (Backhaus and Riemann, 1999). Sleep disorders lead to sleep deprivation which may cause extreme tiredness, loss of concentration, and a pronounced inability to function normally in one's daily routines.

It can be summarized that sleep deprivation, whether involuntary or voluntary, is one of the most common health problems of todays western societies and up to one third of the population is suffering from excessive sleepiness (Harma and Ilmarinen, 1999; Rogers and Grunstein, 2005; Bonnet, 2000).

Sleepiness is adjoint by reduced reaction time, vigilance, alertness, and concentration, so that the ability to perform attention-based activities is impaired. The speed at which information is processed and the quality of decision-making are also affected (Reissman, 1996; Hsiao and Simeonov, 2001). Hence, apart from diminishing the quality of live of the individuals suffering from it, sleepiness and the related phenomena of hypovigilance and stress are among the key causes for serious accidents.

This fact is well known for the personal transportation sector. A retrospective study of the Association of German Insurers (Gesamtverband der Deutschen Versicherungswirtschaft, GDV) revealed that about a quarter of all deadly accidents on Bavarian highways were caused by drivers who had fallen asleep at the steering wheel. Moreover, if impairments of attention are considered, which are highly related to sleepiness, up to three quarters of these accidents can be related to sleepiness (Hell, 2004; Zulley et al., 1995).

Similar results were found in other countries: An English study related 16% of all vehicle accidents on major roads and 20% of all accidents on highways to sleepiness (Horne and Reyner, 1995). An American study on two roads with heavy traffic found that 50% of fatal accidents were related to sleepiness (Reissman, 1996), where another American study on heavy trucks attributed 30-40% of the accidents to sleepiness (Board, 1995). Moreover, a study by the Australien Road Safety Organisation concludes that 25-35% of accidents on the road are related to sleepiness (Fell, 1994). Apart from these examples, according results were found in many other studies (e.g., compare to Lindberg et al., 2001; Melamed and Oksenberg, 2002; Masa et al., 2000; Garder, 1998; Connor et al., 2001).

Although it is difficult to determine the true number of sleepiness related accidents, because of the lack of reliable methods to identify accidents related to sleepiness and separate these from other accident types, the above numbers indicate a severe safety problem caused by sleepiness. In consequence, an international group of leading researchers issued a consensus statement on this topic concluding that

> "sleepiness is the largest identifiable and preventable cause of accidents in transport operations (between 15 and 20% of all accidents), surpassing that of alcohol or drug related incidents in all modes of transportation" (Åkerstedt, 2000).

In the same way, sleepiness is a key cause for serious accidents in aviation. According to the NASA Aviation Safety Reporting System, approximately 21% of the aviation incidents are sleepiness related.

Moreover, major accidents were linked to sleepiness, such as the nuclear catatsrophes of Chernobyl and Three-mile Island, the poisonous gas leak from a pesticide factory in Bhopal (India) as well as the oil spill resulting from the crash of the super-tanker "Exxon Valdez" (Mitler et al., 1988; Folkard et al., 2005; Dinges, 1995).

The processes of automation and globalization negatively contribute to this situation. It requires organizations and arrangements in which constraints of time and place no longer limit human activity (Spath et al., 2006; Bauer and Rief, 2005). On the one hand, modern information technology (IT) enables job nomads to work "on the fly" wherever and whenever they want (Bauer and Stiefel, 2007), but at the same time force them to prolonged working times (Spath, 2006), eventually combined with jet lag. This is especially the case for workers of worldwide operating companies. Competing in turbulent global markets (Westkämper, 2004; Westkämper and Balve, 2003), these companies are forced to optimize the use of resources, e.g. by "global sourcing" (Westkämper, 2006), and, hence, never stop the production process as one part of the company is always in a daylight zone. On the other hand, products with high complexity, produced with high grades of automation, require production all around the clock (Spath et al., 2003), thus requiring shift work.

Shift work in general leads to an increased prevalence of sleep disturbances compared to non-shift workers (Harma et al., 1998; Åkerstedt, 1998a). Taken into account that human errors are most often found to be the root cause for serious incidents and occupational accidents, and that these errors are, among other reasons, strongly related to disturbed sleep (Dinges, 1995; Åkerstedt et al., 2002), it can be concluded that shift workers are in a high risk group for occupational accidents due to an increased prevalence of sleepiness within this group. Leger (1994) even suggests that 52.5% of all work related accidents and injuries are related to sleepiness.

It can be summarized that sleepiness is one of the main causes for severe accidents both in industrial applications and in the transportation sector, evoking economic damage and personal grief. Obviously, according measures should be taken in order to reduce sleepiness related incidents and accidents and support the sustainment of personal performance capabilities.

Although it is clearly desirable to prevent the development of sleepiness itself, the above numbers indicate that this approach by itself can not always be successful. Hence, other complementing solutions need to be developed for cases in which sleepiness is already present. One according approach are technical measures, so called *Hypovigilance-Management-Systems* or *HVMS*.

The development and validation of such a system are the focus and the aim of this work. In order to reach this aim, several topics are addressed, which are described in the next section

1.1. Structure of the Work

First, basic concepts of sleep, sleepiness and according countermeasures are introduced as their understanding is necessary for the analysis and development of Hypovigilance-Management-Systems. Then, requirements for an ideal Hypovigilance-Management-System are developed and basic user groups are identified.

On this basis, current Hypovigilance-Management-Systems are analyzed in order to deduce possible drawbacks of these systems. The focus is laid on the Human-Machine-Interface (HMI) of such systems. It is shown that none of the existing systems meets the requirements and, hence, further research on this topic is needed.

Consequently, the potential of such further research is formulated in terms of research hypotheses. Moreover, the underlying innovations are emphasized and a methodological approach to this research is described.

Following this approach, the requirements of a new universal, multimodal HMI for Hypovigilance-Management-Systems are formulated and an according prototype is constructed methodologically.

This prototype is evaluated with respect to the above hypotheses in an experimental laboratory study and the results of the study are presented and discussed.

Finally, a summary of the work is presented and an outlook to further research is given.

An overview over the structure of the work is given in figure 1.1

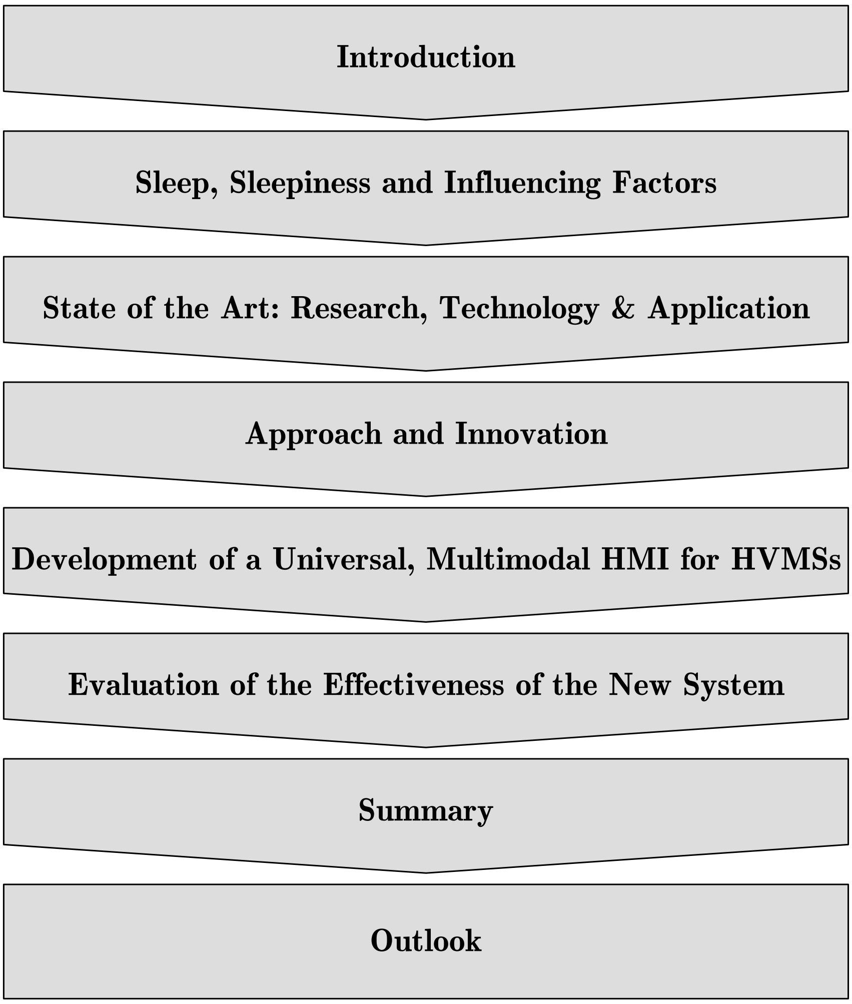


Figure 1.1.: Structure of the Work

2. Sleep, Sleepiness, and Influencing Factors

In order to develop and design effective Hypovigilance-Management-Systems, a basic understanding of sleep, sleepiness, and their influencing factors is needed. Due to space restrictions, only a short introduction can be given. However, basic concepts are presented and references are made to the relevant scientific literature.

2.1. Definition of Sleepiness

Although the term *sleepiness* has been used for reasons of consistence in this work so far, in the original publications cited, different terms were found for the description of the sleepy driver or worker.

The use of either different terms for the same construct or the use of the same term for different constructs is characteristic for the relevant scientific literature. Examples of according terms are *hypersomnia, sleep propensity, somnolence, weariness, tiredness, fatigue, ability to stay awake* and *drowsiness* (compare, e.g., to Johns, 1998; Åkerstedt, 2000; Corfitsen, 1994; Cluydts et al., 2002).

At the same time, Åkerstedt (1998b) states that such a diversity is characteristic for a young research area and Johnson (1982) mentions that research on sleep, sleepiness and performance is a difficult task due to three specific issues (following Weeß et al., 1998):

1. Research on the phenomena mentioned is characterized by a multitude of intermitting variables such as, e.g., the motivation of the participant, thus, imposing strong requirements on the control of the experimental conditions.

2. Sleepiness, performance and the underlying attention-related constructs are of a complex nature, which are difficult to operationalize or prove empirically.

3. An analysis of the relevant scientific literature reveals the above mentioned non-theory related and unsystematic use of terms with the well known negative effects on the scientific discurs.

Conclusively, a discussion of the definition of the concept of sleepiness is needed. A first approach to the definition of the terms mainly used in the literature is made by means of the Merriam-Webster's Collegiate Dictionary (2003):

Sleepiness The readiness to fall asleep.

Fatigue The weariness or exhaustion from labor, exertion, or stress.

Tiredness The state of being drained of strength and energy.

Drowsiness The state in which sleep is induced or tends to be induced.

Johns (1998) adds that *drowsiness* is a transitional state between wakefulness and sleep in which the sleep process has begun already and will probably lead to sleep. Johns distinguishes *sleepiness* from *drowsiness* as being neither a state nor a process and defines it as *sleep propensity* or the probability of falling asleep at a certain time (from van den Berg, 2006).

Different, mostly dichotomous classifications of sleepiness have been published, such as sleepiness vs. fatigue, or state characteristics of sleepiness vs. trait characteristics of sleepiness. An extensive overview over these classifications can be found in Cluydts et al. (2002) and Popp (2005).

This work follows the definition of Åkerstedt and Kecklund (2000, translated by van den Berg (2006)), who define sleepiness as *the inability to stay awake and, hence, a drive to sleep.* However, the above discussion indicates that such a simple definition might not be sufficient in order to completely describe the construct of sleepiness. MacCorquodale and Meehl (1948) already mention that sleepiness, in the first instance, is to be considered a hypothetical construct which needs to be operationalized.

One according approach is promoted by the working group *Vigilance* of the German Association for Sleep Research and Sleep Medicine (Deutsche Gesellschaft für Schlafforschung und Schlafmedizin, DGSM). It has been published by Weeß et al. (1998), who characterize sleepiness by the underlying attention-related constructs. These can explain the functional impairments caused by sleepiness.

The term *attention* itself, again, is a subject of a scientific discussion which is characterized by an inconsistent use of terms (compare, e.g., to Brickenkamp and Karl, 1986; Rützel, 1977; Rapp, 1982; Posner and Rafal, 1987; Poulton et al., 1974). However, the actual discussion seems to converge to a concept of attention which takes into account the former definitions of attention (Weeß et al., 1998). This concept can be attributed to the work of Posner and Rafal (1987). It differentiates three attention-related aspects which form the basis of performance:

Alertness precedes attention and refers to the activation of the central nervous system. Consequently, it forms the basis for the constructs attention and vigilance.

The *tonic* part of this construct is mostly dependent on circadian changes and, thus, not under conscious control. It describes, e.g., the feeling of wakefulness of a person on different days.

The *phasic* part is dependent on intermitting stimuli, e.g. warning stimuli, which lead to a shorthanded rise of alertness. It describes, e.g., the rise in alertness of a person sitting quietly in chair when called.

Vigilance was defined in its classical sense by Mackworth (1957) as a

> "state of readiness to detect and respond to certain specified small changes occurring at random time intervals in the environment."

In other words, it describes the ability to detect sudden stimuli in a monotonous task over a long time. Typical vigilance tasks in this very narrow sense of vigilance are, e.g., so called *watchkeeping tasks*, such as monitoring tasks in a power plant, where automatized processes need to be supervised and reactions are mostly not necessary.

Attention has two sub-constructs, *selective attention* and *divided attention*:

- **Selective attention** is defined as the ability to select relevant stimuli out of the stream of stimuli perceived. For example, a machine operator working in a machine park where several different machines produce audible and visual feedback for the machine operators needs to select and focus on the appropriate feedback information from the machine he/she is working on.
- **Divided attention** is defined as the ability to quickly process information in parallel in an automated but controlled manner. A typical example is the task of driving a car when the driver approaches a junction and needs to survey the crossing traffic, respect traffic signs/lights as well as pedestrians, and coordinate motor tasks such as steering, coupling etc..

Considering the above descriptions, sleepiness mainly refers to the grade of central nervous stimulation (i.e. alertness) and, consequently, influences the individual performance capabilities in terms of vigilance and attention (Weeß et al., 2000).

However, depending on the dynamic of a work system with respect to the cognitive requirements imposed on the user, different of the above constructs become relevant. For the example of driving a car, i.e., performing a task with a high system dynamic in which the user needs to be generally alert and actively involved in searching, problem-solving, predicting and planning, is more an attention based task than a vigilance task. Contrary to that, the low system dynamic task of monitoring a process is more a "pure" vigilance task.

In the literature, the term *vigilance* also has been used inconsistently. As an example, Hockey and Tattersall (1989) define vigilance as a state in which the user is generally alert and actively involved in searching, problem-solving, predicting and planning which does not correspond to the definition of Mackworth (1957).

As sleepiness mainly refers to alertness but, at the same time, the concepts of vigilance and attention need to be considered with respect to performance in work systems, in this work, vigilance is defined as a *measure in which all of the above constructs are positively represented*. The prefix *hypo* origins from the Greek language and means *diminished*. Hence, a state of *hypovigilance* is a state of diminished vigilance. Therefore, in this work, hypovigilance is used to denote the effects caused by sleepiness.

2.2. Basic Models of the Sleep-Wake-Regulation

The aim of this work is to effectively design the HMI of a Hypovigilance-Management-System in order to reduce hypovigilance related mis-performance. Therefore, the development of hypovigilance needs to be prevented by such a device and, if this is not possible, according countermeasures need to be utilized. From the everyday experience, clearly, sleeping should effect both of the above measures in a positive way. However, immediate sleep might not be possible to get at all times, e.g., when driving on the highway. Obviously, more information is necessary on the development of hypovigilance as well as on possible countermeasures. Therefore, in the following, basic models of human sleep-wake-regulation are presented from which influencing factors for hypovigilance will be deduced in the next section.

2.2.1. The Two-Process Model

On the basis of the regulation of different sleep phases and especially the deep sleep phase characterized by Delta-Waves, Borbély (1982) describes the shift between wakefulness and sleep as an interaction of the homeostatic *process S* and the rhythmic *process C* (see also Borbély and Achermann, 1999; Borbély and Achermann, 1992). The two-process-model is depicted in figure 2.1.

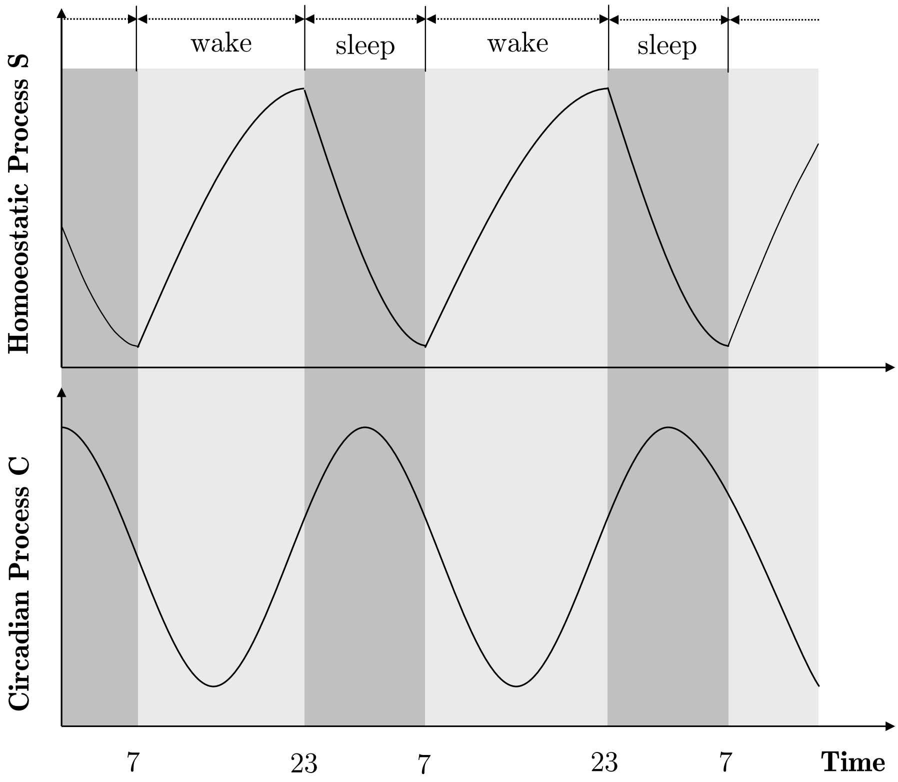


Figure 2.1.: Depiction of Process S and Process C Over Time (following Borbély, 1982)

Process S characterizes the sleep drive and is determined by prior sleep and wake periods. It increases exponentially during wake periods and decreases during sleep periods. Process S interacts with process C, which is controlled by an "internal" clock, the circadian rhythm. The circadian rhythm is an endogenous, relatively constant rhythm with a periodic time of about 24 hours and is coupled to the light/dark cycle.

In other words, process C is responsible for the timing of the rhythmic functions and process S determines what happens during this time, e.g., process C defines when sleep takes place and process S determines the effectiveness of the resulting regeneration (Zulley and Hajak, 2005).

This basic model has been modified and extended (e.g., a third factor has been introduced by Folkard and Åkerstedt (1987), modeling the state directly after waking up, hence, leading to a three-process model) and are still useful, but reach their limits as they neither consider external stimuli nor arousal.

2.2.2. The Four-Process Model

Johns (1998) augments the above model to a four-process model by adding the *wake drive* in addition to the *sleep drive*: whether or not an individual falls asleep is not only dependent on the grade of sleep drive, but also on the grade of wake drive or arousal, which counteracts on the sleep drive. Although Johns (1998) further differentiates between primary as well as secondary sleep drive and wake drive, he indicates that this quite simplified model still needs further improvement.

2.2.3. Model for the Regulation of Sleepiness

From both the models described above, a simplified model for the regulation of sleepiness is deduced (compare to figure 2.2).

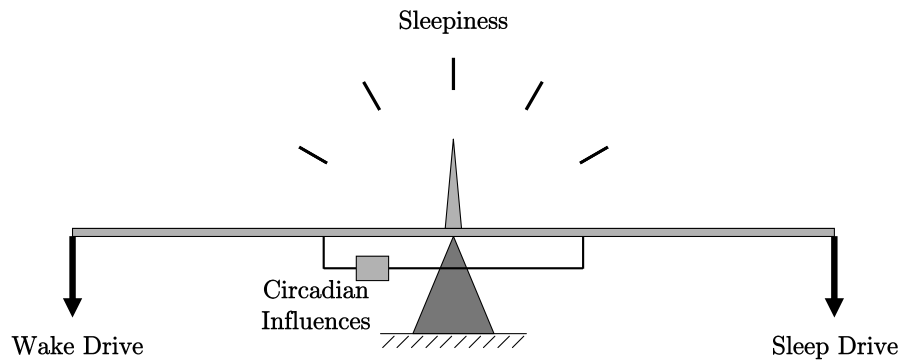


Figure 2.2.: Simplified Model of the Influencing Factors for Sleepiness (adapted from van den Berg, 2006)

In this model, sleepiness is symbolized as the indication of a balance. The two processes *sleep drive* and *wake drive* are represented by the forces acting on both sides of the balance respectively. Sleep drive is increasing sleepiness and wake drive is counteracting sleep drive and, therefore, sleepiness. Circadian influences act as a moderator and are illustrated as a slidable weight on the balance.

2.3. Main Influencing Factors for Sleepiness

In order to control sleepiness by means of technical assistance systems, insight in its influencing factors is clearly needed. Therefore, in the following, these factors are discussed in detail.

2.3.1. Sleep Drive

Sleep drive is mainly related to process S in the model of Borbély and Achermann (1999). Thus, it increases with increasing wake time and/or disturbed sleep periods. Both mechanisms lead to *sleep debt*.

A wide range of factors cause sleep debt, from simply going to bed too late to major diseases such as “fatal familial insomnia”. Moreover, as mentioned in the introduction, the trend to sacrifice sleep in favor of other activities such as work or (shifted) spare time activities as well as the increasing prevalence of sleep disorders in the western societies, leads to a general increase in sleep debt and, hence, sleep drive.

2.3.1.1. Shift Work

Since the beginning of the industrialization in the 19^{th} century, work processes more and more influence the rhythm of life of workers, shifting them more and more away from their natural rhythm of work, recreation and sleep (Spath et al., 2004), thus resulting in disturbances of the sleep-wake regulation and, hence, in sleepiness.

Several professional contexts tend to lead to an increased sleep drive. Among them are top-level management with regular work times of up to 18 hours a day, the health care system with shift durations of up to 36 hours and, most prominent, shift work. From the literature (compare, e.g., to Boggild et al., 1999; Basner, 2005; Boisiard et al., 2003), it can be concluded that 16-22% of the workers are engaged in shift work which causes sleep disturbances for many of the workers (Åkerstedt, 1998a; Harma et al., 1998). Moreover, shift work contributes to sleep drive through a general loss of sleep time as well as the conflict between displaced work hours and the circadian rhythm (Åkerstedt, 1988).

2.3.1.2. Sleep Deprivation

A specific influencing factor of sleep drive is sleep deprivation. The length of wake time profoundly influences process S in the model of Borbély and Achermann (1999) and directly acts on increasing sleep drive. The literature differentiates *total*, *partial* and *selective sleep deprivation* as well as *sleep fragmentation*. The latter two could be used as a model for sleep disturbances (Weeß et al., 1998) and partial sleep deprivation is of particular practical relevance, e.g., when a bus driver gets four hours of sleep only between shifts or when teenagers party late in the night and, consequently, do not get enough sleep.

Total sleep deprivation is of special relevance in this work as it allows to built up sleep drive artificially and quickly, and, hence, hypovigilance, in healthy persons in a controlled manner which allows the conduction of hypovigilance experiments such as the evaluation of the effectiveness of a Hypovigilance-Management-System.

Total sleep deprivation refers to a person not sleeping at all during a defined time period, resulting in the subjective sensation of sleepiness and a significant reduction of performance as has been shown in the meta-analysis of Pilcher and Huffcut (1996). Even short periods of total sleep deprivation lead to a significant reduction of performance. Moreover, the effects of total sleep deprivation are fully reversible through a recovery sleep. In conclusion, total sleep deprivation seems to be a valid and human method for the testing of Hypovigilance-Management-Systems.

However, several factors moderate the effects of total sleep deprivation and need to be taken into account in the design of according studies. Important influencing factors are described below, summarizing the results of Johnson (1982) and Bonnet (2000).

Experimental Task It has been shown that experimental tasks enhance hypovigilance related performance reduction if they are monotonous, have a long duration, have a high complexity, involve working memory, impose external control on the participant, and are lowly automated. Immediate feedback about the correctness of performing the task might mask the sleep deprivation effects through a rise in the motivational level of the participant (Johnson, 1982).

Person Related Factors The effects of sleep deprivation can be reduced if the participant is intrinsically interested or motivated and if he/she feels stimulated by the task. However, if a participant feels bored, the effects of sleep deprivation might be enhanced. Finally, character traits such as extraversion (as opposed to introversion) are associated with an enhancement of the sleep deprivation effects, whereas gender does not seem to have a meaningful influence.

The effect of sleep deprivation is moderated by age though. A study of Philip et al. (2004) has shown that 24 hours of total sleep deprivation affected the reaction time of the young participants (20-25 years) negatively while the reaction time of the older participants (52-63 years) remained almost unaffected.

Situational Factors Physical activation of the participant can counteract the effects of sleep deprivation. Moreover, the climatic conditions might influence effects of sleep deprivation, however, no experimental research has been conducted on this issue and different opinions can be found in the literature (compare, e.g., to Johnson, 1982; Poulton et al., 1974). Finally, drugs can enhance or reduce the effects of sleep deprivation and, thus, need to be controlled.

Sleep Related and Circadian Factors The length of the wake periods influences the effects of sleep deprivation. Moreover, the time at which the experiment is conducted strongly influences the effects of sleep deprivation. A strong circadian “down” generally manifests between 3 a.m. and 4 a.m. as well as between 1 p.m. and 3 p.m.. In the same way, a circadian “high” generally manifests between 7 a.m. and 11 a.m. as well as between 4 p.m. and 8 p.m..

It should be noted that some individuals prefer one circadian “high” phase over the other . Individuals with a relatively early circadian “high” phase are called morning-types. Those with a relatively late circadian “high” phase are called evening-types (Louzada et al., 2004). In the experiment these differences of chronotype could lead to individual differences in performance. A standardized questionnaire, the Morningness–Eveningness Questionnaire (MEQ), has been developed by Horne and Östberg (1976) in order to measure the chronotype of an individual. The MEQ consists of nineteen multiple choice questions, with each answer being assigned a value. Their sum gives a score ranging from 16 to 86. High scores (59-86) identify morning-type individuals, low scores (16-41) correspond to evening-types, and scores from 42 to 58 refer to an intermediate type. A validated German version of the MEQ, the so called D-MEQ, is available (Griefahn et al., 2001).

2.3.2. Countermeasures

Obviously, the best way to decrease hypovigilance and maintain performance capability is to reduce sleep drive by means of an adequate scheduling of work hours according to circadian rhythms (Spath et al., 2004) as well as a proper sleep hygiene including the appropriate treatment of sleep disturbances, if necessary (Åkerstedt and Landström, 1998). However, due to external factors, these longterm measures are often not feasible or only partially effective. Hence, with respect to the goal of this work, insight in short term measures to counteract sleep drive is needed.

Another approach to decrease hypovigilance is to increase wake drive. Therefore, in the following, relevant short term measures to decrease sleep drive and/or increase wake drive are summarized (comprehensive overviews of countermeasures can be found in van den Berg, 2006; Popp, 2005 and Weeß et al., 1998; moreover, Bonneford et al., 2004; Marberger, 2003; Kaneda et al., 1994 and Verwey and Zaidel, 1997 discuss countermeasures with respect to hypovigilant drivers).

2.3.2.1. Sleep, Naps, and Breaks

Åkerstedt and Landström (1998) found little evidence that taking a break significantly reduces hypovigilance. However, they found that sleep at work or naps before or during work is an effective, probably the most effective countermeasure against hypovigilance. Several other studies support this finding (compare i.a. Aurora et al., 2006; Purnell et al., 2002). For example, Macchi et al. (2002) found that for a group of long-haul drivers, napping in the afternoon decreased subjective sleepiness ratings and enhanced psycho-motor performance and reaction times during the night. Comparable effects have been observed in shift workers (Purnell et al., 2002; Sallinen et al., 1998) and in medical interns (Aurora et al., 2006).

2.3.2.2. Drugs

A wide variety of drugs such as *Modafinil* exist which increase wake drive (Czeisler et al., 2005; Wesensten et al., 2002). However, in the focus of this work, these are not relevant and, hence, are not discussed in more detail.

Nevertheless, one widely accepted and used substance shall be mentioned. The effects of *caffeine* mainly have been studied with respect to the driver. It has been shown that caffeine significantly increases driving performance (Philip et al., 2006; Horne and Reyner, 1996). Moreover, the combination of both caffeine and a short nap proved to be more effective then either one of the two by itself (Reyner and Horne, 1997). Although these studies have been done on the subject of the car driver, their results can be generalized.

2.3.2.3. Environmental Stimulation

Several studies have shown that noise can have a weak positive effect on performance in sleep deprived persons (compare, e.g., to Tassi et al., 1993). Presumably, this effect is caused by an unspecific increase in the arousal level and, as a consequence, an increase in wake drive.

Landström et al. (1998) showed that specific disharmonious sequences of sounds, each lasting around 4 seconds, that are presented in irregular intervals of up to 5 minutes significantly enhance wakefulness. Moreover, a high level of acceptance by the participants could be observed. The usefulness of these so called *Landström Sounds* also has been demonstrated in a field study (Landström et al., 1999a). Therefore, it appears to be a promising approach for the short term support of hypovigilant workers.

Intense light, especially of a specific blue color, suppresses the production of melatonine and, thus, influences the circadian rhythm. Moreover, it can increase the level of alertness (Popp, 2005).

There are no clear findings for the effects of the level of temperature. Anyhow, one study found that the reduction of air temperature by 10℃ in repeated sequences significantly increased wakefulness (Landström et al., 1999b). However, in the focus of this work, this approach does not seem to be feasible.

2.3.2.4. Behavioral Countermeasures

Several studies showed that physical activation has short term effects on hypovigilance, but these effects last for about 5 minutes only (compare, e.g., to Bonnet, 2000; Lubin et al., 1976; Angus et al., 1985). Thus, physical activation gives the impression of being effective because there is a short positive effect. However, this might even be dangerous because the effects do not last long and the new decrease of wakefulness might not be perceived. Anyhow, during activation itself, physical activation enhances wake drive.

2.4. Measurement of Sleepiness

It is difficult to measure sleepiness as such. Often, all or a subset of the different underlying constructs as outlined in section 2.1 need to be measured separately, depending on the application scenario.

In the literature, two, sometimes three basic measurement types are described. Van den Berg (2006) distinguishes subjective and objective measures. Cluydts et al. (2002) describes subjective measures but subdivides the objective measures further into behavioral measures and physiological measures. In the present work, the latter conceptualization is followed. However, it is to be mentioned that some of these objective measures are based on judgments of external raters (e.g., facial expression). Although Wierwille and Elsworth (1994) show the validity of such an approach, Dette et al. (2004) point out that the rating always is influenced by the rater, which needs to be taken into account when applying these methods, e.g., by training and supervising the raters.

A detailed description of different methods of measuring sleepiness and its sub-constructs is given in Weeß et al. (2000) and Cluydts et al. (2002). However, many of these methods are mainly used in sleep research and sleep disorder treatment and, hence, are not very important with respect to the focus of this work. Consequently, only a brief summary is presented (i.a., compare to table 2.1) and only methods that are of more importance in the context of this work are described in more detail.

2.4.1. Subjective Measures of Sleepiness

Subjective rating scales for sleepiness are often easy to use and require little expertise in their administration and the interpretation of the results. They measure the subjective, overall rating of sleepiness and can be seen as a holistic measurement tool which addresses all of the underlying constructs at the same time. However, there are inherent problems in using these scales: First, people tend to misinterpret symptoms of fatigue and tiredness as sleepiness. Second, the severity of sleepiness often is underestimated. Pilcher and Walters (1997) showed that with increasing sleepiness, the ability to accurately judge one's own level of sleepiness decreases.

Anyhow, two subjective rating scales are frequently utilized, the *Stanford Sleepiness Scale (SSS)* and the *Karolinska Sleepiness Scale (KSS)*:

Subjective rating scales
Acute Level of Sleepiness
Stanford Sleepiness Scale (SSS, Hoddes et al., 1973)
Karolinska Slepiness Scale (KSS, Åkerstedt and Gillberg, 1990)
visual analogue scales

Global Level of Sleepiness
Epworth Sleepiness Scale (ESS, Johns, 1991)
Sleep-Wake Activity Inventory (SWAI, Johns, 1992)

Behavioral Measures
Behavioral Observation
yawning frequency (Baenninger et al., 1996)
oculomotor activity (Porcu et al., 1998)
eye closing (Mallis et al., 1999)
head movements (Wright and McGrown, 2001)
facial expression (Wierwille and Elsworth, 1994)
actigraphy (Pollack et al., 2001)
mannerisms (Wierwille and Elsworth, 1994)

Performance Tests
reaction time tests (Broughton, 1982)
psychomotor vigilance test (Dinges et al., 1997)
driving simulator (George et al., 1997)
Test of Attentional Performance Battery (TAP, Zimmermann and Fimm, 2005)

(Electro-)Physiological measures
Multiple Sleep Latency Test (MSLT, Thorpy, 1992)
Maintenance of Wakefulness Test (MWT, Martin et al., 1996)
polysomnography (O'Neill et al., 1998)
pupillometry (Pressman and Fry, 1989)
cerebral evoked potentials (Broughton et al., 1988)
electro encephalogram (Torsvall and Åkerstedt, 1987; Åkerstedt et al., 1991)

Table 2.1.: Overview of Selected Assessment Tools for Sleepiness (deduced from Cluydts et al., 2002)

Stanford Sleepiness Scale The bipolar rating scale consists of seven descriptive statements for the characterization of the state a person feels to be in at the time of administration of the scale. The descriptions range from *Feeling active, vital, alert, or wide awake* to *No longer fighting sleep, sleep onset soon; having dream-like thoughts*. Hence SSS is a measure for the acute level of sleepiness.

Karolinska Sleepiness Scale Comparable to the SSS, this bipolar scale covers the wake–sleep continuum by nine different categories. The descriptions of states range from *very alert* to *very sleepy, great effort to keep awake, fighting sleep*. The KSS is a widely used tool in sleepiness research and has already been used in studies on countermeasures for sleepiness (compare, e.g., to Reyner and Horne, 1998). Therefore, it seems to meet the needs for the evaluation study of this work.

2.4.2. Objective Measures of Sleepiness

Objective measures of sleepiness mainly relate to specific constructs such as vigilance or alertness. Accordingly, these measures need to be carefully selected with respect to the specific aim of the study in which they are used. A wide variety of objective measures is known (see section 2.4) and only a selection of the most important measures can be discussed in here.

2.4.2.1. Behavioral Measures of Sleepiness

Sleepiness leads to changes in behavior or to specific behaviors that can be used as indicators for sleepiness. An overview is given in table 2.1. The indicators used most often are discussed below.

Body Posture, Facial Expression and Mannerisms Wierwille and Elsworth (1994) showed that the measurement of sleepiness by trained raters yields valid results. In their work, Wierwille and Elsworth give a clear description of the relevant indicators and match these with sleepiness on a bipolar scale with five levels. Muttray et al. (2007) further improved the description of the indicators.

The main drawback of this method is the high effort needed. However, with respect to "Wizard of Oz" experiments, the judgment of the state of sleepiness of a participant by the above method is a valid and easy to use approach to substitute the sensor/algorithm-system of a Hypovigilance-Management-System by a trained rater.

Eye Parameters Several eye parameters such as eye lid closure time or the percentage of eye lid closure over time (PERCLOS) have been identified to be sensitive to changes in sleepiness. However, some parameters only seem to be influenced at states of severe sleepiness while others are sensitive at lower levels of sleepiness, too. The measurement of these parameters mainly relates to trained raters or to camera based sensors with computation intensive video analysis algorithms. A promising approach to measure eye lid related parameters with only small technical requirements is described in Erdmann et al. (2006).

Actigraphic Monitoring Measuring the activity level of a person by attaching a watch like device, the *actigraph*, to the wrist of the person is often used to measure activity of this person and, to discriminate between sleep and wake phases as well as to estimate sleep duration. In sleep deprivation experiments, actigraphy is used to control the sleep deprivation, i.e. ensure the wake time of the participant.

Performance Tests Sleepiness related impairment of functions is one of the main reasons for accidents, as has been shown in the introduction. The decrease in functioning and performance on specific work tasks can be used as an indicator for sleepiness. This approach has been validated in several studies with experimentally induced sleep deprivation (among others Bonnet, 2000; Johnson, 1982; Dinges and Kribbs, 1991; Pilcher and Huffcut, 1996). As an example, variants of reaction time tests are a common measure of performance (Broughton, 1982). However, ideally, the test conditions should evaluate aspects of performance that are relevant with respect to daily activities (Cluydts et al., 2002) such as different work tasks.

2.4.2.2. (Electro-)Physiological Measures of Sleepiness

These tests have high relevance in the context of sleep research and sleep disturbance treatment. For the development and evaluation of the HMI of a Hypovigilance-Management-System their use is restricted, although it is to be mentioned that pupillometry might be useful to measure alertness in specific cases. Consequently, no further description is included in this work.

3. State of the Art: Research, Technology, and Application

In chapter 2, models of human sleep-wake-regulation were introduced and possible countermeasures for hypovigilance were discussed. It was pointed out that a proper scheduling of work times as well as an adequate sleep hygiene are the most effective countermeasures for hypovigilance as they circumvent the development of hypovigilance and, hence, can be regarded as primary measures in the usual terminology of human factors engineering.

However, because of, e.g., production system restrictions which lead to shift work, hypovigilance presumably will built up despite of the administration of the primary measures, putting the worker in a high risk of endangering him/herself or other people, besides of the reduction of his/her performance level. In these situations, technical support systems are desirable which ensure safety and could help maintain the level of performance. Such systems relate to personal protective equipment in the usual terminology of human factors and safety engineering.

The design and evaluation of the human machine interface (HMI) of a Hypovigilance-Management-System is the focus of the present work. In order to achieve this, first, a brief overview over the functional parts of such a system is given. Then, basic requirements for the user interface (UI) of Hypovigilance-Management-Systems are deduced to serve as a basis for the analysis of actual Hypovigilance-Management-Systems.

3.1. Basic Elements of a Hypovigilance-Management-System

In principles, Hypovigilance-Management-Systems measure the state of vigilance of the respective user and take according measures if a critical state of hypovigilance (as defined in section 2.1) with respect to the work task of the user is reached.

Although there are many possible set-ups of Hypovigilance-Management-Systems, generally, a certain structure is always kept. Figure 3.1 depicts the basic structure of such a system on the example of the structure of the Hypovigilance-Management-System planned to be developed in the SENSATION[1] project.

Relevant data for the measurement of the vigilance state of the user is gathered by different sensors. In order to reduce traffic on the system communication network, these sensors should include a basic pre-processing of data. For example, a camera-based eye-lid-movement sensor should not transmit video data, but information about the eye lid movement such as lid closure time etc.. The sensors communicate with the central system via defined networks: sensors used close to the body are connected to a body

[1]SENSATION is an EU co-funded Integrated Project (IP) of the 6th frame program (FP; SENSATION, 2004)

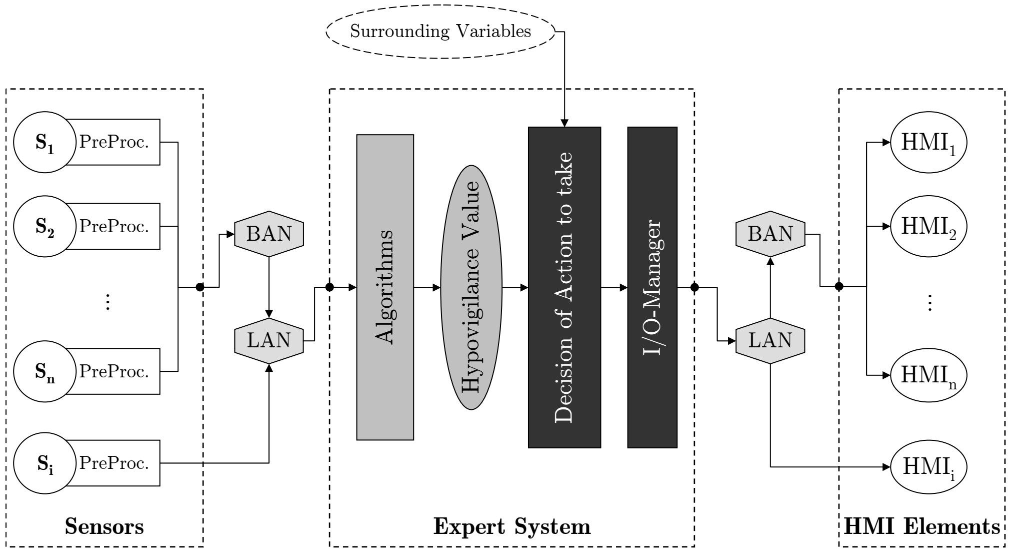


Figure 3.1.: Schematic Diagram of the Structure of a Hypovigilance-Management-System (based on Hagenmeyer et al., 2005). S_x Refers to Sensors, BAN/LAN Refers to Body/Local Area Network, and HMI_x Refers to the Single HMI-elements.

area network (BAN) which itself is connected to the local area network (LAN); other sensors, such as cameras on the dashboard of a car, are directly connected to the LAN.

The pre-processed data coming from the sensors to the expert system, in a first step, is combined by means of according algorithms to a vigilance value on a simple scale. The warning strategy is implemented in a decision-of-action-to-take-manager; with respect to the use context, it takes the actual vigilance state of the user into account, in combination with surrounding variables such as risk level of the actual situation. The action to take decided in this way is communicated to the user through the respective HMI-elements, which are connected to the expert system through the same BAN/LAN-structure that serves the sensors.

3.1.1. Focus of this Work

Much effort is invested in the understanding and the measurement of hypovigilance as can be seen from chapter 2 as well as from section 3.4. With respect to Hypovigilance-Management-Systems, much of the present research has been conducted with the aim of designing valid and reliable sensor/algorithm-systems. However, as will be shown in section 3.4, only little effort has been put in the development of valid and effective HMI. In other words, research, so far, focused on finding out how sleepy a user is, but did not care too much about how to react to the state of hypovigilance measured.

As a consequence, there is a lack of valid and effective warning systems for Hypovigilance-Management-Systems. Hence, this work focuses on the HMI part of Hypovigilance-Management-Systems only. For the investigation presented in this work, it is assumed that a valid and reliable sensor system exists which delivers a vigilance value between one and five with one representing “absolutely awake” and five representing “close to falling asleep” in the wake-sleep-continuum. This vigilance value is considered to be an external input to the warning strategy and, therefore, to the overall HMI of the Hypovigilance-Management-System.

3.2. User Groups of Hypovigilance-Management-Systems

From the introduction, it can be seen that different user groups such as pilots, car drivers or machine operators in a night shift are in the high risk group for hypovigilance related accidents and/or performance degradation. However, clearly, the user needs differ heavily for the different users and, therefore, call for different human computer interaction (HCI)-strategies. In the following, basic user groups are defined in terms of their respective requirements.

3.2.1. Operators vs. Drivers

In a first approach potential users are divided into operator-type users, driver-type users, and mixed-type users. The grouping of these three user types is mainly a function of the dynamic of the work system the user is working in.

Operators work in systems with a low system dynamic, i.e. they do not need to react immediately to information from the system. Still, the user must not fall asleep during his/her working activities. However, a certain degree of hypovigilance might not necessarily lead to concrete danger for the operator or his/her surrounding. An example for the user-type operator is the controller in a nuclear power plant, where most of the systems run automatically and, in addition, are secured by means of back up systems. Thus, if the user gets sleepy and misses relevant system information, several stages of alarm systems will inform the user so that he/she can still react properly. However, if the user falls asleep, he/she might in fact miss relevant information and, thus, events of hypovigilance need to be *detected* and the user needs to be warned accordingly.

With respect to sleepiness related cognitive constructs, alertness and vigilance are in the foreground for operators.

Drivers work in high dynamic systems and, thus, need to constantly be alert and quickly react to events in their surrounding such as, e.g., the movements of another car in the case of the car driver. Even short moments of inattention might lead to severe accidents. Consequently, according Hypovigilance-Management-Systems not only need to detect states of hypovigilance, but need to *predict* such states in order to be able to react appropriately: Clearly, if a car driver closed his/her eyes because of an event of micro-sleep, it may be already much too late to reliably prevent an accident.

With respect to sleepiness related cognitive constructs, alertness and vigilance are important, but divided and selective attention become more important for drivers.

Mixed-Type The above mentioned user types mark the extremes and mixed types exist in the operator-driver-continuum.

3.2.2. Mobile vs. Immobile Users

In a second approach the users are divided by their mobility requirements.

The work place itself might be either stationary or moving, e.g., a work station in a power plant vs. a helmsman on a ship.

Far more important for the design of warning strategies and related HMIs is the mobility of the user relative to the work place or work task. With respect to this definition, there are three user types:

Immobile users are fixed to the work place, i.e. the position of their body is defined and so is the usual line of sight. In this context, for example, a car driver is immobile, as he/she is fixed to the car seat and his/her line of sight should mainly point to the road ahead.

Mobile users move freely in the work surrounding, i.e. neither their geometric position is fixed, nor is their orientation. An example for this user type is, e.g., a night guard on his/her round through the premises of the company during the night.

Mixed-Type Obviously, there is a wide range of possible setups between the two extremes mentioned above. An example is the machine operator who is moving around the machine, but within a very restricted area.

For an immobile user, many elements defined by the work surrounding can be incorporated in the HMI-design (e.g. using the desk chair for a haptic feedback) and information about the defined work surrounding can be used, e.g., for the positioning of visual displays. For the mobile user, this is not possible and, hence, other, more general solutions to the design of the HMI of the Hypovigilance-Management-System have to be developed.

3.2.3. Professional vs. Private Users

A Hypovigilance-Management-System can be effective only if the user complies with the behavior suggested by the system and if the user utilizes the system at all. With respect to this, two different user groups are considered, *professional* and *private* users.

Professional Users might be forced to use the system by company regulations and their compliance with the system could be checked.

Private Users can neither be forced to use the system nor to comply with it but by according changes in the law which is a distant and difficult goal to achieve. Therefore, for the private market, Hypovigilance-Management-Systems need to be designed in way that they find wide acceptance. Anyhow, the effectiveness of such a system, in this case, is based on the willingness of the user to behave in a safe way.

3.3. HMI Requirements of a Hypovigilance-Management-System

In order to do a benchmark of existing Hypovigilance-Management-Systems as well as to develop new Hypovigilance-Management-Systems in case such an analysis reveals significant drawbacks, first, a definition of the requirement of an ideal Hypovigilance-Management-System is needed. Therefore, the requirements for the communication strategy as well as for their implementation in terms of appropriate HMI-elements are presented.

3.3.1. Communication Strategy

In section 2.3, it was stated that the main cause for hypovigilance is sleep debt and that the best countermeasure against hypovigilance is sleep. Moreover, other countermeasures are much less effective. As a result, it was concluded that the best countermeasure against hypovigilance related accidents is a proper shift design and sleep hygiene.

Therefore, if hypovigilance has developed already, technical measures such as Hypovigilance-Management-Systems can reduce the risk of accidents sustainably only if their primary goal is to induce a change of behavior in the user: In short terms, the user should stop his/her work task as soon as possible as this measure best reduces the risk of a work related accident. In mid terms, the user should reduce hypovigilance by getting sleep, or, at least, by napping. In long terms, the user should learn about contributing factors to hypovigilance in his/her life by means of the feedback given by the system.

In order to reach this goal, the user must always be informed about his/her status of hypovigilance. This is achieved by means of a status indicator. If the user is getting more hypovigilant, he/she should be informed at an early stage about this fact as well as about the increasing risk of an accident. Moreover, if hypovigilance still increases and the user is not reacting, an imminent warning should be administered shortly before microsleep will occur in order to arouse the user and prevent accidents as far as possible. As an ultimate measure, the system could try to keep the user awake by means of a vigilance maintenance system, e.g. to support the user stopping the work task. However, the latter two measures should, in the best case, never be needed.

It can be concluded that the design of the communication strategy is crucial for the effectiveness of the Hypovigilance-Management-System with respect to changing the users behavior. From the discussion above, the communication of the Hypovigilance-Management-System with the user can be separated into a normal mode, a warning mode and a vigilance maintenance mode.

3.3.1.1. Normal Mode

Upon activation, the system starts in normal mode in which a status indicator informs the user about the hypovigilance state monitored and indicates that the system is working properly.

Clearly, by its nature, continuous information like the hypovigilance status should be presented in a way that it is not disturbing the user. However, it should be recallable at any time without big effort.

3.3.1.2. Warning Mode

The warning mode is activated when the user reaches a critical level of hypovigilance. Within this mode, depending on the current hypovigilance state of the user and the potential risk of the situation, either a *cautionary* or an *imminent warning* is displayed with the aim to stop the user conducting the work task and, by doing so, avoid accidents.

However, the effectiveness of a warning is dependent on the personal abilities and willingness of the addressed person, or target group, to comply with the warning.

In a first step, relevant information about criteria for an effective warning are discussed. In this context, Wickens et al. (1998) state, that

> "The goal [of a warning] is to get the user to comply with the warning, and, therefore use the product in a safe way, or avoid unsafe behavior."

According to Laughery and Wogalter (1997), a warning message has to pass a sequence of mental hurdles which might hinder the desired subsequent behavior (compare to figure 3.2). Therefore, the warning information has to attract attention, be comprehensive, fit to beliefs and attitudes of the addressee, and motivate him/her performing the suggested behavior. If just one of the steps is not passed, the warning will fail.

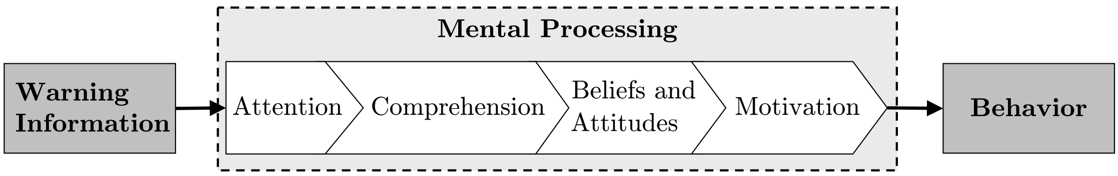


Figure 3.2.: A Model of Human Information Processing Stages Leading to Compliance of Behavior (following Laughery and Wogalter, 1997)

Attention The initial step of each warning is to catch the attention of the addressee. This is specifically important in case of hypovigilant users because one symptom of hypovigilance is the reduction of the attention level.

Comprehension relates to the grade of understanding of a warning by the receiver. Usually, the population of potential users of a warning system includes a wide range of mental competences and experiences. Therefore, the most important principle to achieve comprehension is to design for the low-end extreme and not for the average (Laughery and Wogalter, 1997). As the warning can only be effective if all potential users are able to understand its intention, the reading level for written text must be kept as low as feasible and technical information should only be part of the warning if it is necessary to behave in a safe way.

Pictorials are helpful to increase comprehension as they are perceived at first gaze without active reading. However, not every pictorial will be understood by each individual; therefore, it is recommendable to use only internationally standardized symbols, which are common to the target group.

If the target group potentially includes disabled persons, their special needs in terms of comprehension have to be considered as well. For example, visual displays have to be designed in a way that color-blind users can read them and the loudness of auditory displays has to be adaptable to users suffering from hardness of hearing.

Conclusively, a warning system should provide possibilities of individualization to guarantee comprehension by each potential user.

Beliefs and Attitudes If the content of a warning does not fit to the beliefs and attitudes of the user, he/she is less likely to comply with the warning, especially when the user is familiar with the situation. For example, if someone often drives his/her car in spite of being hypovigilant, he/she will regard this situation as being less critical than it really is. Thus, warnings about these familiar situations are rejected to be irrelevant or not true (Laughery and Wogalter, 1997). Consequently, it is important for the efficiency of a warning system that the user judges the information of the occurring hazard to be true.

Motivation A warning should encourage the user to behave in a safe way and must not encourage unsafe behavior. Laughery and Wogalter (1997) state that the motivation to comply with a warning depends on the risk perception, the severity of consequences, the cost of compliance, and the social influences:

Risk Perception If the risk of a potential hazard is perceived being high, the grade of motivation to comply with the warning is also high.

Severity of Consequences The severer the consequences of a potential hazard are judged to be, the higher is the grade of motivation to comply with the warning.

Cost of Compliance The higher the costs of compliance are the lower is the motivation to follow the suggested recommendations. These costs occur in form of effort, time, convenience or money. Especially in the field of private users, e.g., car drivers, convenience as a cost criterion should not be underestimated.

Social Influence If people hear about, or see others, complying with a warning, their own motivation to comply will increase, too.

Warning Design On this basis, Wickens et al. (1998) stated that an effective warning must first draw attention and then inform about the hazard, the potential consequences and give recommendations on how to act. Optionally, a feedback might be required from the addressee in order to confirm the reception of the information, as depicted in figure 3.3 and described below.

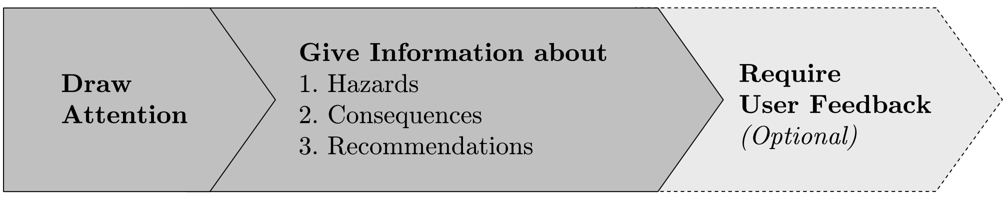


Figure 3.3.: Structure and Content of an Effective Warning

Drawing Attention The initial step of a warning is to catch the attention of the addressee.

Giving Information In the next step, information about the type of hazard, the potential consequences and the recommended behavior is provided.

Type of Hazard Firstly, a description of the upcoming hazard is given. Depending on the frequency of occurrence of a specific hazard, information about rarely occurring events has to be more descriptive than the one applying to situations that are more familiar. Additionally, individuals should not be subject to information overload, particularly in situations of high workload.

Potential Consequences Then, the user needs to be informed about potential consequences that arise if the user does not follow the suggested recommendations. With respect to Hypovigilance-Management-Systems, this is, e.g., the high increase in risk of causing a severe accident.

Recommendations Finally, information about methods to avoid the hazard are given. These recommendations or instructions should indicate the simplest, easiest and most convenient way of safe behavior (Laughery and Wogalter, 1997).

User Feedback In order to guarantee that the warning information has reached the addressee, the system can optionally require a feedback from the user. For a cautionary warning, which is mainly of informative character, a feedback is not necessarily needed. However, for an imminent warning, a user feedback is necessary to guarantee that the warning information has reached the user.

For the implementation of the above steps, detailed definitions of vigilance thresholds as well as definitions of timing information, including iterative warning tiers need to be taken into account; for example, a person might be warned on a more intensive level while being in the same vigilance state, if he/she has been warned already shortly before.

3.3.1.3. Vigilance maintenance Mode

The overall goal of the warning strategy is to stop the user conducting the dangerous work task such as driving a vehicle or operating a machine. However, a vigilance-maintenance mode is needed when an individual reaches a critical level of hypovigilance and is not able to stop the current task immediately. The user has to be kept vigilant for a certain period of time, usually until he/she can securely end the current task and take a rest. Such devices are discussed controversially, as they might encourage the user to behave more hazardous than he/she would do without a vigilance-maintenance device. For example, a car driver might prolong his/her driving time despite being sleepy. Consequently, the adjacent warning must explicitly inform the user that the vigilance maintenance device is for short term use only and cannot substitute sleep.

Several methods have been investigated with respect to vigilance maintenance. All of these aim to increase wake drive, e.g. by creating arousal and, thus, increase alertness (compare to section 2.3.2).

A promising approach to practical vigilance maintenance are so called *Landström Sounds* which have been discussed in section 2.3.2.3 as they are effective, well accepted and easy to administer.

3.3.2. HMI-Element Design

Once the main functions as well as the general structure of a warning are set, details about their technical implementation in terms of discrete HMI-elements are to be defined. General guidelines for HMI-design can be found in the human factors engineering literature (compare, e.g., to Spath et al., 2006; Bullinger, 1994; Luczack, 1998; Schmidtke, 1992). A short but comprehensive summary for the design of specific HMI-elements can be found in the European Statement of Principles (ESoP, 2005) which focuses on in-car HMIs but can be generalized in most of its parts.

Due to space restriction in this work, no general overview over HMI-design is presented. However, specific requirements for the design of the above mentioned functions are discussed below.

3.3.2.1. Status Indicators

The status indicator continually displays the actual hypovigilance state of the user. One appropriate technical solution is the use of a visual display, because it does not arrest attention and the information can be quickly recalled at every time. Lerner et al. (1996) define the following requirements for status indicators:

Perceptibility The status indicator must be designed in a way that the status information is easily perceived. Thus, the indicator lights used have to be bright enough to be perceived at all ambient light conditions, but must not cause direct glare.

Discriminability To achieve a high discriminability of the distinct states, international color-coding (e.g. *red* for *danger*) and well-known international standardized symbols should be used.

Installation Status indicators should not distract the user's attention from other displays necessary for the primary work task; therefore, status indicators must not contain flashing elements.

3.3.2.2. Warning Signals

Lerner et al. (1996) and Bekiaris et al. (2004) conclude that for Hypovigilance-Management-Systems, two levels of warnings are necessary, *cautionary* warnings and *imminent* warnings. Cautionary warnings intend to inform the individual about an upcoming hazard, whereas imminent warnings indicate the actual existence of a hazard (DIN EN 981).

A *cautionary warning* should be administered whenever a critical situation is likely to happen, but at the same time no immediate action is necessary. Here, information about the system's prediction of the situation should be given and the style of the warning should be moderate and have a low level of obtrusiveness.

An *imminent warning* is necessary when the user needs to react immediately in order to prevent an accident. The most urgent alarms should be saved for imminent warnings and should be unique. A certain frequency or pitch should be reserved for use in case of immediate danger.

Moreover, Bekiaris et al. (2004) indicate that a Hypovigilance-Management-System should provide adapted warnings, depending on the type of user impairment and external risk. Since warnings should guide the user's actions, they are to be as specific as possible. Moreover, because of intrapersonal differences in perceptions and differences in work environments, dual modality alarms are judged to be more effective (Fahey and Wierwille, 1995). For example, an auditory tone combined with a haptic stimulus is likely to be more effective over a broad range of users than just a tone. Alarms signifying immediate danger should be presented multimodally, i.e., at least through two sensory modalities in order to improve their likelihood of being perceived.

Lerner et al. (1996) add that an effective warning signal must be intrusive and convey a sense of urgency. However, warning systems in high dynamic work systems must not be as intrusive and urgent that they startle the user, and possibly put him/her in danger, or annoy the user to the point that he/she will deactivate the system.

In the following, the above general requirements are detailed for visual, acoustic and haptic warning signals with the focus of attracting the attention of the user. Means to display more complex information will be discussed in sections 3.3.2.3 and 3.3.2.4.

Visual Warning Signals A visual warning signal which is to be perceivable under nearly all possible lighting conditions must be distinguishable from other visual signals and communicate a specific message to the addressee.

The most important factors with respect to perceptibility are the *contrast* or *luminance difference*, and the *flash rate*:

The luminance of a cautionary signal must be 5 times higher than the luminance of the background; an imminent warning signal must have at least double the intensity of the cautionary signal, i.e. an intensity at least 10 times higher than the background (DIN EN 842).

To improve perceptibility, imminent warning signals should be flashing, but flash-coding should be used for imminent warning signals only. DIN EN 842 recommends a flash rate between 2 Hz and 3 Hz, with equal on and off times. For crash avoidance, warning signals of a flash rate of 5 Hz are recommend to achieve a shorter reaction time (Lerner et al., 1996).

In order to make visual signals distinguishable from each other and, thus, to communicate a specific message or a warning about a special situation, DIN EN 842 recommends the variation of color, flash rate, and of the signal location. Moreover, the use of pictorials can make a signal easier to understand.

Cautionary signals should be in yellow or amber whereas an imminent warning signal should be of red color. The visual signal should be placed in a compatible place, i.e., near or at a location linked to the place of hazard. Pictorials should accord to international standards and must be used if the target group includes color-blind individuals.

Finally, visual signals can only be perceived if they are seen. Thus, the visual output device has to be placed in the field of view and must not be masked by glare.

Acoustic Warning Signals The perceptibility of an acoustic signal mainly depends on the loudness of the signal, the ambient background noise, and the complexity of the sound:

DIN ISO 7731 determines that the signal must exceed 65 dB(A) at each place within the signal reception area, but must not be higher than 118 dB(A).

If the addressee is working at a place with high background noise and/or wears ear-protection, the signal has to be the minimum of 15 dB(A) louder than the masked threshold to guarantee audibility, but should not be higher than 25 dB(A) above the masked threshold (Malter and Guski, 2001). Green et al. (1994) recommend 15 dB(A) above the masked threshold and not more than 115 dB(A).

In relation to pure tones, complex sounds consisting of a range of frequencies and temporal patterns can be more easily identified (Lerner et al., 1996), and, thus, should preferably be used for warnings.

Work environments often present many acoustic signals, although Green et al. (1994) suggest a limitation for the number of different warning tones to three or four. Hence, it is important to make warning signals distinguishable from other signals. Therefore, the signal sounds have to differ from each other in at least two of the following factors: fundamental frequency, frequency oscillation, sound pattern intensity and pulse.

According to DIN ISO 7731, warning signals should contain frequencies between 500Hz and 2500Hz, including two fundamental frequencies between 500 Hz and 1500 Hz. The higher the fundamental frequency of a warning tone is, the more urgent it appears. Moreover, the larger the frequency oscillations within an auditory pattern are, the more urgency is included in the signal (Lerner et al., 1996). In the same way, urgency can be emphasized by rapid glides in the functional frequency. This is important as Bock et al. (1985) showed that a warning signal is most effective, when it is associated with danger.

The warning sound should be composed of 10 or more harmonically spaced components, at least four of which are prominent and in the range of 100Hz to 4000Hz. Most of the energy of lower-priority warning signals should be in the first five harmonics, whereas higher-priority signals should have more relative energy in harmonics 6 to 10.

The higher the intensity of a warning signal is, the more urgent it appears. However, intensity coding should not be used as the only cue to urgency, as most people are poor judges of absolute intensity levels (Lerner et al., 1996).

DIN ISO 7731 points out that pulsed warning signals should be preferred above continuous signals and that the pulse rate should be between 0,5 Hz and 4 Hz. Lerner et al. (1996) emphasize that the duration of the single sound signal must not be shorter than 200 - 300 ms. Otherwise, the tone would not be perceived as being very loud.

In addition to the factors of perceptibility and of individualization, the sound source location, the onset and offset rates and the duration of the warning signal have to be considered as well:

The sound source should be compatible with the direction of the hazard. Laboratory research showed that with brief sound stimuli, especially front-back confusion often occurs. Therefore, directional warning sounds should not be presented in the median plane of the addressee (Proctor and Proctor, 1997).

In order to alert but not to startle the user, Lerner et al. (1996) recommend an onset rate higher than 1 dB/msec but less than 10 dB/msec, whereas the onset and offset rate should be equal.

Finally, imminent acoustic warning signals should be repeated as long as the hazard condition exists or until the user has given a feedback.

Vibrotactile Warnings Another promising possibility to attract an individual's attention is the use of a vibrotactile stimulus. Although the use of vibrating devices is currently not very common, despite the application in mobile phones, their use becomes more and more important, especially in noisy environments. In order to ensure perceptibility, the choice of frequency, intensity and pulse rate is important:

The detection threshold for vibrotactile sensation is lowest at frequencies between 200 and 400 Hz, thus, this frequency range is recommended for the design of vibrotactile warning displays (Sherrick and Cholewiak, 1986).

Lerner et al. (1996) recommend a display intensity 20 - 30 dB above the masked vibratory threshold, as measured at the workplace under all anticipated environmental conditions.

Vibrotactile displays can be either continuous or pulsed; Lerner et al. (1996) could not find any guidelines determining the pulse rate and, therefore, recommend investigating this value in application specific tests.

Vibrotactile displays are less suitable to communicate a specific message, as individuals are not used to distinguish between several vibrating patterns. As the vibrotactile stimulation has to be sensed by the skin, the device has to be worn directly on the skin or at least close upon thin clothing. As described by Sherrick and Cholewiak (1986), the body areas most sensitive to vibrotactile stimulation are the fingertips and the palm followed by forearms, thighs, feet and toes. The buttocks show the lowest sensitivity to vibrations.

3.3.2.3. Screen Displays

Once the system has drawn the attention of the user by means of the above warning signals, more complex information about the type of the hazard, the potential consequences as well as possible countermeasures is to be communicated (compare to section 3.3.1.2).

Screen displays, which represent a specific case of general optical displays, can be used for this purpose. However, the user needs to actively look at the screen and, thus, can be distracted from his/her primary work task. Moreover, screens might not be usable in specific application scenarios of a Hypovigilance-Management-System.

In the context of this work, the relevant information on the screen needs to be perceivable at a glance in order to transmit the warning information quickly as well as to avoid negatively affecting the primary work task. Requirements for appropriate screen information design with respect to perception in terms of typeface, character size, spacing, contrast, color, glare and perceptual grouping is well known and, thus, not discussed further (compare e.g. to Green et al., 1994; ISO 15008; DIN EN ISO 9241).

However, once the information is perceived, it must be understood in a next step. Consequently, the requirements with respect to readability, the complexity of pictorials and the use of technical terms have to be kept as low as feasible:

As the information needs to be perceived quickly, the warning should consist only of a few words or a few short and clear sentences, which focus on the core statement. The use of pictorials can improve and quicken the comprehension, but only if the symbols and icons used are familiar to the user. Moreover, color coding should be used sparsely (Green et al., 1994).

However, with respect to Hypovigilance-Management-System for the user type *driver* (i.e., users in a system of high system dynamic), Fahey and Wierwille (1995) state that the use of visual displays is problematic. If a driver is drowsy and inattentive he/she may be less likely to perceive a visual warning in time to react appropriately. Also, most stimuli presented during driving are presented through the sensory channel of vision. Hence, the use of a visual display may overload this channel, and possibly distract the driver. If a visual signal is used as part of a warning, it should be presented within 15 degrees of the driver's normal line of sight of the roadway (Lerner et al., 1996).

3.3.2.4. Speech Displays

Speech displays, which represent a specific case of general acoustic displays, are an alternative to screen displays with respect to the presentation of more complex information: Their advantage with respect to the perception of the displayed message is the independence of the lighting conditions and of the field of view. However, the presentation and recognition of a speech message takes more time than the recognition of a short written sentence or a pictorial (Lerner et al., 1996). Thus, special attention has to be paid to the perceptibility which depends mainly on the speech quality, the output intensity, the ambient noise, the frequentness of the message repetition, and the presentation rate.

In order to realize good speech quality, the voice message should be recorded by a trained, female, accent-free, native speaker. Furthermore, the playback should not be impaired by temporal and non-linear distortion (ISO 9921).

The intensity has to be taken into account twofold, at voice recording as well as at playback. For message recording, ISO 9921 recommends a vocal effort of 72 dB (A), one meter in front of the speakers' mouth or the microphone. The playback of the warning message has to be loud enough to be clearly intelligible in all anticipated conditions, i.e., the speech message should not be masked by ambient noise, echoes and/or conversation (ISO 9921).

As a spoken message is not necessarily understood at its first presentation, it has to be repeated at least once, but not more than three times, to minimize the potential of embarrassing the user (Lerner et al., 1996). Moreover, the messages should be recallable by the user, e.g., by means of a "repeat" button.

More detailed information about the technical requirements of voice reproducing can be found in ISO 9921.

Similar to written text, the wording of a speech message must as well follow the principle of designing for the 'low end extreme'. Thus, the requirements regarding vocabulary, message length and message content must be kept as low as possible (e.g., compare to Lerner et al., 1996; ISO 9921; Campbell et al., 1997).

With respect to the installation of speech displays for warnings purposes, it has to be taken into account that all other inputs to the according speaker or headphone have to be interrupted automatically when the warning is displayed. If feasible, auditory output from other displays should be muted as well.

3.3.2.5. Manual Input Devices

Suitable for the manual input of a user confirmation are, i.a., pushbuttons. According to Bullinger et al. (1997), the following mechanical properties are recommended:

The contact surface of a finger-operated button should have at least a diameter of 15 mm; a hand-operated push button should show a contact surface of more than 50 mm. Moreover, a finger-operated button should show a concave shape in order to guide the finger to the center of the button. In contrast, a hand-operated button should have a convex shape, which corresponds with the shape of the palm. If the button is also used in dirty work environments, its texture should be rough, e.g. knurled, in order to guarantee good actuation.

The force resistance of a finger-operated pushbutton should be 1–8 N; a hand-operated pushbutton should have a force resistance of 4–16 N.

In order to avoid accidental operation of the button, force free sensor keys are not recommendable. Moreover, the feedback button is to be labeled unambiguously in order to clearly propagate purpose. International standardized pictorials should be used where possible.

In work systems with a high system dynamic, an important requirement for a device for user feedback is that it must not interfere with the user's primary task. Therefore, the pushbutton has to be positioned in a distance reachable without interrupting the primary task. For example, in a car, a recommended position for confirmation buttons is the steering wheel, as this position is compatible with traffic safety, and is convenient for the user.

3.3.3. Usability

A Hypovigilance-Management-System will find wide application only if a good usability is achieved. In the context of this work, at least two aspects of usability are to be addressed: On the one hand the system must not disturb the main task or work task of the user, e.g., driving a car or operating machines.

On the other hand, the HMI must be unobtrusive and reliable in order to guarantee the acceptance of the system by the user: it has been shown that the primary goal of a Hypovigilance-Management-System must be to change the behavior of the user by getting his/her compliance with the warning. Clearly, this can be achieved only if the user accepts the system, especially in the case of private users which can not be forced to comply with the system. Moreover, good acceptance is the basis for a successful marketing of the product and, hence, a key factor for a wide distribution.

3.3.4. Personalization of the Human-Machine-Communication

From the definition of requirements above, a clear need for the personalization of the respective HMI is deduced in order to guarantee effective and efficient warning on the one hand and high user acceptance on the other hand. Three modalities are to be addressed with respect to the personalization of the HMI of Hypovigilance-Management-System.

3.3.4.1. Sensors and Algorithms

Although the sensory system is not the main focus of this work, a short notice on the personalization seems to be important nevertheless:

Relevant psycho-physiological parameters that are important in respect of the measurement of vigilance vary both on an inter-subjective and on an intra-subjective level. The latter variance is comparatively small and has to be compensated for by intelligent algorithms. However, the much bigger inter-subjective variance in the parameters often can not be compensated automatically. Hence, the system must know about the general behavior or reactions of the user of the system. Thus, the system should know the general characteristics of the driver's behavior in advance, i.e., a general "baseline measurement" must be conducted in a vigilant state and stored in the system.

3.3.4.2. Communication Strategy

In addition to the general definition of a communication strategy as outlined above, the strategy must be adapted to the specific requirements of the user such as, e.g., specific restrictions of a user; if a warning is decided to be given both on the acoustic channel (e.g., a warning sound) and on the haptic channel (e.g., a vibrating seat), but the user has difficulties in hearing or even suffers from deafness, then the warning must be issued in a different way in order to still be effectively and efficiently delivered to the user.

3.3.4.3. HMI-Elements

The HMI-elements establish the communication with the user and, thus, are the physical representation of the communication strategy.

On the one hand, the HMI-set-up must be adaptable to the cultural background of the user. For example, a speech output of the system must be at least in a language that the user is able to understand, and, for a most efficient understanding of the information, the message should be in the native language of the user.

Moreover, when designing the Hypovigilance-Management-System for an international market, cultural differences in terms of the semantic background of a warning must be considered and the system must be adaptable to the semantics of different regions. Barber (1994) reports confusion by warnings and uncertainty on how to react to the warning in car drivers, due to an inconsistent use of different warning symbols for the same information and a different definition of the meaning of specific color coding in different cultures.

On the other hand, the characteristics of the single HMI-elements should be adaptable to the personal preferences in order to guarantee a good acceptance. As an example, the volume of acoustic signals should be adaptable in a certain range, enabling the adaptation to personal preferences but guaranteeing physical perception.

3.3.5. Universality

In this work, so far, the different application scenarios have been defined in terms of the system dynamic of the according work system (compare to section 2.1) and different types of users have been distinguished (compare to section 3.2).

All of the potential users of a Hypovigilance-Management-System must be warned effectively with respect to the use context in all of the potential application scenarios. However, considering the many potential application fields, the technical effort to design a specific HMI for every application is enormous. Thus, a Hypovigilance-Management-System should be usable in as many different application scenarios as possible both in terms of the communication strategy employed as well as in terms of the HMI-elements utilized. Hence, a Hypovigilance-Management-System should be "universal" with respect to this definition, although a total universality, i.e., the employability in *all* possible scenarios and with *all* potential users might not be reachable.

3.4. Existing Hypovigilance-Management-Systems

A variety of Hypovigilance-Management-Systems exists, demonstrating the acceptance of the necessity of such systems. However, the systems present only partially meet the requirements for Hypovigilance-Management-Systems that have been laid out so far as will be shown in a benchmark analysis below.

It is to be emphasized that many of the present Hypovigilance-Management-Systems are either in a concept stage or actually under development. Thus, the sources that could be used for the description of these systems sometimes are of a cursory character. For reasons of space restrictions, in this work, only concepts and systems that are at least in a pre-development stage are described. Many concepts that are still in the pure "idea" phase can be found in relevant patent databases (compare e.g. to USPTO, 2006).

First, the existing systems and concepts are introduced where the focus of the descriptions is laid on the HMI. If not mentioned otherwise, no evaluation data of the respective system is available. Then, an analysis of the benefits and drawbacks of these systems is presented.

3.4.1. Engine Driver Vigilance Telemetric Control System (EDVTCS)

The EDVTCS predicts the loss of concentration and alertness via a derivative of electrodermal activity. The electrodermal activity is measured by a portable device implemented as a wrist watch (figure 3.4a). The collected data is transmitted via a radio transmitter to the stationary processor unit depicted in figure 3.4b, where the raw data is analyzed and a vigilance value is computed. The EDVTCS has been in use for five years on the Russian Railways and has been used in road transport for long-haul trips and transporting hazardous goods as well (Whitlock and Pethick, 2002; Neurocom, 2002).

(a) Wrist Watch (b) Stationary Unit

Figure 3.4.: EDVTCS System Elements (Neurocom, 2002)

The warning strategy of the EDVTCS consists of two steps. First, an audible alarm is presented to the user "a few tens of seconds before the user's level of alertness decreases to a critical value" (Whitlock and Pethick, 2002, page A.9). Secondly, an automatic emergency braking mechanism is activated when drowsiness is detected. The user can postpone the moment of braking by pressing the vigilance knob at the electro-pneumatic valve whistle. Should the driver be capable of restoring his/her normal efficiency, the emergency braking process can be canceled completely.

The HMI of the EDVTSC system physically consists of the wrist watch worn by the user and the display of the stationary unit which is indicating the users vigilance level as a yellow bar of variable length. The electro-pneumatic valve whistle of the train is used for the acoustic alarm and is combined with a vigilance knob that is to be pressed to stop the alarm and to simultaneously postpone the moment of braking (Whitlock and Pethick, 2002; Neurocom, 2002).

3.4.2. MicroNod Detection System (MINDS™)

MINDS™ is a capacitance based system that can be embedded in the roof of an automobile, truck or bus to detect head nodding. The sensor data is send to a microprocessor which computes the exact spacial position of the drivers head. If a predetermined threshold is passed, the driver is alerted. In order to minimize false alarms, the system is adapting to the driving behavioral patterns of the individual user. MINDS™ is not yet commercially available, but has been tested in laboratory studies. In figure 3.5 the experimental setup of the MINDS™ is depicted. (Whitlock and Pethick, 2002; Kithil et al., 2005; Complexica, 2001; Bekiaris and Nikolaou, 2002)

Figure 3.5.: Experimental Setup of the MINDS™ (Whitlock and Pethick, 2002). The Ellipse Indicates the Sensor Position.

Based on several experiments, a vigilance threshold is identified which separates drowsy users from awake users. It is defined as three standard deviations of head movement behavior above the "awake" baseline. Kithil et al. (2005) intend to implement a three level warning strategy depending on the percentage of time above threshold. The first warning level is a visual notification. If the time above threshold increases, the visual notification is combined with a short audible notification. If the percentage of time above threshold continues to increase, the audible notification cycle time lengthens and repeats as third warning level. In order to momentarily disable the notification devices, a reset switch is provided (Kithil et al., 2005).

The human machine interface of MINDS™ consists of a visual and an audible signal indicator and a reset button to cancel the warnings. The visual warning signals are presented by LEDs installed within the visual field of the user. No concrete information about the way of presenting the acoustic warnings and the location and design of the reset button is available. (Kithil et al., 2005; Whitlock and Pethick, 2002).

3.4.3. Eye Tracking Alertness Monitor

The eye tracking alertness monitor is a device measuring eye droop, pupil occlusion, and eyelid closure via a camera set up in front of the driver, as depicted in figure 3.6. The eye parameters (eyelid closure, eye droop, pupil occlusion) are estimated from the face image as primary input. If drowsiness is detected, the driver is acoustically notified. Currently, the device has been used in laboratory studies only, but presumably it could be used in all applications where the user is looking into one predefined direction. Thus it may be applicable for all kind of driving tasks (Technology and Ltd., 2005; Whitlock and Pethick, 2002; Bekiaris and Nikolaou, 2002).

Figure 3.6.: Camera of the Eye Tracking Alertness Monitor System Installed in a Car (Whitlock and Pethick, 2002)

The alarm is set off if the eyes remain closed for more than 1.5 seconds or if a sustained pupil occlusion is detected. After a previously specified duration, or when the eyelids are detected to be fully open again, the alarm is deactivated. The computer generated alarm can be either a simulation of a human voice or a beeping sound.

Presumably, the acoustic warning is presented by any loudspeaker which is triggered by the processing unit. Manual interaction with the system is not needed. The camera is embedded in the environment (dashboard) and the alarm is deactivated as soon as fully open eyes are detected.

3.4.4. ABM Drowsiness Monitoring Device (DMD)

The AMB DMD measures EEG signals with two electrodes housed in a baseball cap as depicted in figure 3.7. The EEG data is transmitted to a processor located within 20ft (approximately 6.1 meter) of the user. The main application field of the DMD is in the transportation sector, but ABM is also looking at night-shift workers, security guards, and military personnel as market segments. Although the DMD is on the market, so far, it is mainly used in laboratory trials and driving simulators (Whitlock and Pethick, 2002; Cavuoto, 2006).

At the onset of “drowsy” EEG readings, an auditory warning is presented. The effects of different types of feedback on performance is currently being investigated by the company (Whitlock and Pethick, 2002).

(a) ABM Monitoring Device with Disposable Sensor

(b) Baseball Cap With Cover

Figure 3.7.: ABM Drowsiness Monitoring Device

In order to use the DMD, the user has to wear the equipped baseball cap with the embedded EEG electrodes that dispense a small amount of conductive gel. The sensors are designed to be disposable to maintain hygienic standards for each user. To guarantee the transmission ratio, the user has to stay within a radius of 20ft around the processor.

It is not specified if the audible alarm is emitted by the baseball cap, the processor unit, or an additional loudspeaker (Whitlock and Pethick, 2002).

3.4.5. Vehicle Driver's Anti-Dozing Aid (VDADA)

The vehicle driver's anti-dozing aid (VDADA) is a headband mounted device which is currently tested in three different versions by the U.S. Army. The basic version detects head nods by the use of a mercury tilt switch and warns the user both in an acoustic and vibrotactile way. The second version includes an additional IR based eye closure sensor to trigger the alarm. In addition to the features of the second version, the third one provides CO_2 blasts to warn the user (Rogowski et al., 1997). No picture of the VDADA is available.

As there are three different versions of the VDADA, the warning strategy for each version is slightly different. For the first version, the temple area vibrator and the beeper are activated instantly when a nod is detected. As the second version is additionally equipped with an eye closure sensor, both the beeper and the vibrator are activated at eye closures from one to two seconds or at head nodding. The third version reacts upon the same thresholds than the second one, but provides a three mode warning, featuring a beeper, a vibrator, and pulsed CO_2 blasts at the users temple (Rogowski et al., 1997).

The sensors and the HMI-elements are all included in a headband which is to be worn by the user, and the vibrator and the beeper are integrated into one unit which is located at the temple of the user. For the pulsed CO_2 blasts, a commercial carbon dioxide cartridge is used, providing random blasts to the temple areas of the user.

3.4.6. Driver Fatigue Monitor DD850

The Driver Fatigue Monitor is a product of Attention Technologies. It is the market version of research that has been published under the name *PERCLOS Monitor* and *Copilot* (Barton, 2003a; Ayoob et al., 2005). It is a camera based hypovigilance detection system for in vehicle use, designed to be mounted on the dashboard to the right of the steering wheel. The camera unit is directly attached to the warning unit, hence, only one device has to be mounted (compare to figure 3.8). The video data collected is processed by means of the PERCLOS algorithm that measures the percentage of eye closures within a defined interval (Ayoob et al., 2005; Barton, 2003b).

Figure 3.8.: Driver Fatigue Monitor DD850 With Warning Device and Camera (Attention Technologies Inc., 2006)

The warning strategy aims to encourage the driver to stop and take a rest by informing him/her about the driving time and the way he/she drove with eyes closed. Once the PERCLOS-threshold is crossed, a warning sound is given and the length of the longest single eye closure observed during the integration period is displayed. When the OK-button is pressed, the warning sound terminates and the time since the last warning as well as the total number of warnings given is depicted. After each warning, the sensitivity is raised and the PERCLOS calculation is resumed from zero. Thus, the sensitivity rises from low to medium after the first warning, and to high sensitivity after the second warning.

User interaction with the Copilot system is based on visual information on the display, audible notifications, the use of the OK button, and the functional controls to adjust systems settings.

3.4.7. SafeTRAC

SafeTRAC monitors the road ahead of the vehicle by means of a video camera and tracks lane markings and other road features in order to determine the position of the vehicle in the lane. The driver's level of alertness is computed by analyzing the steering behavior (Assistware Technology, 2006). SafeTRAC is available as an on-dash unit as depicted in figure 3.9a. Additionally, an in-dash and an embedded version is available for OEMs.

Fleet operators represent the main target group for marketing as they can use the data collected for route planning and driver observation.

(a) On-Dash Unit Including Camera (Assistware Technology, 2006).

(b) Alternative Display Contents. Top: Normal Mode, Bottom: Warning Mode (Assistware Technology, 2006).

Figure 3.9.: SafeTRAC

There are two possible warnings: lane departure warning if a lane change without using the turn signal is detected and drowsiness warning if "drowsy or distracted driving patterns" are detected (Assistware Technology, 2006).

The HMI of the in vehicle unit includes a single-line display, a loudspeaker and a volume control. In normal operation mode, the alertness score is continuously presented on the display, as depicted in the upper part of figure 3.9b. When sleepiness is detected, the driver is visually and acoustically warned and informed that it is time to to take a rest. The according output is shown in the lower part of figure 3.9b. In general, SafeTRAC is password protected which allows the fleet management to lockout certain convenience settings (i.e. volume, sensitivity) from being changed by the employee.

3.4.8. Advisory System for Tired Drivers (ASTiD)

The ASTiD computes the degree of hypovigilance of the driver based on the time of day, the quality of sleep in the last 24h, the total driving time, and the actual steering movements measured. The steering movement sensors identify both the degree of monotony of the driving conditions and offsets from the baseline steering behavior (Pernix, 2006; POST, 2005). ASTiD is commercially available.

Figure 3.10.: New ASTiD v4.06 Device Sized to Fit into the DIN1 Radio/Cassette Slot in the Dashboard (Pernix, 2006)

Within the ASTiD system, the individual actual phase of circadian rhythm is computed based on information about the quality of sleep, the length of driving, and the time of day. Assessing these user specific data and the current steering patterns, the system can detect the onset of hypovigilance in advance. Consequently, the driver is warned by audible and visual alerts before he/she is aware of being tired (Pernix, 2006; POST, 2005).

The HMI of the ASTiD system is depicted in figure 3.10. It includes a numeric keypad, a multi function screen and a slot for an HD Card for the storage of personal data. Presumably, the visual alerts are provided via the multi function screen. No information is available with respect to the nature and the way of presenting the audible alerts.

3.4.9. SAM G-3™

The SAM G-3™ is an electronic driver fatigue warning system for trucks and buses that monitors the driver's corrective steering wheel movements via a magnetic sensor. By august 2003, 1500 SAM G-3™ units as depicted in figure 3.11, had been sold to U.S. fleets (Barton, 2003a).

Figure 3.11.: On-Board Unit of the SAM G-3™ (TOMR Technologies, 2004)

The warning strategy of SAM G-3™ is based on the fact that steering wheel movements stop momentarily when micro sleep occurs. If the steering wheel stops moving for a predetermined time, a high decibel acoustic alert is administered. The alarm is terminated automatically when normal steering wheel movements are registered again. If no steering correction is made within one second of the alarm, the cruise control is disabled, hence, slowing down the vehicle.

The on-board unit includes two controls, a power switch, and a turning knob to adjust the time delay of the warning. It is not specified if the alarm sound is emitted by the on-board unit itself or by other means such as the car speakers.

3.4.10. TravAlert®

TravAlert® monitors steering movement through data from a steering shaft sensor. It is automatically activated when a speed of 42 mph is exceeded. If steering patterns deviate from the norm, thus, indicating a lapse in driver alertness, an audible alarm is administered. The sensor data as well as the real time alarm, the duration of the alarm, and the total number of alarms are stored on an EEPROM and can be downloaded (Hartley et al., 2000; Kircher et al., 2002) for post-analysis, e.g., by the fleet management.

It is not specified if TravAlert® is commercially available and/or currently in use in the field.

The warning strategy is based on the identification of improper steering patterns which, in case, trigger a gradually ramping alarm sound after a predetermined time delay of 4 to 13 seconds. Once normal steering patterns are resumed, the alarm is terminated.

Not much information is available on technical details or the company itself and neither is a photo available. However, the system resembles other systems that analyze steering movements. No validation or performance data are available.

3.4.11. ARRB Fatigue Monitoring Device

The fatigue monitoring device has been developed by the Australian Road Research Board (ARRB) and the Australian Coal Association Research Program (ACARP) especially for the application in heavy vehicles used in open coal mines (Mabbott, 2003). It measures reaction times to stimuli in relation to a baseline performance. Depending on the reaction time, the interval between the stimuli is adapted. A decision task is included as the user has to press the button according to the side on which a lamp provides a stimulus and stimulus presentations are random for left and right light.

According to Mabbott (2003), the warning strategy of the fatigue monitoring device includes four levels depending on the response time:

1. Under normal conditions, the device presents a light and audio stimulus every 7 to 10 minutes and the driver has to respond within one standard deviation (SD) of the baseline mean.

2. If the reaction is between one and two SDs slower than the mean, or the wrong button is pressed, the time period between stimuli presentation is shortened to 4 to 7 minutes.

3. If the reaction is between two and three SDs slower than the mean, an alert is sent to the supervisor and the following stimuli will be presented within the next 2 to 4 minutes. At this level the supervisor should contact the operator on the radio to discuss countermeasures.

4. If the reaction time to stimuli is slower than three SDs or is completely missing, the device emits a warning sound. An imminent warning is provided to the supervisor as well. At this level, the operator should no longer drive, but take a nap. Until the supervisor reacts to the warning, the fatigue monitoring unit stimulates the operator every minute.

If the system recognizes faster reactions, the stimulus presentation is slowly moving back to the normal 7 to 10 minutes interval unless the 4^{th} level is reached.

The in-vehicle human machine interface of the fatigue monitoring device consists of two units: the stimulus box and the reaction box. Both boxes are placed on the top of the dashboard as depicted in figure 3.12.

The stimulus box features two illuminated green arrows that point left and right. The reaction box includes the main processing unit, a buzzer, a touch key identification unit and two large, green heavy duty response buttons which have to be pressed for the reaction test.

Figure 3.12.: Fatigue Monitoring Device Installed in a Mining Truck. The Stimulus Box is Located on the Left; the Reaction Box is Placed on the Right of the Steering Wheel (ARRB Consulting, 2006)

The radio is used for the communication with the supervisor. Personal settings like the reaction time baseline are entered on a personal touch key at each log in. Each slow response is transmitted via a radio link to the control room and is shown on the supervisor's monitor ranked by priority.

3.4.12. Actiwatch Alert

The Actiwatch Alert is a wrist-worn accelerometer that comprises an auditory alarm and signal processing electronics (see figure 3.13). It continuously records the wrist movements of the user and generates an audible alarm when no wrist movement is detected within a predetermined time interval. The embedded software stores the accelerometer values, the time of the alarm activation and the time taken to cancel the alarm. The Actiwatch Alert is commercially available and has been tested with civil aviation pilots in the UK (Civil Aviation Authority, 2003).

Figure 3.13.: Wrist-Worn Actiwatch Alert Including a Button to Cancel the Alarm (Camebridge Neurotechnology Ltd., 2006)

The warning strategy of Actiwatch Alert is based on the fact that sleep onset is accompanied by the absence of wrist movements (Civil Aviation Authority, 2003). Actiwatch Alert administers an alarm if no wrist movements are detected during a pre-set time interval of either one, two, five, or 10 minutes. The alarm is terminated by pressing the button on the surface of the watch. Additionally a random alarm generator can be activated to measure alertness by means of reaction time (Camebridge Neurotechnology Ltd., 2006).

The Actiwatch Alert device is of the size of a normal wrist watch and is worn on the wrist. It features an event marker button and a feedback button as well as an acoustic alarm generator.

3.4.13. Doze Alert

Doze Alert is a head nodding sensor which is worn behind the ear similar to a hearing aid. When the head nods forward, the device emits a buzzing sound, which is intended to cause the user to raise his/her head back to the upright position. The Doze Alert unit as depicted in figure 3.14 is commercially available. Originally, Doze Alert was developed for drivers, but it is supposed to be used by night shift workers, nurses, and late-working students as well (Sav-A-Life, 2004).

Figure 3.14.: The Doze Alert Unit (worn behind the user's ear Sav-A-Life, 2004)

The warning strategy is based on a single threshold for sensor/head position. If a certain angle is exceeded, the buzzer is activated until the sensor is in the upright position again.

The HMI of Doze Alert is embodied in the ear worn device. It includes the battery compartment, a lever to select the sensitivity and the buzzer. The sensitivity, i.e. the exact angle at which the buzzer is triggered, can be selected from 18 pre-selected settings.

3.4.14. Stay Alert

Stay Alert is another head nod based drowsiness detector. It consists of a flexible band that is worn around the neck and positions a bulb shaped actuator below the user's chin (compare to figure 3.15). Originally developed for car drivers, the inventor intends to sell

Stay Alert also to shift workers, night guards, students, military sentries, avionics and pilots.

Figure 3.15.: Stay Alert Device in Use (Bang, 2006)

The warning strategy is based on the simple effect that the head drops forward in case of getting drowsy. When the chin falls on the bulb shaped actuator, a squeezing sound is emitted (comparable to a rubber duck) and the bulb is illuminated by a red flashing light.

The HMI of Stay Alert is embodied in the actuator. When nodding off, the user gets an immediate tactile feedback as his/her chin touches the bulb. Additionally a warning sound is mechanically produced by a flute using the escaping air from the elastic bulb. Moreover, the deformation of the elastic bulb results in activating a switch for the flashing light.

3.4.15. Nissan Safety Drive Advisor (SDA)

The Nissan SDA comprises both the measurement of driving time and the measurement of erratic steering behavior. It can be ordered as supplementary equipment for the Nissan Bluebird Maxima. A system schematic is depicted in figure 3.16.

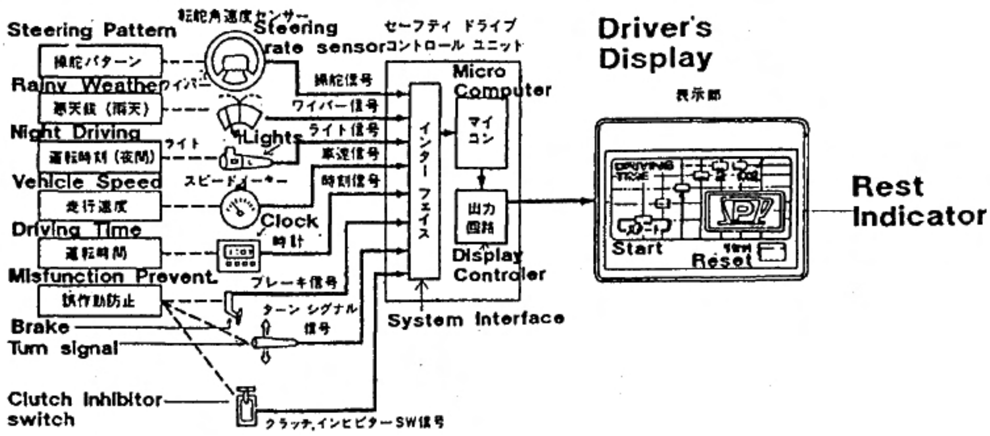


Figure 3.16.: Schematic of the SDA System Layout (from Haworth et al., 1989)

The timing device reminds the driver to take a break within a specific time interval that is computed as a function of the driving conditions. The steering pattern monitor uses a combination of a photo-optical sensor and a velocity sensor to capture the driver's steering behavior (Haworth et al., 1989).

Two independent warning strategies are supported:

In daylight conditions, the timing device measures two hour periods from departure. At the end of this period, a coffee cup is displayed and a buzzer sounds in order to remind the driver to take a break. If the driver does not turn off the warning or the car does not stop for at least five minutes, the buzzing sound is emitted each subsequent hour[2]. In the evening (lights on), or at bad weather conditions (windscreen wipers on) the rest breaks are timed at shorter intervals.

Independently of the timing device, the steering behavior monitor alerts the driver each time erratic steering behavior is detected with respect to deviations from the baseline behavior stored in the system.

The HMI of the SDA includes a dash board display, a buzzer, and a device to terminate the buzzer alarm which is not described in more detail.

3.4.16. Photo Driven Alert System

The Photo Driven Alert System is a prototype of a portable eye blink detector that is worn on the ear as depicted in figure 3.17. Additionally, the system includes a peripheral unit containing an amplifier, a metal detector, and a sound emitting system. The eye blink sensor is connected to the peripheral unit via a cable (Whitlock and Pethick, 2002).

(a) Side View

(b) Front View

Figure 3.17.: Prototype of the Ear-Worn Photo Driven Alert System (Whitlock and Pethick, 2002)

The warning strategy of the Photo Driven Alert System is based on a single vigilance threshold. If the user exceeds the blink rate threshold of one blink per 4 - 6 seconds, an auditory alert is provided.

The HMI of the system includes the ear-worn eye blink sensor and the alarm generator. Thus, the system is somehow intrusive as the sensor has to be worn close to the eye. It is not specified if the alarm can be terminated manually.

3.4.17. Siemens Driver Attention System

The Siemens Driver Attention System was announced in a press release as a system to detect hypovigilance in truck drivers by means of an infrared camera in the dashboard which, supported by according algorithms, measures viewing direction and eye blink parameters.

[2]Similar, purely time-based systems are provided by many OEMs, such as, i.a., VW, Audi, DC, etc.

Figure 3.18.: Schematic of the Siemens Driver Attention System (Siemens VDO, 2006)

It features a two tiered warning strategy. For cautionary warnings, a seat vibration prompts the driver to turn his/her attention back to the road. If the camera registers critical drowsiness, a signal tone of increasing intensity is sounded (Siemens VDO, 2006).

No information about the actual HMI elements as well as about the required user feedback is provided. Although the press release indicates that the system is on the market, an expert interview with one of the system developers revealed that the system is still in the development phase (Giralt, 2006).

3.4.18. AWAKE Hypovigilance-Management-System

Prototypes of a hypovigilance detection and warning system have been developed and tested within the AWAKE project (AWAKE, 2006). Apart from issues related to sensor data fusion or basic research on hypovigilance detection in a vehicle environment, the focus was especially on providing the most usable and acceptable information to the individual driver (Marberger et al., 2004). The result is the most advanced Hypovigilance-Management-System known to the author.

The structure of the AWAKE prototypes is depicted in figure 3.19. They consist of several subsystems that are closely linked to each other.

The *Hypovigilance Detection Module (HDM)* analyzes driving behavior, eyelid movements, and steering grip forces and provides high level information on the driver state (i.e., three levels of hypovigilance). The *Traffic Risk Estimation Module (TRE)* uses a range of vehicle sensors to obtain information on specific traffic hazards (e.g. frontal collision or lane departure) and computes a general level of traffic risk. The *Driver Information Module (DIM)* is based on a smart card application and provides static and dynamic information on the current driver and, hence, serves the personalization of the system. The output of the modules are coordinated by a central information manager

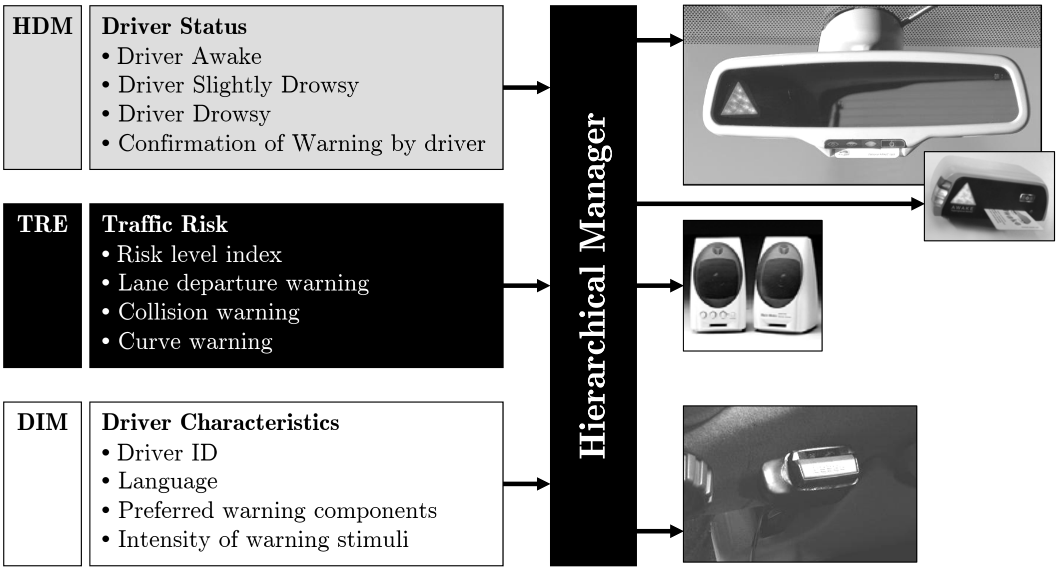


Figure 3.19.: Schematic of the AWAKE Hypovigilance-Management-System (Hagenmeyer et al., 2005)

unit, the *Hierarchical Manager (HM)*, and are used to activate the according warnings (Hagenmeyer et al., 2005).

The HMI is multi-modal and consists of acoustic, visual, and tactile components, namely a central device accommodating visual indicators, a smart card reader, acoustic output devices, and a seat belt vibrator. Specific information and warnings are issued according to the following rules:

- If the driver is diagnosed being fully awake only imminent warnings related to “frontal collision”, “lane departure” or “critical curves ahead” can be activated by the system.
- If the driver is diagnosed as being in an intermediate state of vigilance, warnings related to lane departure, frontal collision and critical curves are activated at an earlier point of time followed by the recommendation to take a rest.
- If the driver is diagnosed being critically drowsy, the system catches the driver’s attention by means of multimodal stimuli and recommends taking a rest. All associated driver assistance systems that monitor driving performance are set to a sensitive mode to account for the higher risk situation.

In conclusion, the AWAKE system features a warning structure that follows the requirements defined in section 3.3.1.2. However, with respect to hypovigilance warnings, the system includes only one tier of warning and mainly is used for the sensitivity setup of the other warning functions, such as lane departure warning. Moreover, no vigilance maintenance function is included. Furthermore, the system can be used in cars and trucks only.

3.5. Rating of Existing Systems

The above systems were analyzed with respect to the requirements for Hypovigilance-Management-Systems described earlier in this chapter. In order to do so, the requirements first have been summarized in a matrix. For reasons of space restrictions, the complete matrix is not included in here, but is depicted in appendix A.

From the requirements, six categories were deduced, namely *Universality, Warning Modes, Warning Quality, HMI, Usability* and *Personalization*. In order to analyze the existing systems described in section 3.4, these categories have been operationalized as described in table 3.1.

The existing systems were analyzed with respect to these categories as is shown in table A.1. For each of the above categories, a summarizing index has been computed (see table 3.2). The exact method used to integrate the single results is explained in appendix A.1.

None of the systems is universal: About half of the systems (10/18) are partly universally employable, i.e., can be at least used either in a mobile way or have predictive characteristics and, thus, can be utilized in work systems of high system dynamic. The other half is not at all universal in this sense.

None of the systems features a comprehensive communication strategy: One third (7/18) of the systems is characterized by a mediocre communication quality, i.e., includes either a normal mode or a vigilance maintenance mode. The rest of the systems is characterized by a poor communication quality.

The quality of the actual warning of the systems is somehow better: Half of the systems (9/18) administers warnings of mediocre quality, two systems even administer warnings of high quality, i.e., first attract attention, then, provide more complex warning information and, finally, require a user feedback. All of the systems attract attention in one or the other way, however, with respect to an effective hypovigilance warning, this measure by itself is too simple.

The technical implementation of the warning strategy in terms of the HMI is mediocre for a third (6/18) of the systems and good for another third (5/18). A third (7/18) does not include a satisfying HMI with respect to, e.g., multimodality, choice of sensory channels, or adaptability of the warning intensity.

The usability of the systems with respect to safety and obtrusiveness, overall, is good. Two thirds (11/18) of the systems feature a good usability and the other third at least features a mediocre usability. It is to be mentioned that only two aspects of usability have been taken into account. At least of the same importance are other dimensions of usability such as learnability or acceptance. However, these dimensions can only be analyzed in user tests but can not be deduced from a literature review, and, hence, cannot be addressed in this work.

Only half (9/18) of the systems are personalizable at all, out of which only three systems are fully personalizable.

No system features a satisfying warning strategy and an according HMI at the same time. Two systems, namely the AWAKE-system and the ARRB Fatigue Monitoring Device take into account all of the important categories, however, they do not fulfill all requirements.

Category	**Operationalization**	**Description**
Universality	Mobility-Index	System suitable for mobile workers
	Predictive Warning	Warning administered when critical hypovigilance level reached only, or already beforehand; warning strategy adapts to vigilance history of the user
Warning Modes	Normal Mode	Normal mode with status indicator supported
	Vigilance maintenance Mode	Vigilance maintenance mode supported
Warning Quality	Attracting attention	Attention attracted in the first step of the warning
	Complex Warning Information	Information provided on • Nature of Hazard • Potential Consequences • Behavior Recommendations
	User Feedback Required	Confirmation of the warning required
HMI	Multimodality	Warning signal multimodal
	Choice of sensory channels adequate to application scenario	Selection and combination of sensory channels meaningful
	Warning Intensity adjustable	Increase in warning intensity possible
	Localization of display	Displays placed according to human factors guidelines
	Masking of warnings	Warning technically designed in a way that they are not masked, e.g., by a loud surrounding
Usability	Situation Endangerment	Work situation is not endangered by the warning system
	Non-Obtrusiveness	Wearing and using the system is unobtrusive
Personalization	Personalization possible	Warning strategy and HMI adaptable to the user

Table 3.1.: Description of the Categories for the Analysis of Existing Systems and their Operationalization

Product	Universality Index	Communication Quality Index	Warning Quality Index	HMI Quality Index	Usability Quality Index	Personalization Quality Index
Engine Driver Vigilance Telemetric Control (EDVTCS)	◐	◐	◐	◐	◐	○
Micro Nod Detection System (MINDS)	○	○	◐	●	◐	○
Eye Tracking Alertness Monitor	○	○	◐	○	●	○
ABM Drowsiness Monitoring Device	○	○	○	○	◐	○
Vehicle Drivers Anti Dozing Aid (VDADA)	◐	○	○	●	◐	○
Driver Fatigue Monitor DD850	○	○	◐	●	●	●
SafeTRAC	○	◐	○	◐	●	●
Advisors System for Tired Drivers (ASTiD)	◐	◐	○	◐	◐	◐
SAM G-3	○	○	◐	◐	◐	◐
TravAlert	○	○	◐	○	●	◐
ARRB Fatigue Monitoring Device	◐	◐	●	●	◐	◐
Actiwatch Alert	◐	◐	◐	○	◐	◐
Doze Alert	◐	◐	◐	○	◐	◐
Stay Alert	◐	○	○	○	◐	○
Nissan Safety Drive Advisor	○	○	◐	◐	●	○
Photo Driven Alert System	◐	○	○	○	◐	○
Driver Attention System	○	○	○	◐	●	○
AWAKE Hypovigilance-Management-System	○	◐	●	●	●	●

Table 3.2.: Summary of the Analysis of Existing Hypovigilance-Management-Systems. An Empty Circle Indicates that the Criterion is not Satisfied, a Full Circle Indicates that the Criterion is Fully Satisfied

Therefore, it can be concluded that there is no Hypovigilance-Management-System present that fulfills all requirements for the warning strategy and HMI of Hypovigilance-Management-Systems as outlined in this work.

4. Approach and Innovation

In the previous chapter, requirements for the communication strategy as well as for its technical implementation in terms of the HMI have been presented. It was pointed out that Hypovigilance-Management-Systems should follow a specific, three tiered warning strategy and that the warning itself should follow a specific structure as a prerequisite for the overall system to be effective. Moreover, for the same reason, the HMI of such systems should follow the well known human factors guidelines.

In the same way, it has been emphasized that hypovigilance causes performance and safety problems in many different application fields and, therefore, Hypovigilance-Management-Systems are needed in all of these application fields. Consequently, for cost reasons, it is desirable that a Hypovigilance-Management-System is designed in a way that it is effective in application fields of different system dynamics and mobility grades. An important characteristic of such a system is the possibility to adjust the warning strategy as well as the HMI to the respective application field and to the respective user.

If these requirements are fulfilled and combined with good usability and, hence, a good acceptance of the system, the resulting system is assumed to effectively counteract hypovigilance and, thus, reduce errors. It might help sustain or enhance personal performance capabilities.

However, the analysis in the previous chapter showed that only some of the existing systems show a good performance in single rating categories. None of the existing systems fulfills the full set of criteria derived. Even the AWAKE system, which was rated best in the system comparison, is not suitable for mobile users, and does not consider the vigilance history of the user. Thus, it cannot be regarded being universal. In the same way, the communication quality of the AWAKE system is restricted as it does not include a vigilance maintenance function. It is summarized that no system is present which features a satisfying warning strategy and HMI, especially with respect to a universal employability.

Moreover, none of these systems has been validated in terms of its effectiveness in respect of the reduction of errors and the enhancement of performance in a real working task.

Clearly, with respect to work safety and productivity, further research is needed.

4.1. Hypotheses

As a research hypothesis for this work, it is claimed that it is principally possible to generate a Hypovigilance-Management-System setup that fulfills all of the above mentioned requirements.

Furthermore, it is claimed that, by fulfilling these requirements, this system is effective in terms of the reduction of errors and the enhancement of performance in real working tasks.

4.2. Method and Innovation

For the development of an effective, universal warning strategy and HMI of a Hypovigilance-Management-System, a new hybrid development approach is developed and followed in which a theory based development is supported by the application of specific data at a very late stage only, in order to compensate for presumably weak requirements data from the application sites:

The overall requirements can be derived from the descriptions in chapter 3. However, in order to serve as a set of definite requirements for a methodical design, they need to be refined and detailed. Specifically, they need to be adapted to the application scenario of the Hypovigilance-Management-System. Because the aim of this work is to develop a universal system, different application scenarios need to be considered. However, it is sophisticated to get general requirements information about Hypovigilance-Management-Systems from potential application sites. Due to restrictions of time and budget, it would be very challenging to visit all of the application sites in order to investigate their nature. Therefore, the requirements engineering needs to be conducted distantly, e.g., by means of a questionnaire survey. Because the people on site usually are neither aware of the specific characteristics of hypovigilance and related Hypovigilance-Management-Systems, nor are experts for HMI development, their answers will be of cursory character if no very specific questions are asked. However, this is only possible, if a general knowledge about the functions and basic setup of the system is already present.

Hence, the system is firstly developed in a theory driven process as far as possible with specific design parameters left open as input variables to the design process. Once the overall design is clear, it is possible to collect application related requirements on a much more specific and detailed basis (compare to figure 4.1).

Therefore, first, on the basis of the requirements described, a basic warning strategy is developed and according basic HMI-elements are deduced.

Then, a set of representative application scenarios is chosen. The specific requirements of these application scenarios are collected by means of a questionnaire survey. The data is analyzed with the aim to identify requirements clusters which enable the development of one solution that suits all application scenarios or, at least, the smallest set of solutions possible, following the idea of a building kit. The result of this procedure is a clear and definite set of requirements which forms the basis for the actual development of the system.

Following a methodical engineering approach, the final warning strategy and the according HMI will then be developed and implemented. Where necessary, optimization experiments with individuals will be performed. The result is the prototypic implementation of a Hypovigilance-Management-System which fulfills the requirements discussed in chapter 3.

Once the system is developed, it is to be investigated if the above research hypotheses can be corroborated. Therefore, it is to be shown that the system developed indeed fulfills the requirements defined, and, especially, that it truly reduces errors and enhances performance in a real life working situation. As no Hypovigilance-Management-System has been validated in this way before, this approach is considered being a true novelty.

By the design approach chosen, the system developed should fulfill the requirements and be universal in the defined sense which relates to the first of the above research

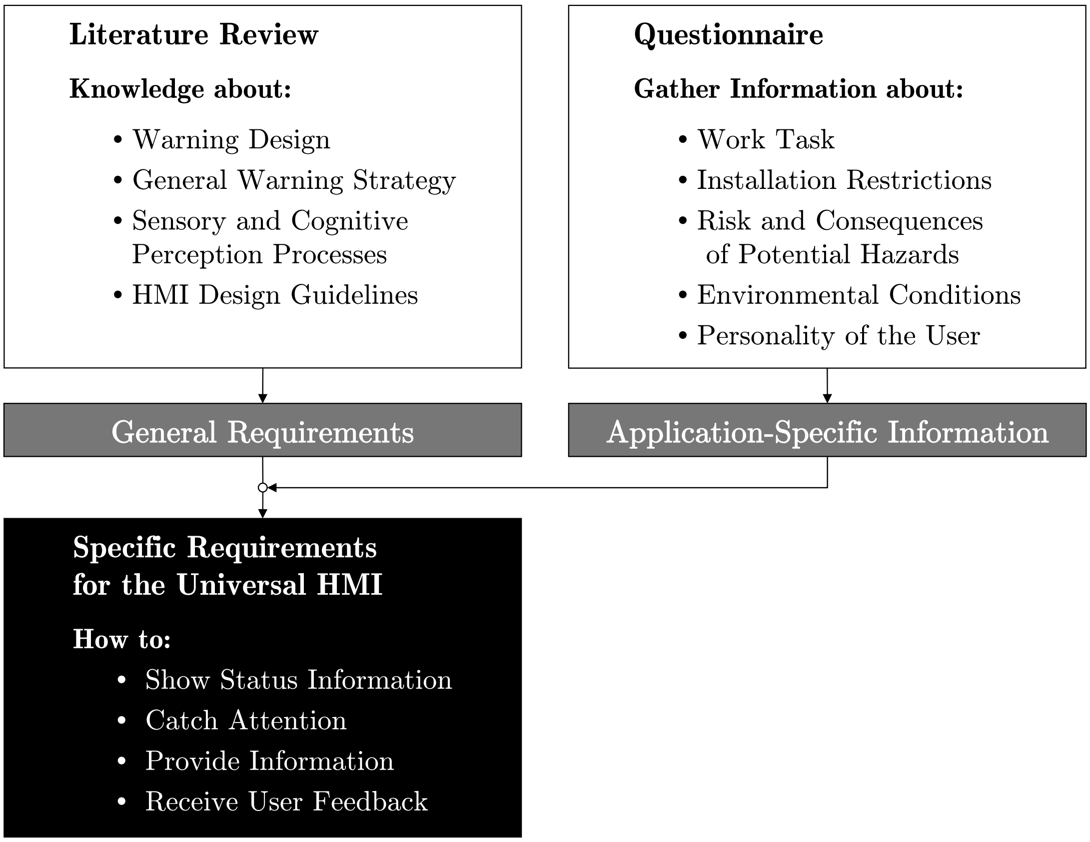


Figure 4.1.: Approach to the Requirements Analysis

hypotheses. As there is no system present that fulfills all of the requirements, the successful development of such a system would be a true innovation.

In order to prove the effectiveness and usability of the system, one of the application scenarios out of the requirements analysis will be chosen in which the system developed will be tested. In this test, the system will be compared to both a test group without a Hypovigilance-Management-System (*control group*) and to one with a Hypovigilance-Management-System featuring an arbitrary warning strategy (*positive control group)*. The first comparison allows to prove the overall effectiveness, the second one allows to determine if a positive effect found in the first comparison is caused by the specific design of the system or just by the intervention itself.

5. Development of a Universal, Multimodal HMI for Hypovigilance-Management-Systems

In the previous chapter, the approach taken in this work has been presented and discussed. Its application as well as the according results, i.e., the actual development of the HMI are presented in this chapter.

First, the warning strategy will be defined as far as possible in a theory driven approach. On this basis, a raw definition of the HMI-elements needed will be deduced. This general setup will then be detailed by means of a questionnaire survey, which collects relevant requirements from a chapter of representative application scenarios. The data of this survey will be clustered with the goal to deduct the smallest setup of HMI-elements possible with respect to the application scenarios. This setup will then be constructed in detail.

5.1. Theory Driven Pre-Development of the HMI

Two relevant parts need to be considered for the development of the HMI of a Hypovigilance-Management-System: the warning strategy, or communications strategy, and its physical implementation in terms of the HMI-elements.

5.1.1. Warning Strategy

The warning strategy of the Hypovigilance-Management-System outlines the basic sequence of the human machine communication. In section 3.3.1, the short term, mid term, and long term goals of a Hypovigilance-Management-System have been introduced and, on this basis, general functions were deduced. These can be translated into an according communication algorithm. One cycle of of it is depicted in figure 5.1.

The current hypovigilance value of the user represents the basic input to the warning process. In the normal mode, the current hypovigilance value is displayed on a status indicator. If the hypovigilance value exceeds a first predetermined threshold, the system switches to the warning mode and displays a cautionary warning. If a second, critical threshold is reached, the system displays an imminent warning. If the critical hypovigilance value is exceeded and the work task can be aborted immediately, the user is requested to do so without time delay. If the task can not be aborted immediately, the vigilance-maintenance system is activated. Moreover, if a third person can substitute the hypovigilant user, the substitute has to be informed by the system, to take over the task.

For each of these warnings, a user feedback is requested in order to confirm the reception of the message. If no feedback is given, the warning is repeated. If the user still gives no feedback, it can be assumed that there is a severe problem. In the case of a cautionary

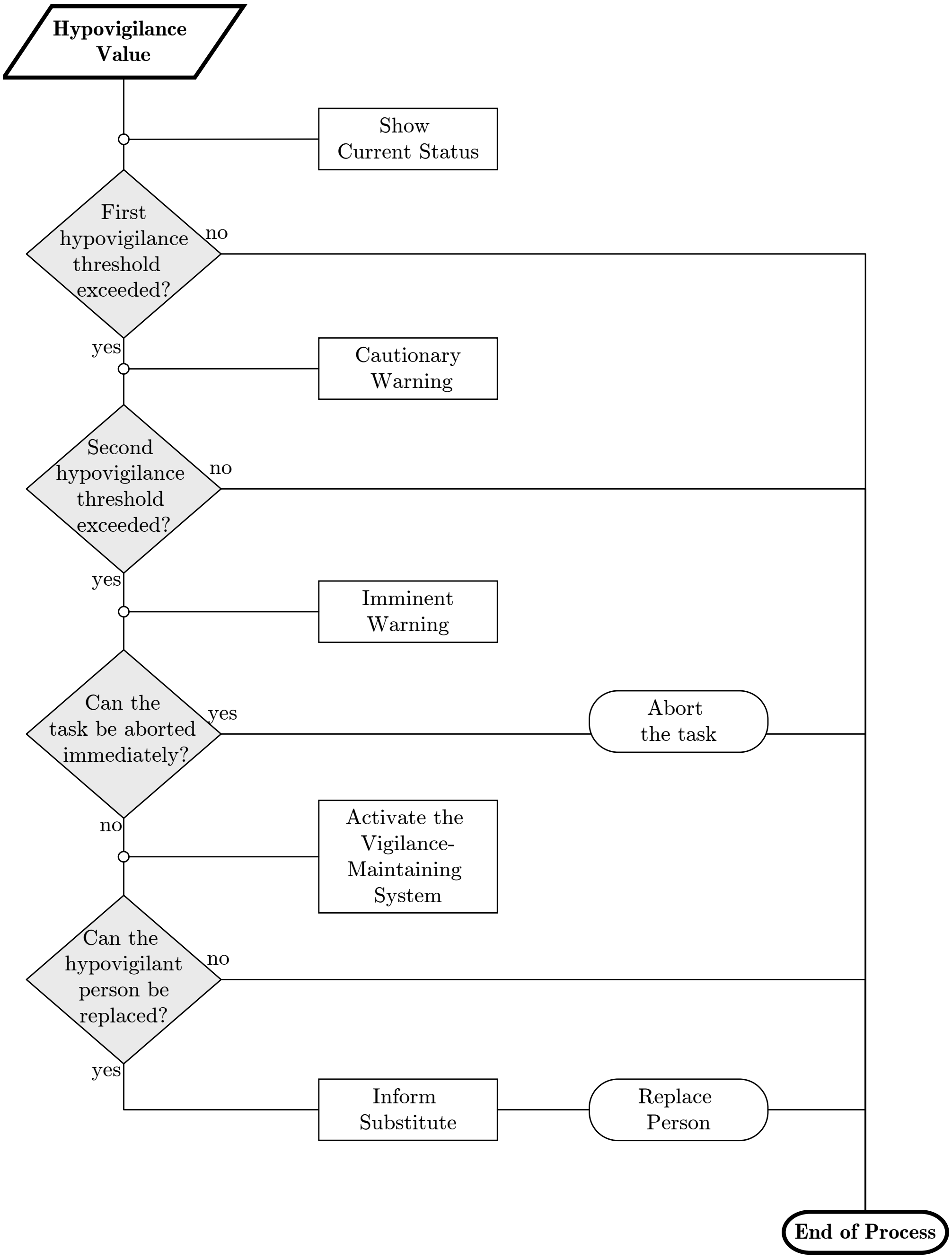


Figure 5.1.: Depiction of the General Warning Algorithm

warning, the system administers an imminent warning. In the case of an imminent warning not being confirmed, the system keeps displaying the most intense warning as, obviously, no more intense warning can be produced.

Moreover, especially for work systems with a high system dynamic, the previous user state needs to be considered, i.e., if a person was rated hypovigilant and a warning has been displayed but is rated less hypovigilant again, the thresholds for future warnings need to be lowered. As an example, if a person was extremely hypovigilant and, thus, received an imminent warning but becomes intermediately hypovigilant again (in terms of the sensor measurement), it can be assumed that the more vigilant judgment may be caused by the stimulation of the imminent warning itself, and, hence, the effect might not last long, i.e., the vigilance of the person might drop again soon. In consequence, the system must be more sensitive for a certain period thereafter.

Depending on the specific situation, the first warning is necessary at different levels of hypovigilance. In situations that require high attention, an anticipatory warning is needed, whereas in other situations, no warning is needed unless the monitored individual is nearly falling asleep.

For the purpose of this work, following the approach and definitions of Wierwille and Elsworth (1994), a hypovigilance range from level 0 to level 4 is defined to characterize the different states of hypovigilance:

- **Level 0:** Awake
- **Level 1:** First signs of hypovigilance
- **Level 2:** Clear signs of hypovigilance
- **Level 3:** Strong signs of hypovigilance
- **Level 4:** Nearly falling asleep (including micro sleep)

The vigilance levels at which the different warnings are administered depend on the actual application scenarios and need to be adjusted.

5.1.2. HMI-Elements

From the general warning algorithm depicted in figure 5.1 as well as from the general structure of a warning message depicted in figure 3.3, necessary basic HMI-elements can be deduced. In order to continually display the actual vigilance state of the user, a *status indicator* is needed. Moreover, for the administration of warnings, a *device to catch attention* as well as a *device to display complex warning information* is required. Finally, a *device for user feedback* should be available. No further attention is paid to the HMI-device informing a third party where necessary, because in this case, usual monitors or voice messages on phones can be used.

For all of the above mentioned devices, general design options and guidelines have been presented in section 3.3.2. However, the selection of the sensorial channel as well as the detailed technical definition is dependent on the actual application scenario. Hence, this information is gathered by means of a questionnaire survey, as it is described in the next section.

5.2. Application Requirements Survey

In order to find a most universal setup, a set of application scenarios is to be analyzed, which represents most of the potential application scenarios.

5.2.1. Survey Method

5.2.1.1. Selection of Application Scenarios

In section 3.2, the potential users, and, with this, the according application scenarios of a Hypovigilance-Management-System have been characterized and grouped by the system dynamic and the mobility of the user. Consequently, applications are to be chosen that cover the range of mobility as well as the range of system dynamic.

The applications chosen as well as their grade of mobility and system dynamic is depicted in terms of a portfolio analysis in figure 5.2. Four quadrants are identified: low mobility with low system dynamic, low mobility with high system dynamic, high mobility with low system dynamic and high mobility with high system dynamic.

The portfolio analysis demonstrates that the set of application scenarios chosen covers all four quadrants and, hence, can be considered being representative.

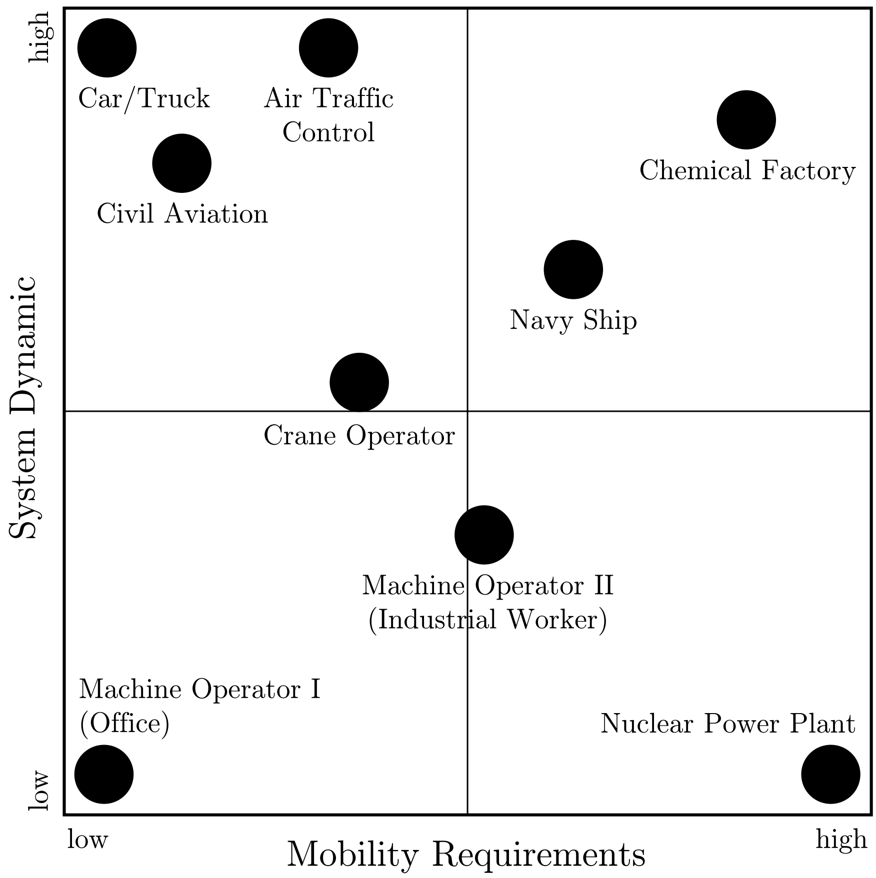


Figure 5.2.: Portfolio Analysis of the Application Scenarios Chosen

5.2.1.2. Choice of Respondents

The questionnaire was distributed in eight nations worldwide to experts leading in their field of expertise. The set of respondents included experts both from the academia and the industry.

5.2.1.3. Structure and Content of the Questionnaire

The general warning strategy is to be adapted to the according application scenario related requirements. Therefore, the thresholds and variables of the general warning strategy have to be fed with specific data from the application scenarios: Critical hypovigilance thresholds have to be defined according to the respective work task, as well as to the risk and consequences of potential hazards. Moreover, information is needed whether the work task of the user can be aborted immediately, i.e. whether he/she can "leave everything behind" and go for a rest. Additionally, data about the feasibility to replace the hypovigilant user by a substitute must be stored within the system, in order to predefine whether the information of a third person has to be integrated into the warning strategy. In addition, the user's ability of comprehension and his/her professional qualification have to be considered in the design of the warning messages.

The requirements for the physical HMI-elements mainly focus on the environmental conditions and on installation restrictions due to the work task. In the same way, the user's mobility in the work task and information about the physical abilities of the standard users are important influencing factors for the design of the HMI.

Therefore, five main categories for the questionnaire are identified and discussed in detail below. For the sake of readability, the questionnaire itself is included in appendix B.

Overall description of the work task The initial part of the questionnaire aims to give an overview of the work in the considered application scenarios. Questions about the user's mobility point at the necessity of the HMI components to be mobile too. Moreover, the questions related to the work task require information on the possibility to abort the task or to replace the worker when hypovigilance reaches a critical level. Additionally, in order to improve the quality of the workplace description, photos of the work place should be attached to the questionnaire.

Restrictions to install or wear HMI devices In the second section of the questionnaire, installation restrictions and existing communication devices are inquired. Additionally, the permission to wear specific types of devices is investigated with the goal to use such devices to incorporate parts of the HMI. Moreover, the use of protective equipment is investigated because it might limit the application of HMI output devices that are worn close to the body, such as vibrotactile devices. Finally, the output devices favored to give a feedback or to warn the user are surveyed; although the respondents are not HMI-experts, and, thus, their answers to this last question might be of cursory character, these might include ideas for suitable, application specific solutions anyway.

Description of potential hazards The risk and consequences of hypovigilance related incidents influence the design of the warning strategy and of according thresholds. Therefore, the possible application specific hazards are investigated both with respect to daytime and nighttime conditions. Initially, the frequency of hypovigilance warnings estimated is asked. Subsequently, the risk and the consequences of endangering oneself, other persons or the environment, as well as own or foreign property is interrogated with respect to normal and hypovigilant conditions. Additionally, the influence on the estimated risk of exogenous factors, such as bad weather conditions or traffic intensity is surveyed. Finally, the hypovigilance level at which a feedback or a warning is necessary is asked to be rated by the respondents.

Environmental conditions of the work place Warning information presented by means of an HMI must not be masked by the ambient conditions. For example, auditory output of an HMI must be perceivable despite of ambient noises. Therefore, the questionnaire inquires information about noise, vibrations, lighting conditions, and climate, whereas the latter one especially refers to technical restrictions for the design of the HMI.

Personality of the user The personal characteristics of the standard user determine the content and, thus, the effectiveness of a warning. Therefore, information about possible disabilities, professional qualification, comprehension levels and motivation of the user is requested. The survey concludes with a question about the possibilities to force the user to use a hypovigilance management system

For pre-testing, the questionnaire was reviewed by three independent experts for HMI development who were involved in the SENSATION (2004) project.

Technically, the questionnaire has been implemented as an interactive MS Word document in which most of the answers could be either given by means of a check box or chosen from a pull down menu. Hence, it could be distributed, answered and gathered electronically.

5.2.1.4. Method for Data Analysis and Requirements Definition

The approach to the analysis of the questionnaire data is depicted in figure 5.3.

The initial step of the data analysis is a descriptive characterization of each application field, in order to get an overview of the scenarios included in the analysis. From these overviews, for each scenario, the specifications for the warning strategy and the possibilities and limitations of the use of potential HMI elements are deduced.

In the next step, these single conclusions about the warning strategy and the adequate HMI design are summarized, in order to find clusters of similar requirements. On this basis, the requirements for the possible technical realizations of the HMI components are concluded. Due to space restrictions, the overview over each application scenario is omitted but summarizing conclusions are presented.

5.2.2. Requirements for the Warning Strategy

The requirements of the single application fields with respect to the need for a vigilance maintenance system, information about a substitute worker, and about the hypovigilance threshold for the cautionary warning are summarized in table 5.1. It is stressed that the information given below is based on the results of the questionnaire survey. As the questionnaire was answered by experts of the respective application, it is assumed that all information given is correct. E.g., if it is mentioned that it is not possible to substitute a worker in the chemical factory, this information is considered being a fact.

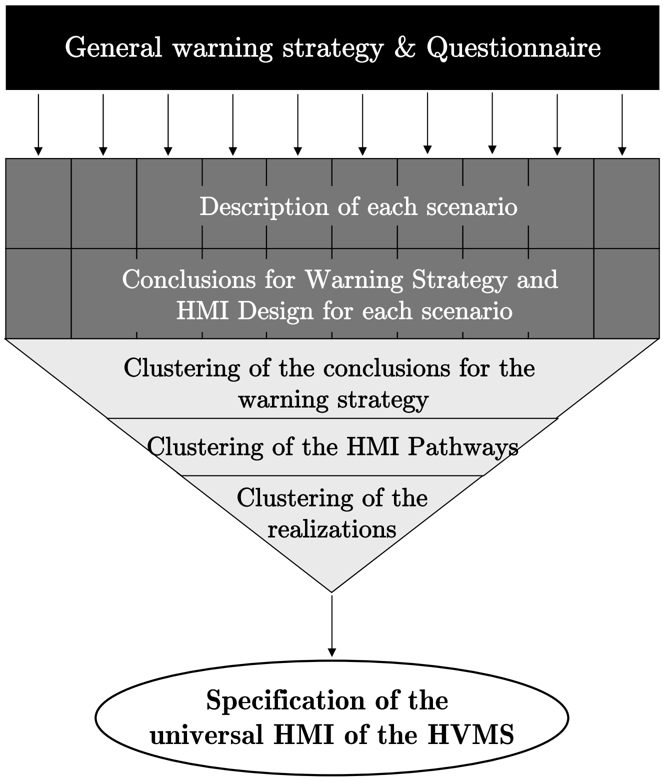


Figure 5.3.: Approach to the Data Analysis

	Passenger Car	Driving Simulator	Civil Aviation	Crane Operator	Navy Ship	Air Traffic Control	Chemical Factory	Nuclear Power Plant	Machine Operator I	Machine Operator II
Vigilance-Maintaining System needed?	**Yes**	**Yes**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**
Information of Substitute necessary?	**No**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**No**	**Yes**	**No**	**No**
Hypovigilance level for cautionary warning	**1**	**1**	**1**	**2**	**2**	**1**	**2**	**2**	**no info**	**2**

Table 5.1.: Basic Requirements of the Application Scenarios (*no info* indicates a missing answer in the questionnaire)

The following conclusions are drawn: In all but three application scenarios, a vigilance-maintenance system is needed in order to help the user to abort the work task safely, as the respective work tasks cannot be aborted immediately. However, in three cases, no vigilance maintenance device is necessary. Both the worker in the nuclear power plant and the industrial machine operator can abort their work task immediately and, hence, don't need any further support with respect to vigilance maintenance. In civil aviation, there are always two pilots present so that a hypovigilant pilot can immediately abort the work task of steering the airplane by handing over to his/her co-pilot.

Moreover, by the results of the questionnaire survey, in four scenarios only, a substitute is surely available who can be informed to take over the work task. Consequently, the information of a substitute-worker is meaningful in these four scenarios only.

The critical hypovigilance level for the cautionary warning differs widely over the scenarios depending on the dynamic of the respective work system. Consequently, this parameter must be manually adjustable for each application field.

Conclusively, two clusters with respect to the level for the first warning can be formed. At time critical work tasks, such as driving a car, a truck (as well as a truck simulator) or a plane and at the work task of air traffic controllers, anticipatory warnings are recommended. Therefore, anticipatory warnings should be given early, i.e., at hypovigilance level one. In the other scenarios, a cautionary warning can be accepted that is given at a higher hypovigilance level, i.e., at level two.

5.2.3. Requirements for the HMI Communication Pathways

The selection of the communication pathways is dependent on the ambient conditions, the installation restrictions and the mobility of the user during work. The conclusions from the scenario descriptions about the general communication pathways for the signals to attract attention, the presentation of complex information and the devices for system input are depicted in table 5.2. Mobile and stationary devices are differentiated where *stationary* relates to devices that are a part the work environment, and *mobile* relates to devices that are worn by the user.

With respect to the three main parts of the warning strategy, the following clusters of HMI-characteristics have been derived.

5.2.3.1. Warning Signals to Catch Attention

- Due to installation restrictions and the mobility of the users, visual warning signals are only reasonable in two scenarios.

- The use of acoustic warning signals can interfere with the presence of noises at the work place. Consequently, acoustic warnings are applicable without restrictions by the ambient conditions in three scenarios only.

  Moreover, acoustic warnings potentially interfere with the privacy of the user, if they are audible for the surrounding (e.g., the vigilance warning for a bus driver should not be audible for the passengers).

- The vibrotactile pathway is reasonable to convey warning signals in six of the ten scenarios and is not excluded at any workplace. Nevertheless, a vibrotactile warning

		Equipped Vehicle	Driving Simulator	Civil Aviation	Crane Operator	Navy Ship	Air Traffic Control	Chemical Factory	Nuclear Power Plant	Machine Operator I	Machine Operator II
Warning Signal	visual	-	-	-	+	-	-	+	-	-	-
	acoustic	o	o	o	+	o	+	+	o	-	o
	vibrotactile	o	o	o	+	+	+	+	+	+	o
Complex Information	Text on a mobile display	-	-	-	+	+	+	+	+	+	-
	Text on a stationary display	+	+	+	+	-	-	+	-	-	+
	Text on a Head up display (HUD)	+	+	+	+	o*	-	-	-	-	-
	Speech output	o	o	o	+	o	+	+	+	-	o
Input	Manual input by a mobile device	-	-	-	+	+	+	+	+	+	+
	Manual input by a stationary device	+	+	-	+	-	-	+	-	-	+
	Speech recognition	o	o	o	+	o	+	+	+	-	-
Privacy	Can acoustic warnings interfere with the user's privacy?	**Yes**	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**Yes**	**No**

Legend:	+	Reasonable HMI	o	Restrictions by ambient conditions	o*	Restrictions by user's mobility	-	Not recommended

Table 5.2.: Evaluation of Communication Pathways With Respect to their Use in Different Application Scenarios

at the aircraft must not be confused with the already existing vibrotactile stall warning.

Hence, for all scenarios, a vibrotactile device is applicable to catch the user's attention. As a multimodal approach can enhance the perception of the warning signal, it might be augmented by an acoustical and/or visual warning.

5.2.3.2. Complex Information

The presentation of information on a display strongly depends on the visibility of this system, and, therefore, of the positioning of such a device. Consequently, the data is analyzed with respect to text on a stationary display, text on a mobile display and text on a head up display.

- Mobile text displays are not recommended if their use distracts the user's attention from a time critical task, i.e., mobile text displays should not be used at the passenger car, the driving simulator and the civil aviation.
- The installation restrictions within some scenarios do not allow the use of text messages displayed on a stationary screen. However, stationary displays can be installed in all scenarios in which a mobile display cannot be used for safety reasons.
- The use of head up displays is not possible at all work places, because a projection field such as a windshield must be available in the user's field of view. In consequence, the head up display cannot be used at office-like work places or for mobile workers.
- Contrary to text displays, speech output is reasonable in all but one of the considered scenarios.

In conclusion, speech output is recommended as a universal communication pathway to convey complex information. However, the privacy of the user is to be considered.

5.2.3.3. User Input to the System

- Although possible, manual input by a mobile device is not recommended for driving tasks, as the user should not be forced to take his/her hands away from the steering wheel.
- Manual input via a stationary device is restricted in half of the scenarios, because no additional device can be installed in the workplace environment.
- As ambient noises interfere with speech recognition, this pathway is problematic in six scenarios.

In conclusion, the most universal pathway for system input is a mobile manual input device. In specific application scenarios, such as driving a car, a stationary solution is to be preferred, although a mobile device is usable if it is easily reachable in order not to distract attention.

5.2.4. Requirements for the HMI-elements

From the theory driven pre-development and the application requirements survey, the following requirements are deduced. General information that has been presented in section 3.3.2 (e.g., vibration frequencies) is not repeated.

5.2.4.1. Status Indicator

For the continuous indication of the user's vigilance state, a visual status indicator using the international color-coding is recommended.

By the survey, a traffic light-like scale is preferred compared to a bar plot-like indicator. Depending on the mobility of the user, either a stationary or mobile device is preferred:

A stationary status indicator that is a part the working environment should be located in a way that it does not interfere with the work task and that the status information can be recalled at any time.

A mobile status indicator can best be located at the user's wrist, as a wristwatch-like device can be worn in all considered application fields. In this way, the information is to be recalled actively as the wrist is not necessarily in the field of view of the user, which could be seen as a drawback. However, the current hypovigilance status is no time critical information and, therefore, the localization at the wrist is reasonable.

With respect to a most universal solution, a mobile device is selected for the HMI-setup because it can be utilized in all application scenarios.

5.2.4.2. Device for Vibrotactile Warning Signals

A vibrotactile device should be placed close to the user's skin. From the devices questioned in the survey, a wrist worn device as well as a chest band seem to be suitable, as both are on the skin and both can be worn in all application scenarios[1].

Moreover, the survey yields that a vibrotactile warning signal is applicable at all scenarios but with restrictions because of ambient vibrations in four scenarios:

At the industrial work place, oscillations are induced by the feet, so they should not interfere with a vibration signal at the wrist or the chest if they are of reasonable amplitude and of typical low frequencies.

In the case of the navy ship, the aircraft, the passenger car or the truck simulator, the whole working system is shaken by oscillations caused by the environment and the engines. As these oscillations are transmitted to all parts of the body that are directly connected to the working system, the vibrations can be transmitted, for example, by the steering unit into the hands and the forearms of the driver. Nevertheless, vibrations can only be masked by oscillations of close frequency, though the high frequent, pulsed warning signal will not be masked by low frequent ambient oscillations.

In contrast to the other application scenarios, within the aircraft, a vibrotactile warning signal is already used in order to alert the pilot in case of stall. The vibrotactile warning is induced through the vibrating steering unit. Therefore, an additional vibrotactile

[1] The use of a chest band-like device was considered not to be allowed for the car driver; it is assumed that this answer was given for usability reasons of acceptance and safety reasons with respect to interference with the seat belt. No restrictions are seen if the device is unobtrusive and does not interfere with the seat belt.

warning device close to the hands, e.g. at the wrist, is not recommended, as it might be confused with the stall warning and the pilot might intuitively react in the wrong way.

Consequently, a vibrating device similar to a chest band is applicable in all application scenarios. In some application scenarios, masking effects need to be considered. Therefore, the vibrations induced by the device should be of a pulsed nature.

5.2.4.3. Device for Acoustic Output

The result of the previous analysis of the adequate communication pathways shows that speech output is the most universal way to transmit complex information to a hypovigilant person, but his/her privacy must not be invaded. In order to protect the privacy of the user, an acoustic message has to be presented in a way that it is exclusively audible for the user. Consequently, the auditory output has to be presented via a headphone-like device. Additionally, the sound or speech emitted directly at the ear is less likely to be masked by ambient noises than auditory output via a normal loudspeaker. Nevertheless, the wearing of a headphone-like device must not mute important ambient sounds like other alarms. Therefore, the device used should only cover one ear.

By the survey, the work task does not allow the use of a headphone in three scenarios. On closer examination, these answers do not interfere with the use of speech output directly at the user's ear: Within the air traffic controller-task, the headphone is not allowed, because the operator does already wear a headset, which might be integrated into the warning system. For the industrial worker, a headphone is not suitable as the worker often needs to wear ear-protection; this problem can be solved by the use of ear-protection with built in headphones. In the passenger car, a headphone is forbidden, but the use of an ear clip, comparable to the headset of a mobile phone, is allowed.

Consequently, a headphone-like device to display auditory messages is applicable at all work places considered.

5.2.4.4. Input Device

As the required system input is exclusively needed for confirmation purposes, a mobile manual input device, for example a pushbutton, is suitable. In order to minimize the number of HMI elements, the confirmation button can best be placed on the wristwatch-like device. In this way, the pushbutton is available at any place the user has to work at and the user's mobility is not restricted. Moreover, a mobile device is applicable without any preparations in the working environment and, therefore, convenient and cost effective for the employer.

For the application in the car, the push-button might be integrated in the steering wheel (Marberger, 2003) so that the driver is not forced to take his/her hands off the steering wheel.

5.3. Design of the HMI

A methodical design approach in the style of VDI 2221 is followed for the design of the HMI in order to ensure the quality of the final solution, e.g. by preventing the solemn use of the "first idea in mind" and by supporting the composition of truly new solutions.

5.3.1. Definition of Requirements

The requirements defined above are of a descriptive nature. For the purpose of design, on their basis, a detailed product specification was to be compiled. It has been fixed in a requirements list and is included in appendix C.

5.3.2. Conceptualization

The above requirements were investigated and active principles were developed in an interdisciplinary, structured brainstorming workshop. First, active principles with respect to informational aspects were deduced. Then, technical solutions for their implementations were discussed. The according results were transformed into two morphological matrices which are included in appendix D in figure D.1 and figure D.4.

On the basis of the informational morphological matrix, nine communication solutions variants were deduced (compare to figure D.2). In order to select the best solution variant, first, informational variants that do not fulfill the guidelines defined above were rejected. Then, a value-benefit-analysis (VBA) was conducted on the remaining solutions. Therefore, the following criteria were defined:

Quality of drawing attention	Quality of user activation
Understandability of Information	Plausibility of Information
Obviousness of Information	Cognitive Strain imposed on the user
Concept of operation plausible	Operation steps fast to perform
Duration of starting up the system	System feedback clear in content and timing
Response time to user input	Warning intenseness adaptable to work task
Usable for mobile workers	System personalizatiable
Grade of affright	Respecting privacy of the user

Table 5.3.: Criteria for the Analysis of the Informational Solution Variants

These criteria were weighted against each other in a pairwise comparison which resulted in *quality of drawing attention*, *Quality of user activation*, *understandability of information*, and *grade of affright* being the four most important criteria. *Duration of starting up the system* and *Response time to user input* were rated as the least important criteria. A detailed depiction of the comparison can be found in figure E.1.

The different solutions were then compared in terms of their fulfillment of the above criteria and a value of benefit was computed. A detailed depiction of the calculation of the value of benefit is depicted in figure E.2.

Variant 9 was found to best fulfill the requirements (compare to figure D.3). It features a continuous display of the actual vigilance state of the user. In case of a warning, it attracts attention multimodally by a vibrotactile signal combined with a static light and a melody. For imminent warnings, the signals are intensified by a shorter vibration interval, a blinking flashlight and a higher sound volume. Complex information about the warning is provided by speech messages which is to be confirmed by a finger input. The vigilance maintenance system provides Landström Sounds combined with pulsed vibrations. Data for the personalization is externally stored. Should the system fail, an error message is given through speech output.

In order to implement this warning strategy in terms of hardware, a similar development approach was taken, this time on the basis of the morphological matrix for technical solutions (compare to figure D.4). Eight variants have been developed and compared by means of a value-benefit analysis (compare to figure D.5). Therefore, in addition to the fulfillment of the guidelines defined above, the following criteria have been chosen:

High coverage of application scenarios	Anthropometric adaptability
Quality of presentation of vigilance states	Physical strain on user
Optically integratable work environment	Interference with main work task
Unobtrusiveness of the devices	Simplicity of personalization
Functionally integratable in work environment	Compliance with HF-guidelines
Protection of privacy of the user	Protection against external use
Clear operation modalities	Grade of Mobility of the user
Simplicity of technical implementation	

Table 5.4.: Criteria for the Analysis of the Solution Variants for Technical Implementation

Again, these criteria were weighted in a pairwise comparison (see figure E.4). The grade of fulfillment of the variants with respect to these criteria was judged and a value of benefit was computed (compare to figure E.5). Variant seven (compare to figure D.6) was rated highest. It uses an earphone for acoustic output, LEDs for visual output, a vibration unit included in accessories such as a chest band or belt and a button as a feedback device. The vigilance state is displayed by three LEDs. All other adjustments are done by means of buttons and personal information is stored on a smart card.

5.3.3. Design and Composition of the Warning Strategy

The final communication strategy has been developed on the basis of the above conceptualization. It is depicted in terms of a system state diagram in figure 5.4.

The circles represent system states whereas the arrows represent transition paths from one state to the other. The dashed arrows represent unlikely state transitions, which,for reasons of homogeneity, are considered nevertheless. Three levels of sleepiness are considered: *awake*, *sleepy* and *very sleepy*. Moreover, warning modes and thresholds adapt to the application scenario and to the user's sleepiness history, i.e., different and earlier warnings are administered, if a user has been identified as being sleepy earlier. Therefore, the two conditions *sleepy systrophe* and *awake systrophe* are defined.

The system starts in state 1 upon activation. The status indicator shows a continuous green light and waits for vigilance values to come in from the sensor system (compare to section 3.1). If the vigilance value measured exceeds 2, the system transitions to state 2 and administers an informatory warning: The status indicator switches to yellow and a melody in combination with two pulses of vibration are presented, followed by the voice message

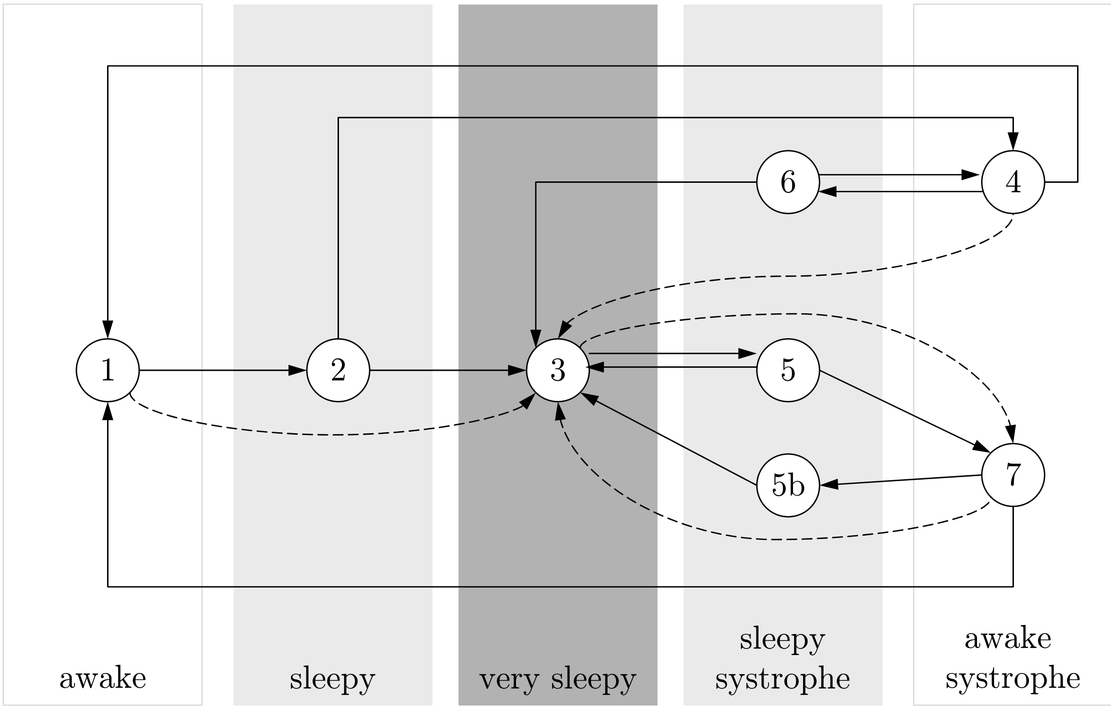


Figure 5.4.: State Diagram of the Final Communication Strategy

> "You are sleepy. Your safety is endangered, so please take a break. Please confirm by pressing the confirmation button."

If the user does not confirm the message, the whole warning is repeated after a repetition time t_r with $t_r = 10$sec. This time span has been chosen as it is short enough with respect to safety but, at the same time, should give the user enough time to press the confirmation button even if he/she needs to finish another operation first, such as handling a machine. The selection of $t_r = 10$sec should be confirmed in a user test and, if necessary, be adjusted. If, after ten seconds, the user still does not confirm the warning message, the system assumes a severe vigilance problem and switches into the imminent warning state (state 5).

If the user confirms the message, the system stays in state two until a vigilance value V of 1 or 5 is measured.

Being in state 2 and the sensory system indicates that the user is fully awake again (vigilance value of 1), the system switches to state 4, "remembering" that the user has been warned already, and, after 10 minutes in this state, back to the basic awake state, therefore compensating for eventual mis-measurement.

If a vigilance value V of $2 \leq V \leq 4$ is measured, the system repeats the warning (state 6), however, the request to take a brake is intensified by the following speech message:

> "You are very sleepy. There is an increased risk of an accident. Please take a break immediately and sleep for at least 10 minutes. Please confirm by pressing the confirmation button."

The same repetition scheme as described above is used in case the user does not confirm the message.

From any state, the system switches into the imminent warning state (state 5) if a vigilance value $V = 5$ is measured. The status indicator switches to red, the flashing light is activated together with continuous pulses of vibration which are only stopped upon confirmation of the following voice message:

> "You are extremely sleepy. There is a high risk for an accident. Please take a break immediately and sleep for at least 10 minutes. Please confirm by pressing the confirmation button."

The voice message is repeated until it is confirmed by the user. Then, the vigilance maintenance system is activated, presenting Landström Sounds in arbitrary intervals, each one in combination with two pulses of vibration. The user is informed about the activation of the vigilance maintenance system by the following voice message:

> "The vigilance maintenance system is activated now. It is intended to increase your alertness for a short time only. It is not a compensation for sleep."

It is stressed that the vigilance maintenance system is not intending to keep the user on the work task as long as possible, but to help the user stop his/her work task safely, e.g., drive safely to the next highway exit.

If a user has been very sleepy, the system remains in the vigilance maintenance mode until a vigilance value $V = 1$ is measured (state 3 for $V = 5$ and state 5 for $2 \leq V \leq 4$). The status indicator remains red and the imminent warning procedure is repeated in case a vigilance value of $V = 5$ is measured again.

In case a vigilance value of $V = 1$ is measured, the system switches to state 7: a beep is presented and the status indicator switches to yellow, indicating that, despite of the judgment *awake*, a high risk of an accident persists. The following voice message is replayed:

> "Sleepiness is not detected anymore. The vigilance maintenance system will be deactivated."

If no other vigilance value than 1 is measured, the system remains in state 7 for 30min. taking the vigilance history of the user into account. After this time, it is assumed that the user indeed is really awake again and the system switches back to state 1. Otherwise, the system switches to state 5b, in which two vibration pulses are given, the status indicator switches to red and the following voice message is replayed:

> "You are very sleepy. There is an increased risk of an accident. Please take a break immediately and sleep at least for 10 minutes. Please confirm by pressing the confirmation button."

The same repetition scheme as described above is used in case the user does not confirm the message. When the message is confirmed, the following message is replayed:

> "The vigilance maintenance system is activated again. It is intended to increase your alertness for a short time only. It is not a compensation for sleep."

Consequently, the vigilance maintenance system is activated again.

A summary of the communication strategy in terms of the thresholds (i.e., vigilance values) at which state transitions are initiated as well as a summary of the system actions described above is included in appendix F.

5.3.4. Design and Composition of the HMI-Elements

The elements described above have been integrated in three devices which are distributed over the body of the user. They are intended to communicate to each other wirelessly in order to enhance usability. The body area network (BAN) modules of the SENSATION project were chosen for this integration:

The SENSATION *User Interface Communication Module* (UICM) in combination with the SENSATION *Sensor Communication Module* (SCM) establishes the connection of the single HMI-elements to the body area network. It includes all necessary hardware drivers. Hence, only the electronic output elements as such need to be defined. The UICM/SCM combination delivers a voltage of 3.7 V and measures $53 \times 33 \times 11\,\text{mm}^3$ including the battery which is to be considered in the design of the HMI elements, as these have to include the related communication hardware. The UICM/SCM combination talks to the *Personal Data Processing Unit* (PDPU) which represents the center node of the BAN. It is connected wirelessly to the expert system with the warning algorithm via a local area network (LAN; compare to figure 3.1). For the mobile worker, the PDPU is mounted on the belt at the side of the hip.

A wrist worn device has been chosen as the central element of the HMI which includes the status indicator, the flashlight for imminent visual alarm as well as the buttons for user feedback, message repetition and volume control. Additionally, a vibration unit is to be fitted either in the lower chest region or on the forearm. Moreover, a driver for the ear speaker is mounted on the shoulder. The design of these elements is described below.

5.3.4.1. Wrist Worn Device

The center of the user interface is represented by a watch-like device. The border ring of the "clock-face" is used as a status indicator; it is lighted green, yellow or red, according to the detected user state. The center of the "clock-face" flashes white in case of an imminent alarm and acts as a push-button for the user feedback at the same time. All lighted parts need to be transparent but should disperse the well focused light of the LEDs for better visibility. Consequently, they should be made of milk-transparent material. In addition, buttons for the repetition of acoustical warning messages as well as for the adjustment of sound volume are included. A first design sketch is depicted in figure 5.5.

For the status indicator, four common 3 mm low-current LEDs per color were chosen, consuming 2 mA at 2 V each, therefore, guarantying battery life of at least one work shift. For the flashlight of the imminent alarm, a white 3 mm high intensity LED was chosen, consuming 20 mA at 3.7 V. This relatively high energy consumption can be neglected in terms of battery lifetime as the imminent visual alarm is considered to be administered only seldom. For the user feedback, a flat push button of the size $12 \times 12 \times 3.5\,\text{mm}^3$ was chosen and micro push buttons of the size $6 \times 3 \times 2\,\text{mm}^3$ were chosen for the repetition and volume function. Switching the device on/off is realized by a micro switch of the size $10 \times 8 \times 2.5\,\text{mm}^3$.

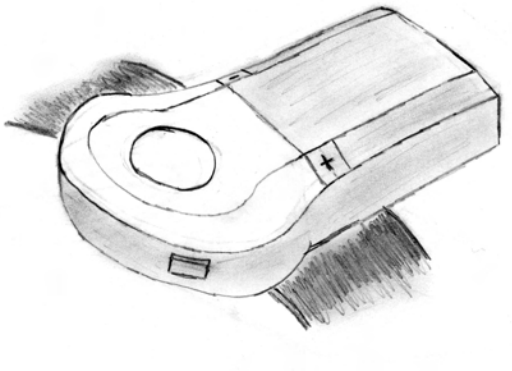


Figure 5.5.: Sketch of the Wrist Worn Device

The buttons and the switch are directly connected to the UICM. Therefore, no further according circuit diagram is included. For the LEDs, series resistances are needed. They were calculated and included in the circuit as is depicted in figure 5.6.

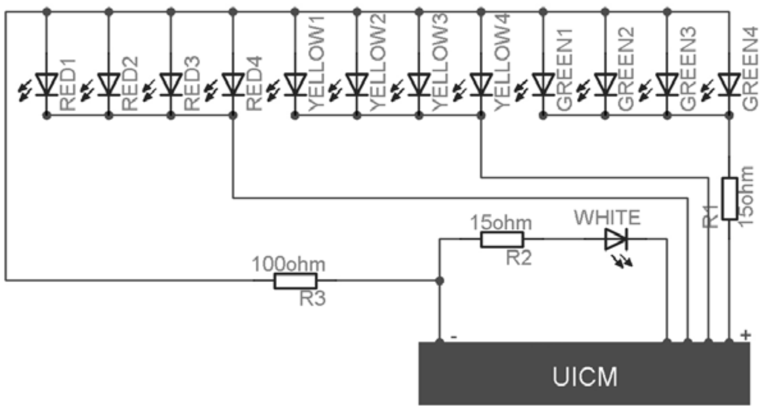


Figure 5.6.: Circuit Diagram of the Wrist Worn Device

On the basis of the design sketch and the above data, the final device has been designed. An explosion view of the final device is depicted in figure 5.7 and the mounted device is depicted in figure 5.8.

The bottom part as well as the lid of the device consist of reinforced plastic. They include mountings for the pushbuttons as well as the on/off-switch. The bottom part also includes mountings for the wristband. Both parts are connected to each other by countersunk screws, holding the transparent, illuminated cover and feedback button in place. These consist of sandblasted acrylic glass and include blind holes as a housing for the LEDs.

5.3.4.2. Belt Unit

From the work above, four possible positions for the mounting of a haptic feedback device were identified: the forearm, the upper arm, the belt buckle and the side of the hip

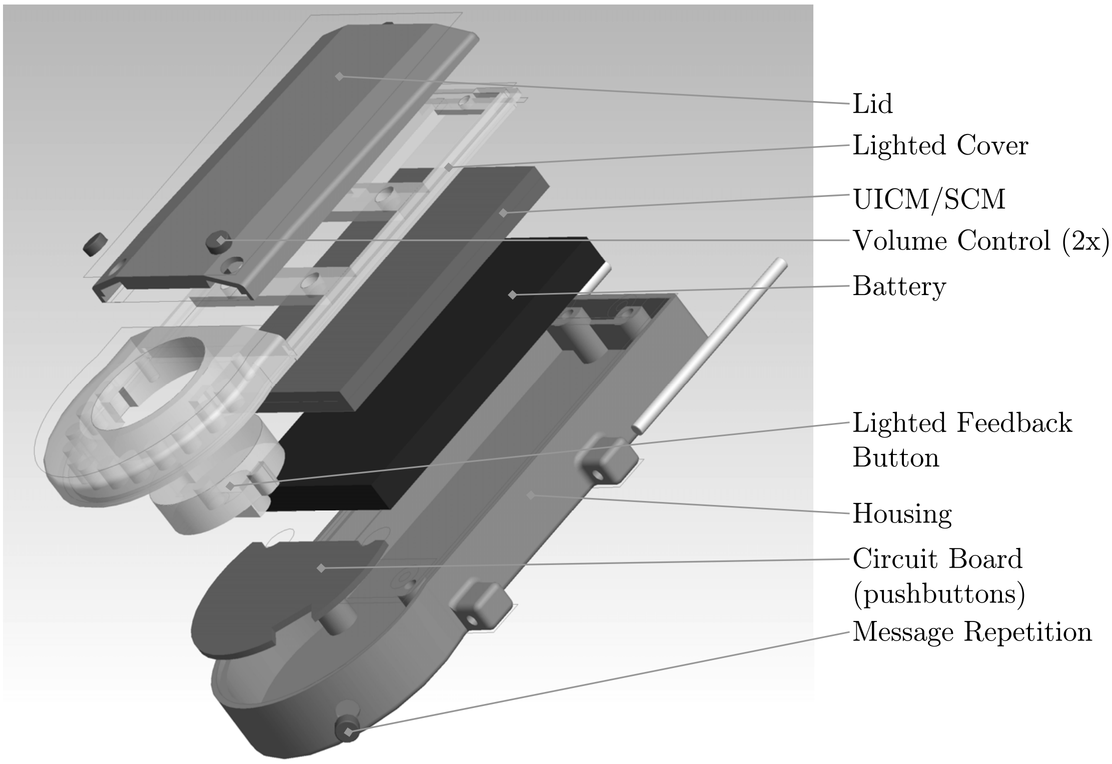


Figure 5.7.: CAD Explosion View of the Wrist Worn Device

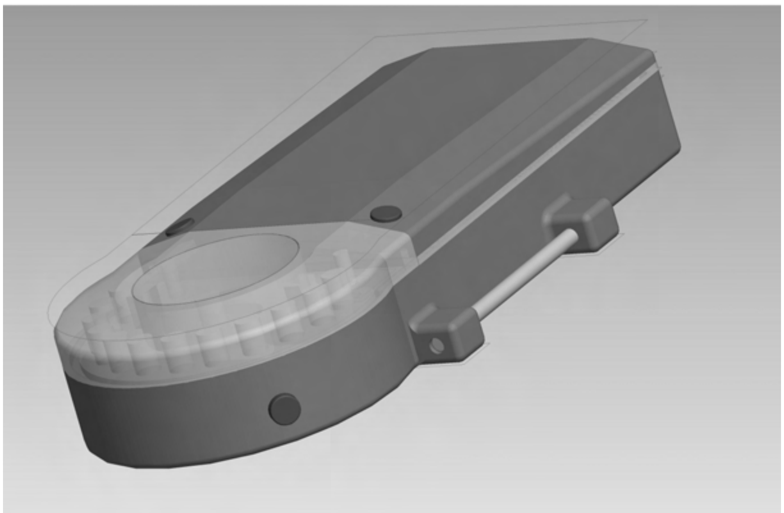


Figure 5.8.: CAD Drawing of the Mounted Wrist Worn Device

(considering the belt as a lower chest band). However, no clear advantage for one single position could be deduced. In order to identify the best possible position on the body, a usability study was conducted on 12 individuals (7 of them being male; age variation between 28 and 52, mean age 38, BMI variation between 18,8 and 30,64, mean BMI of 24).

A vibration device was developed on the basis of a SIEMENS mobile phone with vibration alarm mounted on a belt, which could be controlled by means of a driver software (compare to figure 5.9).

Figure 5.9.: Vibration Device for the Vibration Usability Study

The device was first placed in the closed palm of the participants, in order to generate a reference value. Then, it was placed on the wrist, on the upper arm, on the belly and at the side of the hip respectively (compare to figure 5.10).

(a) Wrist Trial (b) Side of the Hip Trial

Figure 5.10.: Vibration Usability Study

Ratings of the different positions were collected by a usability questionnaire which is included in appendix G. The according results are depicted in figure 5.11.

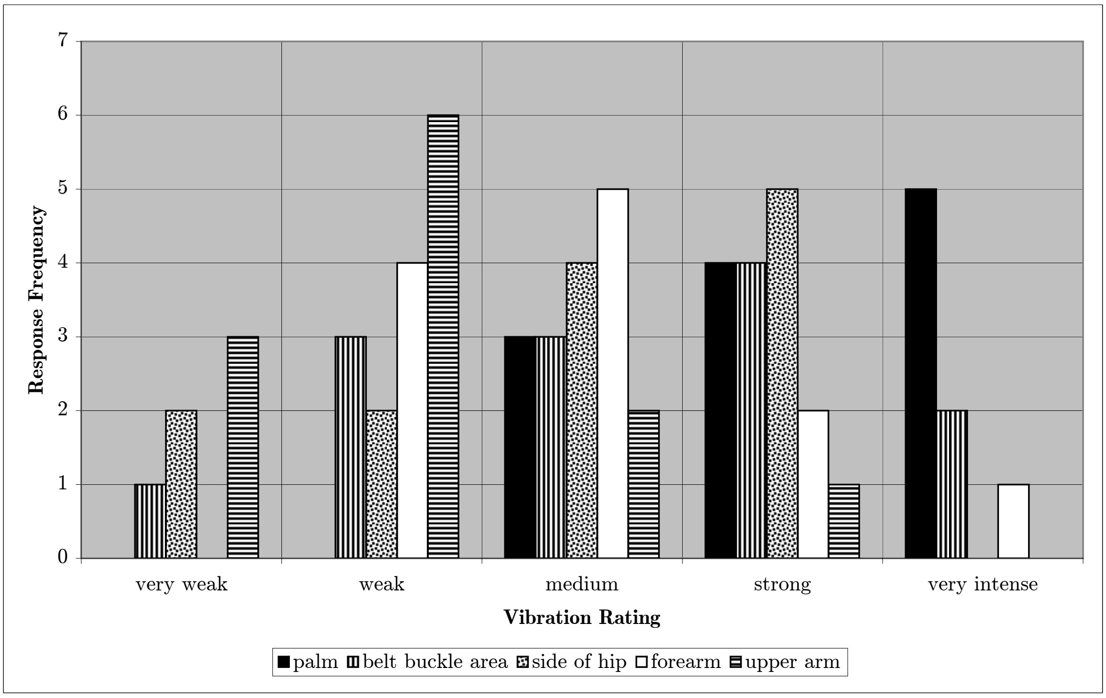


Figure 5.11.: Results of the Vibration Usability Study

It can be concluded that, overall, the side of the hip or the belly were the best positions for the induction of a vibration warning. An occupational physician from the University of Mainz, Germany, was interviewed in order to clarify if there were any medical implications in inducing vibrations on these positions of the body (Muttray, 2005). No such implications were stated. However, the physician annotated that there might be a slight risk in mounting a device on the belly if the person falls on the device, in case of a weakness of the tissue in the belly region. Hence, the device was defined to be mounted on the side of the hip: in this position, the vibrations are injected to the hip bone and, therefore, well perceived.

Because it is simple to integrate a small wire in a belt, for cost reasons, it was decided to connect the vibration unit on the belt by means of a wire to the PDPU, saving a UICM/SCM combination. As the PDPU delivers 3.3V logic voltage but only very limited current and the vibrations are created by a small standard eccentric motor, a motor driver circuit needed to be integrated in the vibration device. The according circuit diagram is depicted in figure 5.12.

A housing for the eccentric motor, the battery and the according circuit board was constructed which can be mounted on a belt. An explosion view of this housing is depicted in figure 5.13.

All housing parts consist of reinforced plastic. They are connected to each other by countersunk screws. The eccentric motor and the circuit board are glued to the housing by two-components glue which hardens non-elastically, therefore guarantying the efficient transduction of vibrations to the housing.

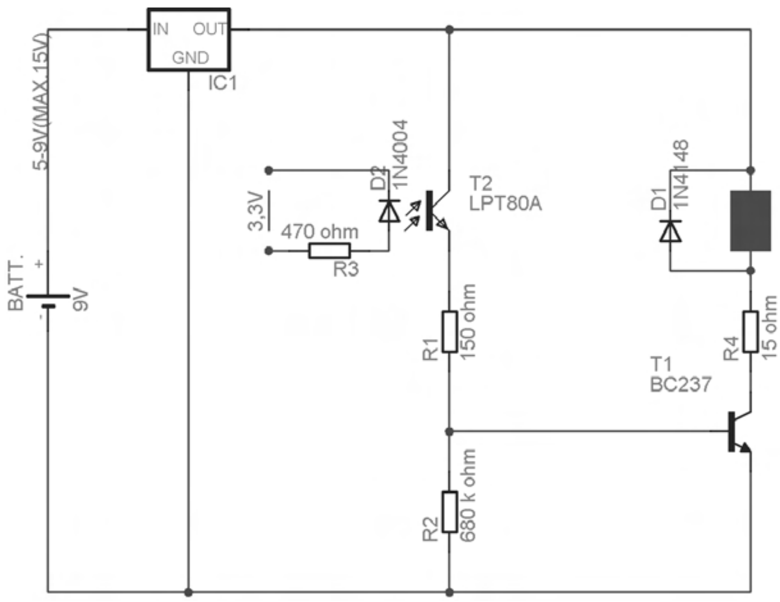


Figure 5.12.: Circuit Diagram of the Vibration Device on the Belt

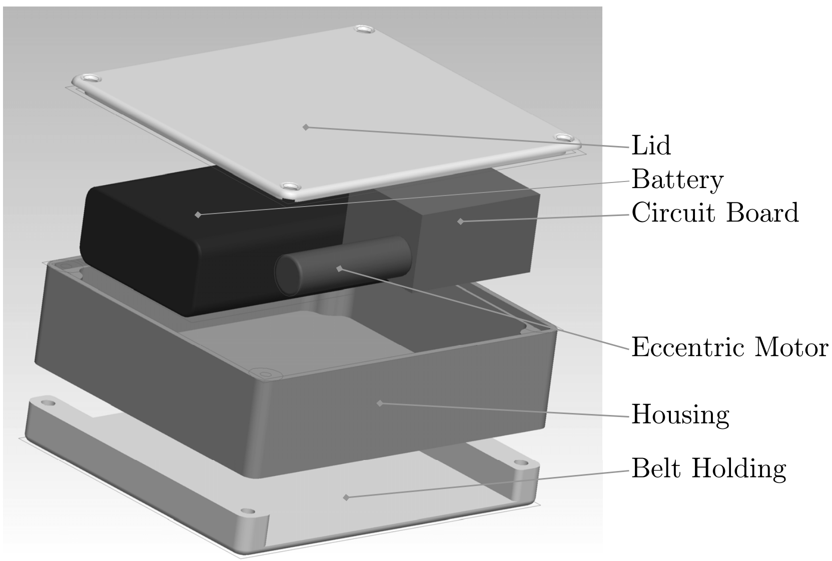


Figure 5.13.: CAD Explosion View of the Belt Unit

5.3.4.3. Shoulder Unit

For the presentation of audio signals, SONY MDR-J10 headphones were chosen as these are lightweight and comfortable to wear over a full work shift but hold steadily on the ear (compare to figure 5.14).

Figure 5.14.: Earspeaker SONY MDR-J10

As the UICM/SCM-combination includes all driver electronics necessary, the headphones just need to be directly connected to it. Hence, only a housing for this combination and the according battery was to be constructed. It is mounted on the shoulder by means of hook-and-loop fasteners. An explosion view of this housing is depicted in figure 5.15.

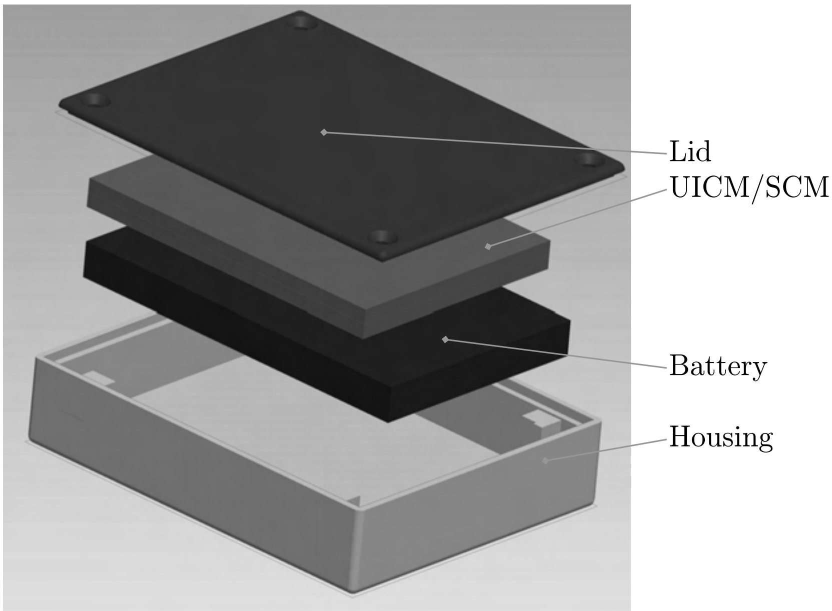


Figure 5.15.: CAD Explosion View of the Shoulder Unit

All housing parts consist of reinforced plastic. They are connected to each other by countersunk screws and include the mountings for the UICM/SCM as well as the battery.

5.4. Implementation of the HMI

The warning strategy and HMI-elements developed need to be tested for their efficiency in order to prove the hypotheses presented in section 4.1. However, at the time this work has been written, the SENSATION BAN was in its final prototype stage, and, thus, not yet available for the HMI. Therefore, and as the aim of this work is not the testing of a market ready product but a proof of principle, the HMI has been implemented in a wired version.

5.4.1. Warning Strategy

The warning strategy has been implemented in the software system *SwitchBoard* (Fraunhofer IAO, 2006), which is a visual programmable interface for measuring and simulation systems. It enables the simple integration of different software and hardware elements.

The software implementation consists of three main elements: the interface to the algorithms which compute a vigilance value on the basis of the data measured by different sensors, a finite state machine and the interface to the HMI-elements.

The connection to the algorithms is established via a TCP/IP-connection. In this way, the vigilance computation algorithms can either be implemented on the same machine as SwitchBoard or on a different machine, then being connected by a standard ethernet line. For the purpose of testing the warning strategy, paralelly, a manual user interface has been implemented, allowing to enter vigilance values by the keyboard.

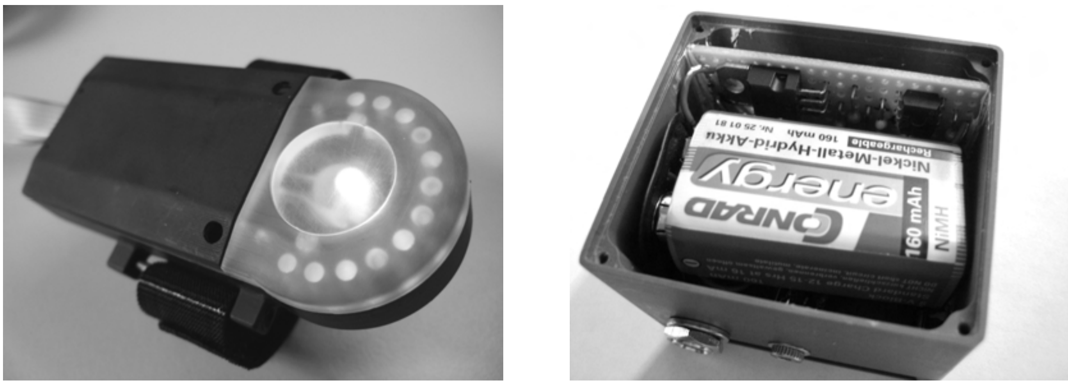
The warning strategy itself has been implemented as a finite state machine. The state transitions are triggered by changes in the incoming vigilance values. The finite state machine produces numeric HMI-output codes, which are interpreted in a C-Parser-module, the interface to the HMI-elements.

This modular implementation solution allows to drive different HMI-output setups. The actual implementation translates the numeric HMI-output codes into driver commands for the Meilhaus ME-96 I/O-card (Meilhaus Electronic GmbH, 2006), which is used in the testing of the HMI. However, the driver module for the connection of the warning strategy to the SENSATION BAN is already prepared and included.

5.4.2. HMI-elements

The Pro/Engineer-CAD-data was exported to a 3-axis-CNC-milling machine which produced the different parts. All parts were made of PVC. Only the lighted cover of the wrist worn device (including the lighted button) was made of acrylic glass and was sand blasted after milling in order to create a frosted surface. Manual post-processing was applied where necessary (e.g. tapping of threadings) and the electronic parts where installed. The shoulder device has not been produced as it houses the wireless communication electronics only. For testing purposes, the headphones were directly connected to the sound card of the driving computer. The final devices are depicted in figure 5.16a and figure 5.16b respectively.

The connection of the computer driving the warning strategy software and the HMI-elements has been established by a digital I/O-card (Meilhaus Electronic GmbH, 2006) and a self-constructed interface driver circuit board.



(a) Final Wrist Worn Device (b) Final Belt Unit

Figure 5.16.: Final HMI-Elements

6. Evaluation of the HMI

In chapter 4, it was hypothesized that it is possible to design a warning strategy and an according HMI for Hypovigilance-Management-Systems which fulfill the requirements discussed in chapter 3. Special attention has been given to the utilizability of such a system in different work contexts. Moreover, it was hypothesized that an according Hypovigilance-Management-System is effective, i.e., reduces the number of errors made by the user and, hence, the number of accidents, and that it maintains the user's performance level.

The first hypothesis is fulfilled inherently by the design of the HMI for a Hypovigilance-Management-System as described in chapter 5 because the requirements formed the basis for the design.

However, the second hypothesis is to be investigated. It has been pointed out that, so far, no Hypovigilance-Management-System has been evaluated with respect to its efficiency in real working conditions.

The best proof for the effectiveness of the Hypovigilance-Management-System developed in terms of the reduction of errors and the enhancement of performance would be a long-term study of at least 6 month in the real application context, e.g., with all workers of at least one production plant in the night shift; in the positive case, the group using the Hypovigilance-Management-System would do less errors and/or be more productive than a control group without a Hypovigilance-Management-System.

However, the conduction of such a long term study clearly is beyond the scope of the present work. Moreover, an industrial partner only would accept the necessary intervention in regular production break patterns and production rhythms, if the effectiveness of the intervention has been basically proven.

Therefore, a pilot study is to be conducted, i.e., a laboratory experiment which enables to investigate the explicit effect of one specific parameter (e.g., for this work, the effect of a Hypovigilance-Management-System) on other paramters (e.g., for this work, the error rate and performance). In order to achieve this, all other factors influencing the target parameters but the one to be investigated need to be controlled. Hence, most homogeneous test conditions both with respect to the test scenario as well as to the participants are to be created (compare, i.a., to Mainzer, 1982; Bortz, 1993; Kern, 1997; Bortz et al., 1990).

Consequently, the system is tested with three groups of participants, the treatment group, the control group and the positive control group: A comparison of users with the system designed[1] (treatment group) to a group with no warning system (control group) enables to investigate the effectiveness of the system. A further comparison of the treatment group to a group with a system providing random warning signals (positive control group) allows to find out if the results were caused by the proper design of the warning strategy and HMI-elements or if they are caused by the intervention itself.

[1] Referred to as *Sensation system* or *Sensation warning strategy*; as the experiments were to be conducted with German participants, the speech messages were translated into German.

Therefore, on the basis of the general hypothesis above, the following three research hypotheses are derived which can be evaluated empirically.

1. Users of a warning strategy with random output perform better than users without any warning strategy

   Measure 1: productivity

   Measure 2: number of mistakes

   Measure 3: combination between productivity & number of mistakes

2. Users of the Sensation warning strategy perform better than users of a warning strategy with random output

   Measure 1: productivity

   Measure 2: number of mistakes

   Measure 3: combination between productivity & number of mistakes

3. Users of the Sensation warning strategy perform better than users without any warning strategy

   Measure 1: productivity

   Measure 2: number of mistakes

   Measure 3: combination between productivity & number of mistakes

6.1. Experimental Work Task

The experimental evaluation of the Hypovigilance-Management-System should have a high practical relevance. Therefore, a real life work task was to be chosen. From the representative list of application scenarios (see section 5.2.1.1), the *Machine Operator II* is chosen: It is an industrial worker with a work task that, on the one hand, requires the mobility of the user, and, on the other hand, has a high practical relevance as industrial work often includes shift work. For the experiments, the effects of shift work are to be simulated by means of sleep deprivation.

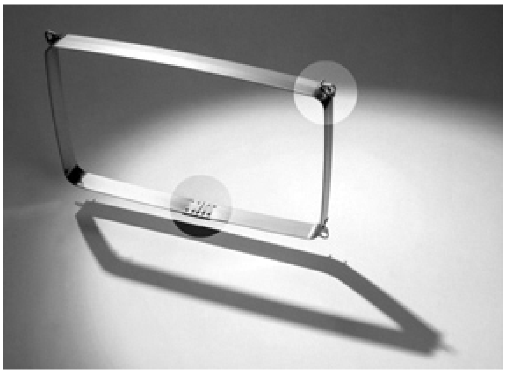
Therefore, a typical task of an industrial worker is selected: For testing reasons, it should be monotonous, have a long duration, have a high complexity, involve working memory, impose external control on the industrial worker and should be lowly automated because these factors enhance performance decrements in sleep deprived individuals (Bonnet, 2000). However, for testing purposes, the task should not be dangerous for the worker, but should be of an error-prone nature in order to not endanger the worker but to be able to measure error and performance rates.

For the purpose of evaluating the HMI of a Hypovigilance-Management-System, the original work task is to be mapped to a standardized laboratory work task. Therefore, the laboratory work task will represent an exemplary implementation of typical industrial work situations. It is designed on the basis of the original work task, however, it is adjusted to the requirements of a valid, standardized test task which allows the reliable measurement of performance.

6.1.1. Resistance Welding of Rim Bands

The resistance welding of rim bands is a typical task that fulfills these requirements: Welding rim bands is a repetitive positioning task which is carried out in a three-shift schedule. It requires mobility and is known to produce different kinds of mistakes (Bonnet, 2000).

A rim band is a metal component of a television screen (compare to figure 6.1a). Its function is to counter the vacuum induced tensions in the glass tube, thus increasing strength and safety of the tube. Furthermore, the rimband holding the tube is mounted into the television or monitor housing by means of stackable lugs welded to the rim band (compare to figure 6.1b).



(a) Rim Band

(b) Stackable Lug

Figure 6.1.: Rim Band and Detail of Stackable Lug (Admeco, 2006a)

6.1.1.1. Welding Procedure

Because rim bands are produced in large quantities, their production has been semi-automated. The operator of the welding unit carries out the following procedure (see also figure 6.2):

1. The operator positions a rim band in the center of the welding unit.
2. The operator activates the process by pressing two operation buttons simultaneously.
3. The unit tightens the rim band and fixes it in an exact position.
4. The unit positions and welds stackable lugs on each of the 90 degrees bends of the rim band.
5. The operator releases the two operation buttons when the welding process is finished.
6. The unit releases the rim band.
7. The operator removes the rim band from the unit and puts it in a storage box.

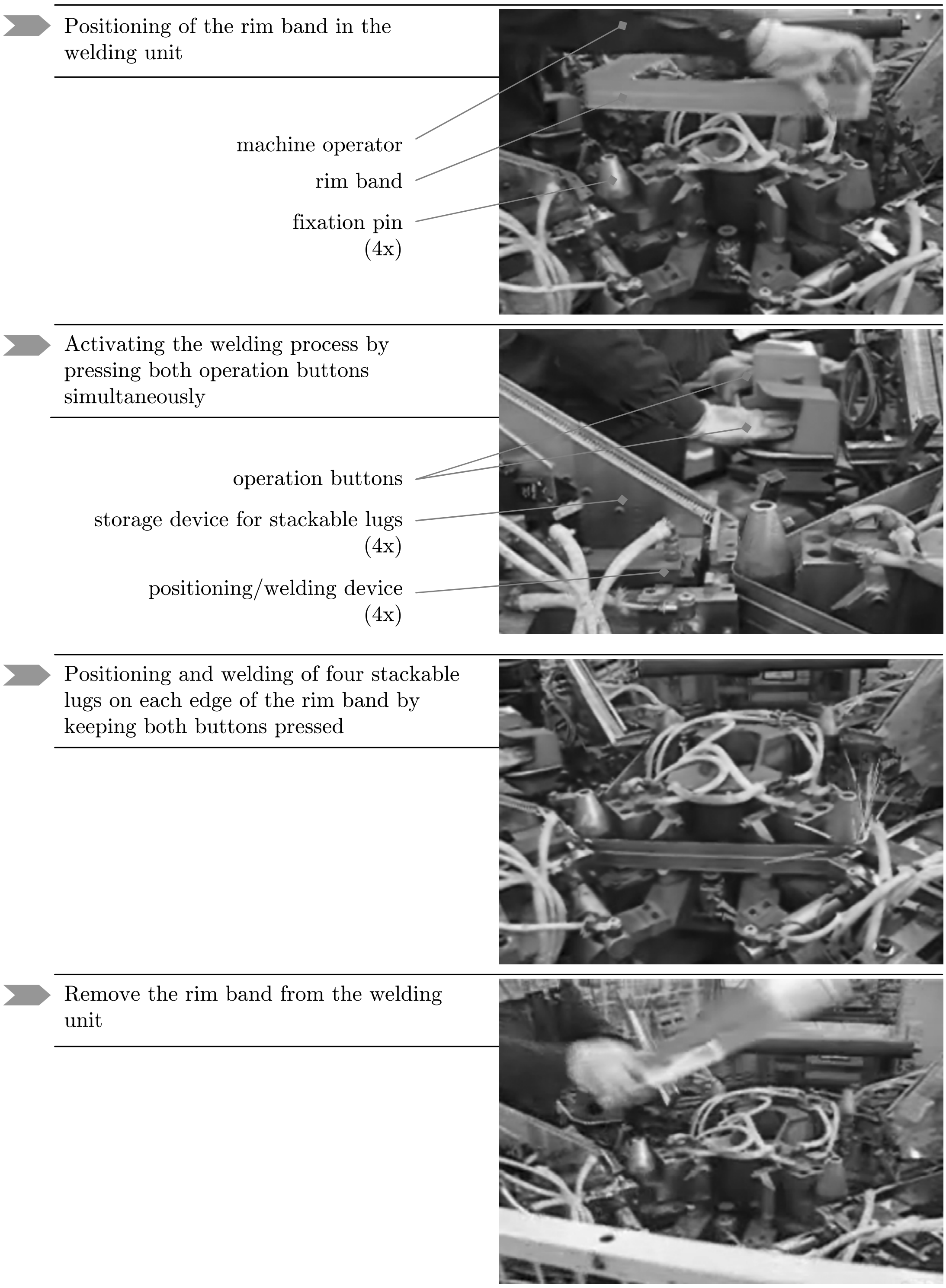


Figure 6.2.: Procedure for the Welding Process of the Rim Band (the low resolution of the pictures results from their extraction from a video; Admeco, 2006b)

6.1.1.2. Dual Task

The operator might also monitor the production process of the stackable lugs which is fully automated. Hence, the industrial worker only has to ensure that the production process of the lugs is supplied with raw material and needs to remove the produced lugs when the buffer of the production machine is (nearly) filled.

In consequence, the operator mainly is involved in rim band welding, but needs to monitor the production process of the lugs which is considered being a dual task. For the operation of the latter process, he/she needs to be mobile between the two machines.

6.1.1.3. Possible Errors

The industrial worker can cause errors. Dependent on the impact, these can be divided in the following categories: production delay, damage to product, damage to tool, damage to machine, damage to building/environment and, eventually, personal injury.

Although it is mostly impossible to directly compare the errors (e.g., it is difficult to state how many damaged products are equal to a personal injury), these incidents can be sorted by means of an ordinal scale (e.g., personal injury is surely worse than damage to a product).

6.1.2. Selection of Tests for the Experiment

As pointed out in the introduction of this chapter, it was not possible to conduct tests with the original operators of the welding stations. Moreover, in the original work environment, it is not possible to control the surrounding conditions of the experiment adequately (see section 2.3.1.2 and 2.3.2 respectively).

Therefore, the original work tasks were analyzed with respect to cognitive and motor functions and was mapped to according laboratory tasks which accurately depicted the requirements of the original task. A *psycho-motor task* was combined with a *divided attention task*, together forming a *factory test* of high practical relevance, as is described in the following.

From the description of the dual task above, it is concluded that mainly psycho-motor skills and mental skills are needed for the rim band worker in order to perform well:

Psycho-motor skills depend on the degree of cooperation between mental and physical skills. A bad cooperation leads to an inaccurate movement of the limbs. For the rim band worker this can result in a decrease of the ability to position rim bands accurately causing a delay in the production and/or scrap. A psycho-motor test will be used to test this skill.

For welding rim bands, perceptual speed, alertness, attention, reasoning and memory are important *mental skills*:

Perceptual speed enables the industrial worker to react quickly to stimuli in him/her environment, e.g., to rapidly note that the welding process is completed or that an error occurred.

Alertness in this specific case denotes the ability of the worker to observe relevant process parameters.

Attention, especially divided attention, in this case, denotes the ability of the worker to successfully conduct the dual task.

Reasoning, in this case, enables the worker to understand why errors occur and how they can be avoided. Especially, the worker needs to decide when he/she leaves the main process of rim band welding in order to empty the buffer of the machine producing lugs. An optimum has to be found, so that no mistakes are made and the amount of products is not affected negatively.

(Working) Memory is involved in remembering the production procedure as well as necessary steps.

In addition to the factory test, specific cognitive skills were tested with sub-tests of the standardized neuro-psychological test battery *Tests of Attentional Performance – Mobility* (TAP-M, Zimmermann and Fimm, 2005).

The selection of experimental tests is described below in detail.

6.1.2.1. Psycho-motor Test

Several standardized psycho-motor tests are available to test gross manual movements, fine manual movements or a combination of both. The rim band welding task belongs to the latter category.

A typical related, standardized test is the Stromberg Dexterity Test. This test was developed in 1945 as one means of employee selection for jobs which require speed and accuracy of arm and hand movements (i.a., assemblers or welders). The Stromberg Dexterity Test requires the applicants to discriminate and sort 54 biscuit shaped discs which are to be inserted into a form board as quickly as possible.

Because the aim of this work was to test the HMI of the Hypovigilance-Management-System in a most natural situation, a specific psycho-motor test was developed on the basis of the Stromberg Dexterity Test, simulating the welding process of the rim bands under controlled conditions. The psycho-motor test made it possible to measure the participant's hand-eye-coordination as well as alertness and attention by counting the number of correct units produced and the number/kind of mistakes made during the test.

The test utilized a "psycho-motor device", 50 rim bands and four storage devices (see figure 6.3). The psycho-motor device did not contain any moving parts and no real welding did take place. Thus, any chance on physical harm was avoided. However, the participants could still make the same kind of mistakes like the "real" industrial workers.

Psycho-motor Device The psycho-motor device consisted of a wooden plate, four PVC-blocks, two toggle switches, a light barrier, and a red LED (see figure 6.4). The PVC-blocks were mounted on the wooden plate. Each block had a slot in which one of the corners of the rim band had to be positioned. A good hand-eye coordination was required because the slots were only one millimeter wide. A light barrier and four sub-miniature switches in the slots of the PVC blocks enabled to check if the operator had positioned the rim band correctly. The imaginary welding process was activated by pressing the two toggle switches simultaneously. A red LED, mounted in the middle of the wooden plate, simulated the imaginary welding process.

Figure 6.3.: Basic Elements of the psycho-motor Test

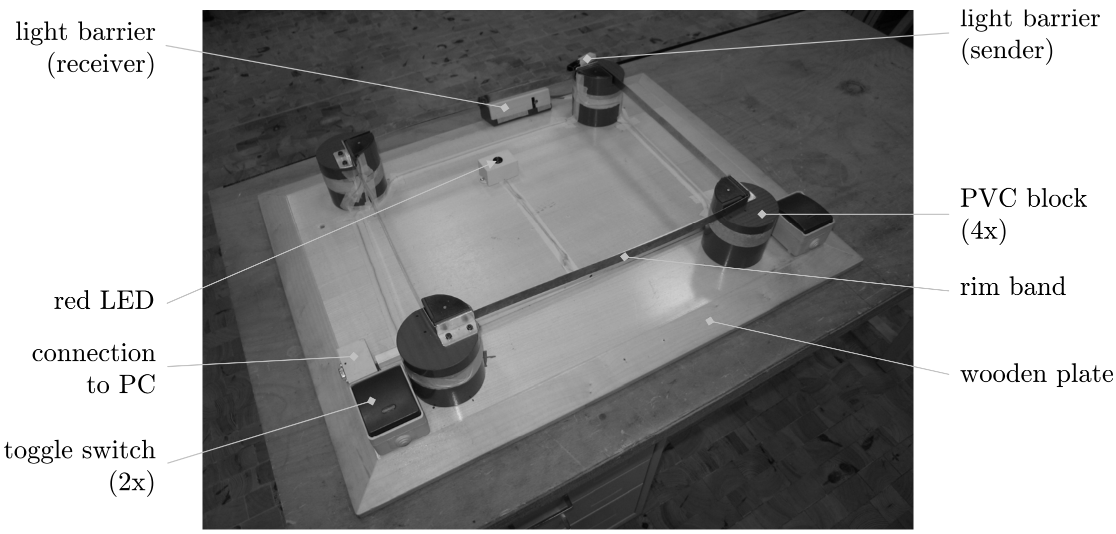


Figure 6.4.: Psycho-motor Device with Rim Band

Rim Bands The rim bands for the test were made of a steel tape of a width of 16 mm and a thickness of 0.5 mm. The steel was cut, bend, and welded resulting in a rim band with a size of 390 mm by 450 mm (see figure 6.5). Each rim band was marked with a white label indicating its orientation (front/back and left/right). This label could be spotted automatically by the light barrier of the psycho-motor device. Half of the rim bands had the label at the same side as the welding spot (compare to figure 6.1), the other half had the label at the opposite side, in order to avoid a too obvious indication of the orientation as the welding spot is an eye-catching marker. Since the rim bands had sharp edges, the participants needed to wear gloves for safety reasons.

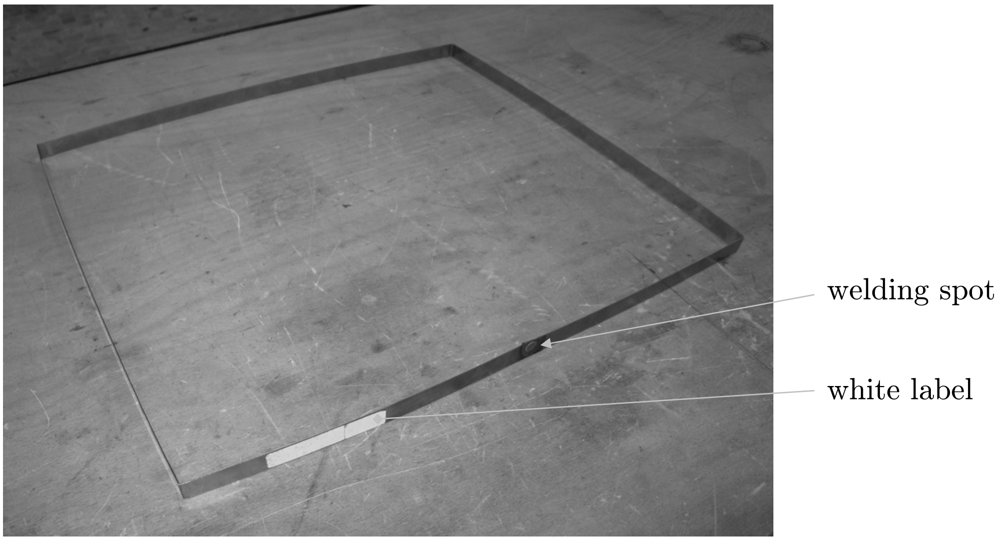


Figure 6.5.: Rim Band

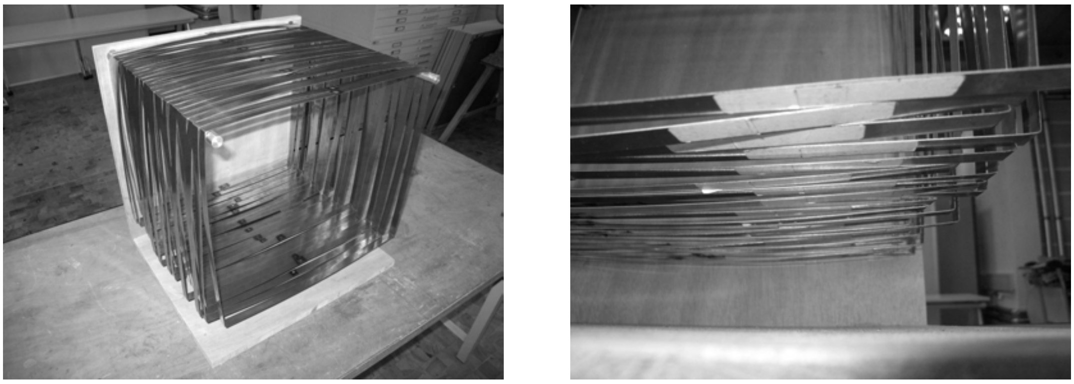
Storage Device The rim bands were difficult to pile up. In order to reduce individual difference in performance due to interpersonal differences in piling abilities, four storage devices were built (see figure 6.6a) in which the rim band were hung systematically.

Each device had space for 25 rim bands. Two storage devices were positioned on the left side of the psycho-motor device and two were positioned on the right side of the psycho-motor test. Half of the storage devices were filled with rim bands, the other half was left empty. The bands were hung with the labels pointing to the floor, making it impossible to see their position (see figure 6.6b). Almost all labels were positioned on the right side and only single labels were positioned on the left side, thus, creating a vigilance task following the definition of Mackworth (1957).

Procedure The participant had to carry out the following procedure to complete the psycho-motor task succesfully:

1. The participant takes a rim band from the storage device.

2. The participant positions the rim band in the psycho-motor device with the white label in the upper right corner.



(a) Storage Device for 25 Rim Bands (b) Positioning of Rim Band Labels

Figure 6.6.: Storage Device

3. The participant activates the imaginary welding process by pressing the two toggle switches simultaneously (the red LED activates and keeps lighting for 15 seconds, indicating the imaginary welding process, and the psycho-motor device determines if the rim band is positioned correctly).
4. The participant releases the toggle switches when the LED stops lighting.
5. The participant hangs the rim band in one of the empty storage devices.

For a continuous work process, four storages devices were needed: The participant took unwelded rim bands from one storage device and, after welding, put them into a storage device for finished rim bands. Once a storage device was filled with welded rim bands, it was taken away by an assistant and the rim bands were repositioned with respect to the white labels, returning to the test site as “new” unwelded rim bands.

Errors It was possible to make three kinds of errors during the psycho-motor tests: First, incorrect positioning in the corners of the psycho-motor device (see figure 6.7), or, second, incorrect orientation of the rim band with respect to light barrier (see figure 6.8) indicated the production of a scrap part.

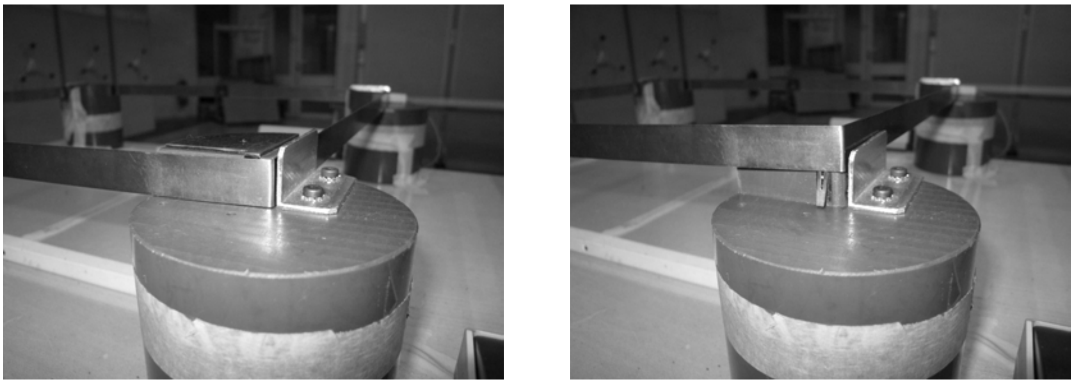
Third, the early release of one or both of the two toggle switches, i.e., while the red LED was still activated, indicated the interruption of the welding process for safety reasons and, hence, the production of a scrap part was well.

The according software was implemented in SwitchBoard (Fraunhofer IAO, 2006), which controlled the system and stored the results automatically in a log-file.

6.1.2.2. Divided Attention Test

The dual task of operating the machine producing the lugs while welding rimbands was represented by a computer simulation: The participants had to supervise a simulated semi-automated production process while conducting the psycho-motor task.

In the simulated production process, manufactured lugs were deposited in a buffer with a maximum storage capacity. The task of the participants was to remove the finished units when this limit was (almost) reached. It is expected that it becomes more difficult to fulfill the divided attention task when sleepiness increases.



(a) Correct Positioning of Rim Band (b) Incorrect Positioning of Rim Band

Figure 6.7.: Sub-Miniature Switches

(a) Correct Orientation of Rim Band (b) Incorrect Orientation of Rim Band

Figure 6.8.: Infrared Light Barrier

User Interface The simulation was implemented in Macromedia Director MX 2004 (Adobe Systems Inc., 2006). Figure 6.9 shows a screenshot of the lay-out of the UI. As the experiments were to be conducted with German students, the language of the UI was German.

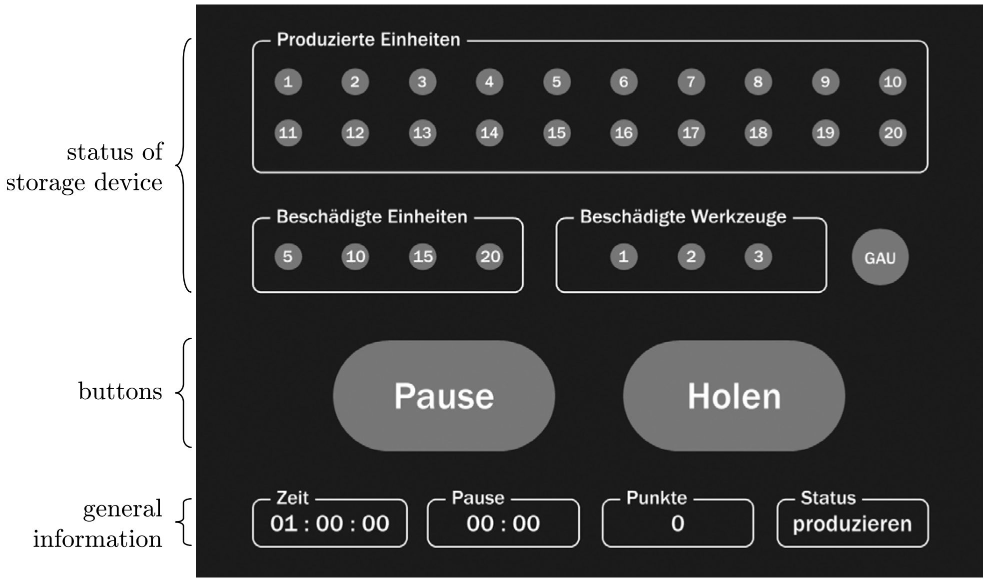


Figure 6.9.: Screenshot of the Lay-Out of the Divided Attention Test

The upper part provided information about the status of the machine buffer ("Produzierte Einheiten" [engl.: units produced], "Beschädigte Einheiten" [engl.: units damaged], "Beschädigte Werkzeuge" [engl.: tools damaged] and "GAU" [Größter Anzunehmender Unfall, engl.: worst case scenario]). The center part contained two buttons ("Pause" and "Holen" [engl.: get parts]). The lower part of the screen provided general information ("Zeit" [engl.: time], "Pause", "Punkte" [engl.: points] and "Status").

The software was installed on a computer with a TFT-touch screen[2] with the simulation filling the whole screen so that the buttons could be pressed directly on the screen even by gloved hands. All results were stored automatically.

Simulated Work Task Empty slots in the machine buffer were represented by gray circles in the "Produzierte Einheiten" box. Every ten seconds, an additional circle turned green, indicating the deposition of a produced lug. The buffer could be "emptied" by pressing the "Holen" button. Then all green circles changed back into gray circles again. After a waiting time of 30 seconds, representing the duration of the emptying process, the simulation started all over again. The delay forced the participants to empty the storage box as late as possible in order to achieve a high production rate.

If the participant did not press the "Holen" button in time, it was assumed that parts in the buffer would be crushed, eventually accumulating and even destroying the production tool head, hence, introducing an error hierarchy. For the same reason, an assumed GAU was included, representing personal injury, e.g., by flying parts if the machine was not stopped.

[2]ELO TFT Touchscreen 1926L, size: 19 inches, resolution: 1280x1024 dots.

These errors were first represented by yellow circles ('Beschädigte Einheiten"). Every yellow circle represented five destroyed units in the storage device. When four yellow circles were displayed, all units in the storage device were damaged. If the participant still did not react, orange circles ("Beschädigte Werkzeuge") indicated the progressive damaging of the tool. Depending of the reaction time, this lead to the necessity to repair the tool and, hence, the simulation was blocked for one, three, or five minutes respectively.

If the user still did not react, the "GAU" circle was lighted and a sound was emitted.

In order to facilitate work breaks, the simulation could be interrupted by pressing the "Pause" button. The text on the "Pause" button then changed from "Pause" to "Weiter" [engl.: continue]. The simulated work process continued, when the "Weiter" button was pressed.

Feedback During the simulation, the participants received feedback about the amount of experimental time left in the "Zeit" box and the total amount of minutes spent in breaks in the "Pause" box. The total number of units produced was displayed in the "Punkte" box and the status of the semi-automated production process was indicated in the "Status" box, namely producing, repairing, waiting, and taking a break.

6.1.2.3. Tests of Attentional Performance

In addition to the factory test, relevant cognitive constructs (refer to section 2.1) were measured with the standardized neuro-psychological test battery *Tests of Attentional Performance-Mobility* (TAP-M, Zimmermann and Fimm, 2005). The test battery was used in its German version as the participants were of German origin. The test battery is computerized (compare to figure 6.10), all results are stored automatically. For reasons of test-time restrictions, only two subtest could be used, "executive control" and "alertness". Both tests included a short training session before the actual measurement.

Figure 6.10.: Setup for Alertness Test and Executive Control Test

Executive Control Test The *Executive control* test provides a global impression of the mental status of an individual. It measures aspects of working memory, divided attention, mental flexibility, selective visual attention, choice reaction and inhibition. It provides information about the speed/accuracy trade-off on predefined stimulus configurations, which are presented one at a time.

The executive control test generates colored numbers and letters in the center of a black computer screen, i.e., a red number, a blue number, a red letter or a blue letter could appear. Red numbers and blue letters are critical stimuli: The participant received the instruction to react as fast as possible to these stimuli by pressing the left button for red numbers and the right button for blue letters. If a blue number or a red number appeared (non critical stimuli), the participant was instructed not to press any of the two buttons (compare to figure 6.11).

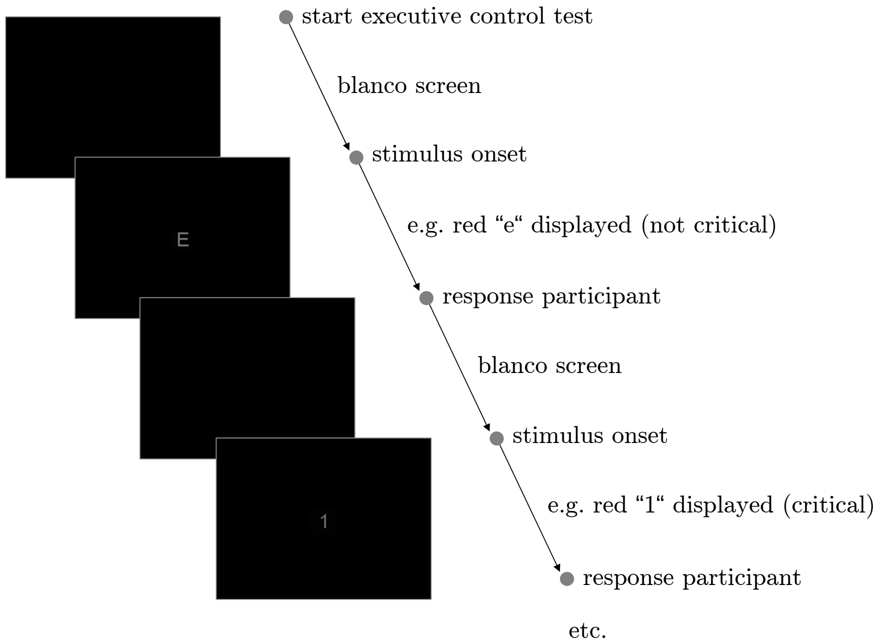


Figure 6.11.: Test Procedure of the Executive Control Test

Relevant test parameters were: reaction time, the number of reactions on incorrect stimuli and the number of ignored correct stimuli.

Alertness Test The *alertness* test examines the tonic alertness of the participants. The task of the participants was to monitor a black computer screen. They received the instruction to press a predefined button as fast as possible every time a white cross appeared. In case of no user reaction, the next trial was started automatically after two seconds and the program registered that no response was given (compare to figure 6.12).

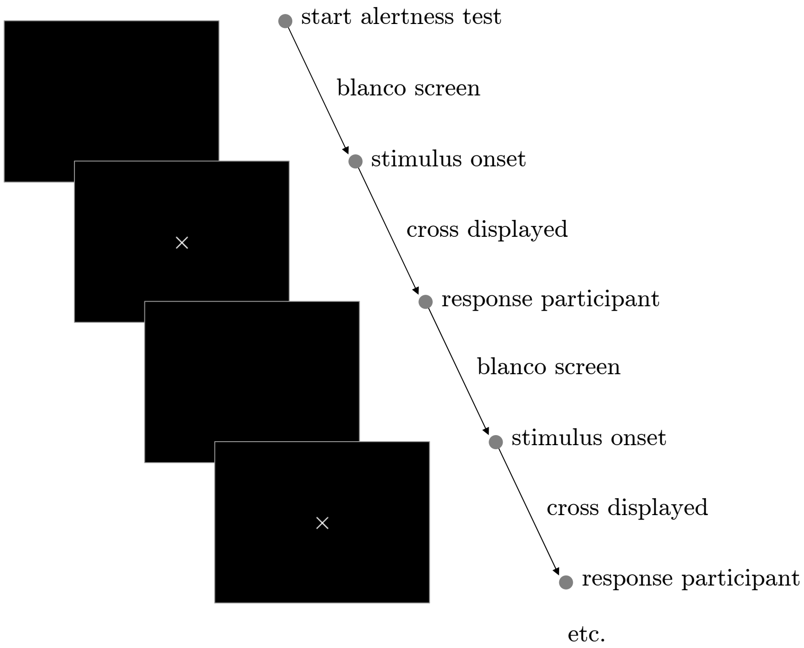


Figure 6.12.: Test Procedure of the Alertness Test

6.2. Method

Four independent variables were defined: treatment group (with three categories: no warning strategy, random warning strategy, and Sensation warning strategy), time of day (with two categories: evening and morning), sex (with two categories: male and female) and chronotype (with three categories: morning type, intermediate type, and evening type). Additionally, for the TAP and the KSS, the variable time of measurement (with two categories: before and after) was included.

The dependent variable for the factory test was performance. This variable was divided into the number of units correctly produced and number/kind of mistakes made. The dependent variable for the KSS was self-rated sleepiness and for the TAP it was the reaction time and the number/kind of mistakes made.

The experiment was divided into two sub-experiments. One of them was conducted in the evening (from 6:00 p.m. to 8:00 p.m.) with the goal of reducing learn effects as well as to create a baseline measurement. The other sub-experiment was conducted in the morning (from 4:30 a.m. to 8:00 a.m.) in order to maximize the effects of sleepiness. Here, the three groups received different treatments.

The experiment mainly used a between-group-design, the participants were randomly assigned to one of the three treatment groups. The groups were parallelized with respect to sex and chronotype.

The experiments were conducted from 26 September till 30 October 2006. An overview over the experimental design is given in figure 6.13.

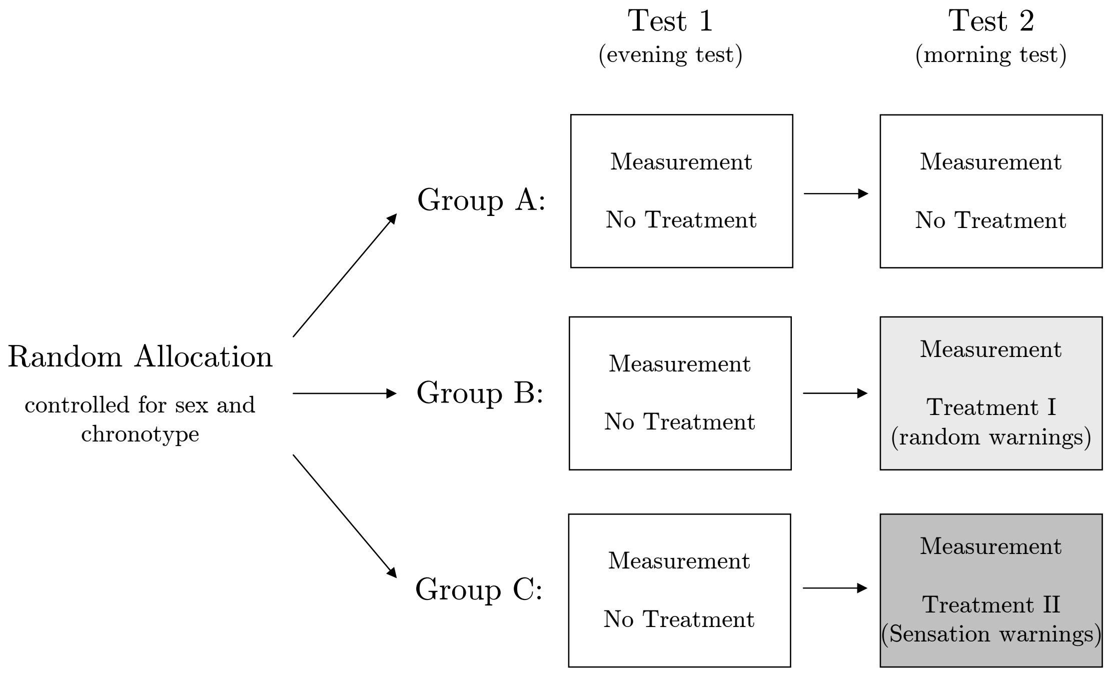


Figure 6.13.: Schematic Overview over the Experimental Design

6.2.1. Participants

In the introduction of this chapter, the necessity to control both the test conditions and the test participants has been pointed out. Consequently, the group of participants is to be chosen carefully.

Although the final target group for the Hypovigilance-Management-System are industrial workers in shift work, this group is not suitable for the purpose of the evaluation experiment. It was pointed out that all influencing factors for the dependent variables need to be controlled. Besides the use of the Hypovigilance-Management-System, the most important influencing variable is hypovigilance. As shift workers often suffer from a disturbed sleep-wake regulation (compare to section 2.3.1.1), they represent an inhomogeneous group with respect to regular individual hypovigilance levels. Moreover, it is difficult to acquire professional workers for a two day laboratory experiment including sleep deprivation; the low number of potential participants further complicates the control of other influencing variables such as sex or chronotype.

In section 2.3.1.2, it was pointed out that the reaction time of young participants was influenced negatively by sleep deprivation while the reaction time of older participants remained almost unaffected (Philip et al., 2004). As, for the experiments, hypovigilance is to be induced by means of sleep deprivation, the participants should be chosen from the younger age group. A very homogeneous group of this age is represented by students (Greenberg, 1987; Reynolds et al., 2000). Moreover, it is comparably easy to acquire students and, thus, to create a "participant pool" which enables to further control the final participant group with respect to sex and chronotype. Thus, students were chosen as participants for the evaluation experiments.

Moreover, the sample size was to be defined. For the sake of test efficiency, the smallest set of participants possible is to be chosen. Poulton (1974, page 20) states that for tracking and manual control tasks (such as the experimental tasks described above),

> "[...] 6 people [per test group] is the smallest number to use in order to be able to generalize the results with reasonable certainty. More than 6 people are necessary, if 1 or 2 people perform very differently from the rest."

In the same way, Mainzer (1982) states that, on the basis of estimated 10% variance and a probability value $p = .95$, a sample size per test group of eight to ten people is sufficient.

A high variance within each test group was very unlikely because the groups were homogeneous as described above. Therefore, a sample size of eight people per test group was chosen, summing up to 24 participants over all.

Consequently, 24 students (12 male and 12 female) were acquired. All students had German as native language, their age ranged between 22 and 31 years ($M = 25.5$, $SD = 2.4$).

Students who did not follow a usual sleep pattern (i.e., 7-9 hours of sleep between 10:00 p.m. and 10:00 a.m.), and students who traveled over more than two time zones within two months before the experiment were excluded because their circadian rhythm might be shifted what could have led to a difference in sleepiness in comparison to the other students.

The students who participated were free from any physical, mental or sensory impairment (by self-disclosure). Each participant received 100 EUR allowance.

6.2.2. Laboratory Setting

The experiments were conducted in the ergonomics laboratory at Fraunhofer IAO/IAT University of Stuttgart. There, three areas were created: a factory setting, a control room and a rim band repositioning corner. All areas were separated from each other by movable walls in order to reduce the interaction of participants and staff to a minimum.

6.2.2.1. Factory Setting

For the psycho-motor test, three tables were positioned in a U-shape (see figure 6.14). The middle table was used for the psycho-motor device and the other two tables were used for the four storage devices.

The divided attention test was located on a table three meters behind the psycho-motor device. Next to the touchscreen, a part of the table was available for the participants to rest during the breaks. This space offered the same kind of relaxation as a table in an ordinary factory cafeteria. All tables were 0.85 meter high and restricted the workspace of the participants to a size of 1.5 by 2 meters.

The wired expert system connection of the HMI of the Hypovigilance-Management-System was hanging from the ceiling in the middle of the factory setting (compare to figure 6.14). During the experiment, it was fixed on the trouser waistband at the back of the participants for pull-relief. From this "central connection point" all other wires were fixed on the body of the participants by means of hook-and-loop fasteners. In this way, the participants could move freely in the factory setting and were only marginally constrained by the system.

Moreover, a video camera was positioned in front of the psycho-motor device. It filmed the participants during the factory test.

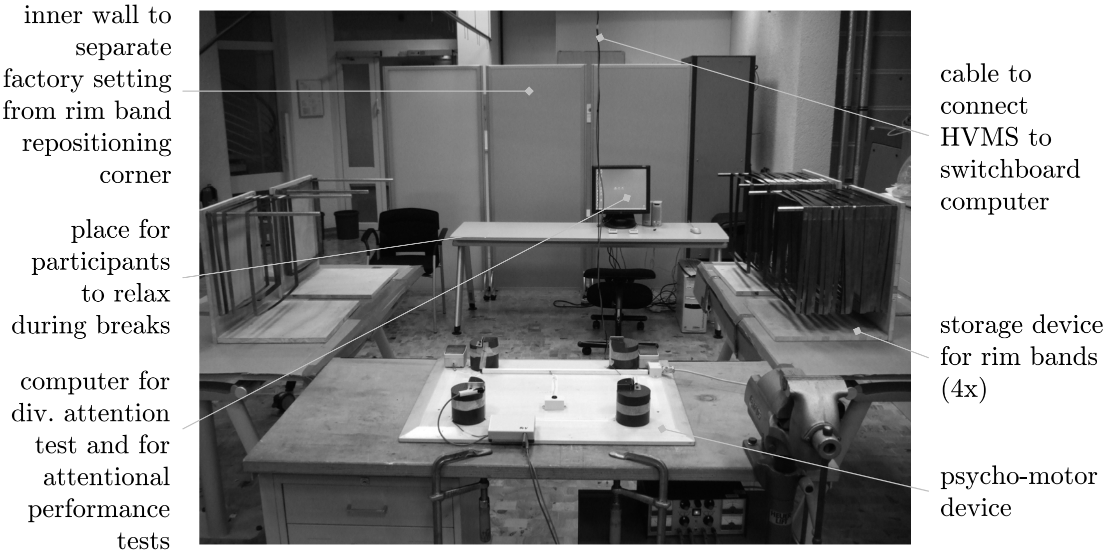


Figure 6.14.: Setting of the Factory Test

The temperature, relative humidity, sound intensity, and light intensity of the factory setting were controlled in order to ensure comparability of the test results. According measurements took place 15 minutes before each evening/morning test and 15 minutes after each evening/morning test. The results indicate usual industrial conditions. Moreover, it can be concluded that environmental conditions were comparable between the evening and morning experiments.

A monotonous sound was produced by the ventilator of a computer server in the room. The monotonous sound was used to mask the noise produced during the repositioning of the rim bands.

6.2.2.2. Rim Band Repositioning Corner

The "welded" rim bands needed to be repositioned as outlined above which was done in the rim band repositioning corner behind the movable walls of the factory setting (compare to figure 6.14). There, a table was installed to deposit the rim band storage devices.

6.2.2.3. Control Room

The test leader was located in the control room, in which the video signal from the factory setting was recorded on a computer and displayed on a 20 inch color television screen. In this way, the test leader was enabled to rate the hypovigilance level of the participants and operate the warnings strategy of the Hypovigilance-Management-System accordingly[3], which was installed on another computer that also gathered the psycho-motor test data. Figure 6.15 shows the set up of the control room.

Figure 6.15.: Setting of Control Room

6.2.3. Procedure

The procedure of the experiment is is schematically shown in figure 6.16.

6.2.3.1. Preparation

Upon registration for the experiment, the participating students had to fill out a questionnaire inquiring demographic and chronobiological data (by means of the standardized German morningness-eveningness-questionnaire, D-MEQ, Griefahn et al., 2001). The questionnaire is included in appendix H. Based on this information, the students were matched for sex and chronotype. Then, they were randomly assigned to one of the three treatment groups. All the participants were provided with a general information sheet.

Important test parameters were investigated in two pilot studies. It was found that sleepiness effects were masked by high arousal levels of the two test participants. Three major adjustments were made: First, the test time was increased from one and a half to three hours, which is closer to the normal 8 hour shift. Second, the imaginary welding time was increased to 15 seconds which is slightly higher than the original welding time but enhances the monotony of the task. Third, the preliminarily planned financial bonus for the production of a certain number of units was canceled because the bonus strongly activated the participants and, hence reduced the effects of sleep deprivation. This adjustment is justified by the fact that workers mostly are paid by accord rates; their aim

[3]Since the sensory system of the Hypovigilance-Management-System still is in development and as the aim of this work is to develop and test the HMI of such a system, a *Wizard of Oz* approach was chosen to test the HMI in which the test leader “manually replaces” the sensory system and provides a vigilance rating to the warning system.

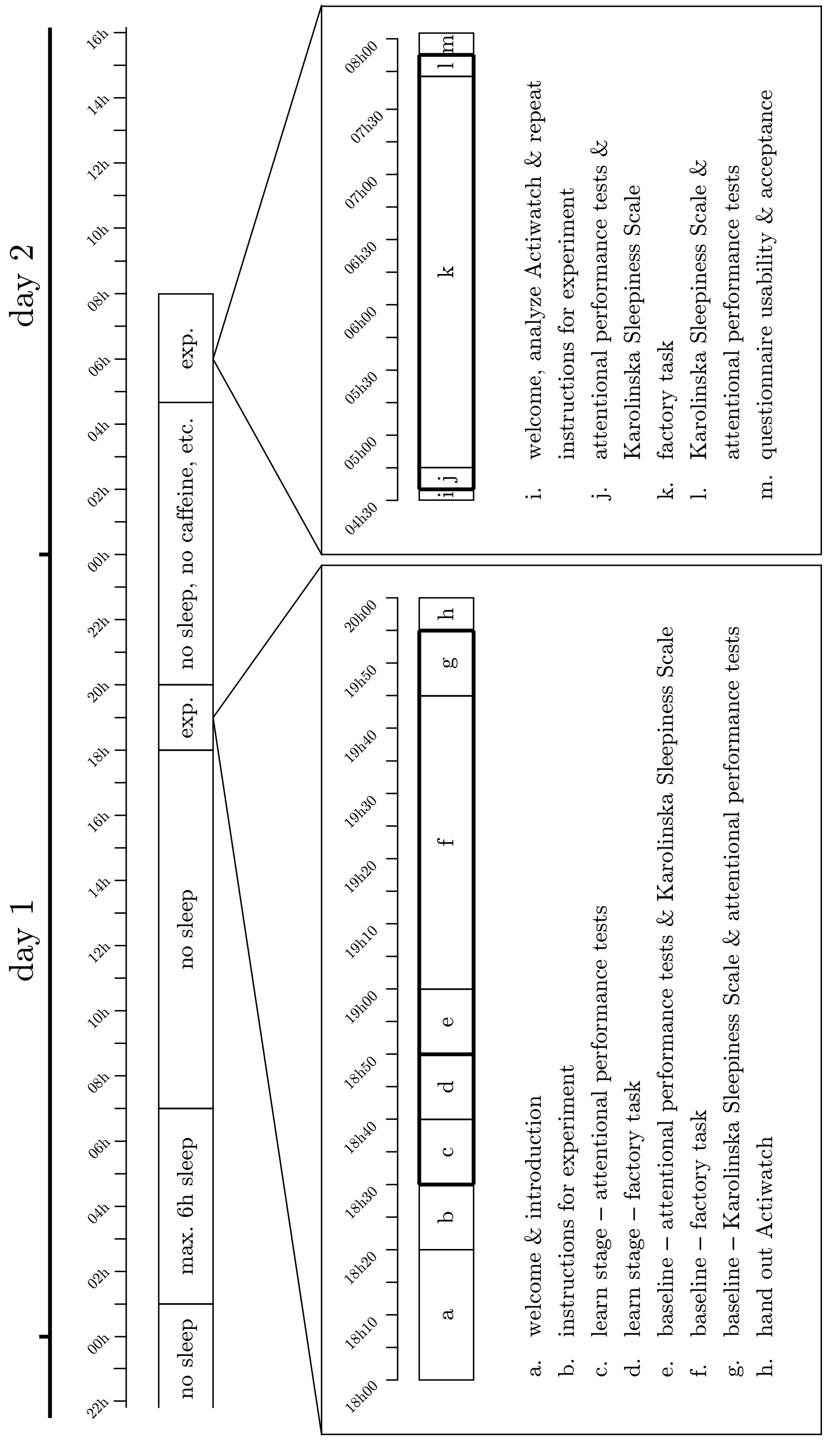


Figure 6.16.: Procedure of Experiment

is not to produce less than the accord level because this way, they would loose money, but also not to produce more because of fear of adjustment of the accord level.

Three days before the experiment, the participants underwent partial sleep deprivation: Each participant was instructed to follow a specific sleep–wake schedule: The night before the evening test, the participants were not allowed to sleep more than 6 hours. It was recommended to go to bed at 1 a.m. and to wake up at 7 a.m. the latest.

6.2.3.2. Evening Test

The evening test started at 6 p.m. and took about 2 hours. First, the participants were re-informed about the test aim and test procedure as well as about potential risks. An informed consent was signed.

The aim of the evening test was twofold: On the one hand, the participants should learn the methods and tests used. On the other hand, a baseline measurement was to be conducted. All participants completed the learn and baseline phase under the same conditions.

Therefore, the factory test was executed one time for 10 minutes in order to reduce learn effects and a second time for 45 minutes in order to create a baseline level. At both tests, the participants wore the Hypovigilance-Management-System, although it was not activated. Moreover, the participants were not allowed to take a break during the factory test.

The TAP-tests were administered three times: before the first factory test run and both before and after the second factory test run.

The KSS was filled in by the participants both before and after the second factory test run.

6.2.3.3. Time Between the Evening Test and the Morning Test

Between the evening test and the morning test, the participants underwent total sleep deprivation. It was checked if the participants really stayed awake by means of actigraphy.

The participants stayed at the test site. During the night, they were not allowed to sleep. To pass time, a computer with an Internet connection and a television set with a video recorder were available. The participants were free to do what they liked, however, the consumption of stimulating drugs was prohibited. It was recommended to drink water, milk or (fruit) juices.

Usual sanitary facilities were provided.

6.2.3.4. Morning Test

The morning test started at 4:30 a.m. and took 3.5 hours. Basically, the baseline measurement was repeated as described above, however, three major differences were implemented: exposure to different treatments, increase in test time, and the allowance to take breaks.

The three groups were exposed to different treatments as described in the introduction of this chapter: One group received no warning messages. Nevertheless, for reasons of comparability, they had to wear the deactivated Hypovigilance-Management-System. The second group received random warning messages. These did not match their actual level of sleepiness. The last group received the Sensation warning messages. These were timed correctly in accordance with the sleepiness level of the participants.

The participants were allowed to take breaks during the morning test. The no-warning group had to rely on themselves in order to start and stop breaks. The random warning group and the Sensation warning group got technical assistance to find the optimal moment, although they were free to ignore the suggestions of the warning messages. The Hypovigilance-Management-System woke up the participants of these two groups 10 minutes after the start of the break.

At the end of the morning experiment, the participants had to fill out a usability and an acceptance questionnaire (see appendix I).

6.3. Results

The software package SPSS 14.0 (SPSS Inc., 2006) and PopTools (CSIRO, 2006) were used for the analysis of the data recorded in the experiments. The data of the usability questionnaire was qualitatively analyzed with MS Excel. The results are presented in four sections in the following: namely, factory test, KSS, test for attentional performance, additional analysis, and usability questionnaire.

All quantitative results reported were statistically tested on a significance level of $p \leq .05$. The effect sizes r_i were calculated for significant results mainly, in order get information about the magnitude of the observed effect, i.e., 0 indicating a very small effect and 1 indicating a very large effect. Effect sizes can be compared across different analyses that measured different variables. All results have been computed on the basis of exact numbers but are presented rounded off to two decimals for the sake of better readability.

6.3.1. Factory Test

The psycho-motor test and the divided attention test were analyzed separately because they tested different underlying cognitive constructs and, hence, a combined score is not meaningful.

Before running the statistical analysis, a performance score P was calculated for the psycho-motor test. This score is based on the ratio between the quantities Q_i of correct products and incorrect products manufactured:

$$P = \frac{Q_{correct\ units}}{Q_{correct\ units} + Q_{incorrect\ units}} \tag{6.1}$$

The result is a number between zero and one. A low number indicates a low performance and a high number indicates a high performance.

6.3.1.1. Difference Between Evening and Morning Test

First, it was analyzed if there was a difference between the evening and the morning experiment. It should support the assumption that the total sleep deprivation and early start time of the experiment had an effect on the results for the factory test.

For the psycho-motor test, the variables performance, productivity, and the amount of errors were analyzed. The number of errors was calculated by adding the number of incorrect positioned rim bands, incorrect rim band orientations, and interrupted welding processes. Because the impact of each error was assumed to be identical, i.e., damage of the rim band, these errors were summarized in a single score.

The divided attention test was analyzed for the variables performance, productivity and number of damaged units. To eliminate the performance difference due to duration, the morning score was divided by four because the morning experiment took four times longer than the evening experiment.

In this analysis, only the no warning group was included because an increase in performance was expected for the other two groups as a result of the warning intervention:

$$H_0 : \mu_{evening} = \mu_{morning} \quad (6.2)$$
$$H_1 : \mu_{evening} < \mu_{morning} \quad (6.3)$$

The descriptive statistics are shown in table 6.1.

Test	Measurement	Time	M	SD	N
psycho-motor	performance	evening	0.93	0.08	8
		morning	0.95	0.06	8
	productivity	evening	79.13	6.58	8
		morning	74.34	6.23	8
	errors	evening	6.63	8.83	8
		morning	4.53	6.62	8
divided attention	performance	evening	0.98	0.02	8
		morning	0.98	0.03	8
	productivity	evening	224.38	7.91	8
		morning	215.78	15.19	8
	damaged units	evening	4.38	4.17	8
		morning	5.16	6.66	8
	damaged tools	evening	0	0	8
		morning	0.13	0.23	8

Note: M..mean Value, SD..standard deviation, N..number of participants

Table 6.1.: Descriptive Statistics for the Differences at the Factory Test Between Evening and Morning in the No-Warning Group; $N = 8$

For the divided attention test, the number of GAUs caused were not included in the table because the no warning group did not cause any GAUs, neither in the evening, nor in the morning.

The data was non-parametric because the assumption of normality (test of normality by Kolmogorov-Smirnov and Shapiro-Wilk) and homogeneity and/or the assumption of variance equality (Levene's test) were violated. Therefore, the Wilcoxon signed-rank test was selected which is the non-parametric equivalent of the t-test for dependent samples, and is used to test differences between groups if there are two conditions (i.e., morning vs.

evening) and the same participants have been exposed to both conditions. The according results are presented in table 6.2.

Test	Measurement	Comparison	T	Sig. p	r
psycho-motor	performance	morning vs. evening	26.00	.26	-.28
	productivity	morning vs. evening	32.00	.05	-.49
	errors	morning vs. evening	28.00	.16	-.35
divided attention	performance	morning vs. evening	11.00	.92	-.03
	productivity	morning vs. evening	26.00	.26	-.28
	damaged units	morning vs. evening	10.50	1.00	.00
	damaged tools	morning vs. evening	3.00	.16	-.35

Note: T..Wilcoxon-T, p..error probability, r..effect size

Table 6.2.: Results of Wilcoxon Signed-Rank test for Differences Between Evening and Morning Test

Only one significant value was found. The participants produced significantly less rim bands in the morning ($M = 74.34$) than in the evening ($M = 79.13$, $T = 32.00$, $p = .05$).

6.3.1.2. Differences Between Treatment Groups in the Evening Test

For the psycho-motor test, the variables performance, productivity and the amount of errors were analyzed.

For the divided attention test, the variables *performance*, *productivity* and *number of damaged units* were analyzed. Because none of the tools was damaged and no GAUs occurred at the evening test, these two variables were excluded from the statistical analysis.

No differences between the three groups in the evening test were expected, because all groups worked under the same condition. Therefore, the according statistical (null) hypotheses are

$$H_0 \quad : \quad \mu_{no\ warning} = \mu_{random\ warning} = \mu_{SENSATION\ warning} \tag{6.4}$$

$$H_1 \quad : \quad \text{at least two means are unequal} \tag{6.5}$$

Descriptive statistics of the according data are shown in table 6.3.

The data was non-parametric. Therefore, the data was analyzed using the Kruskal-Wallis test. This is the non-parametric equivalent of the one-way independent ANOVA and is used for testing differences between groups if there are more than two conditions (i.e., no warning strategy, random warning strategy and Sensation warning strategy) and different participants have been used in all conditions.

No significant results were found. The null-hypothesis could not be rejected. For the psycho-motor test, no significant difference in performance (Kruskal-Wallis-$H(3)$=0.42, n.s.), productivity ($H(3)$=0.82, n.s.) and number of mistakes made ($H(3)$=0.50, n.s.) could be found. In the same way, for the divided attention test, the variables performance ($H(3)$=2.33, n.s.), productivity ($H(3)$=0.97, n.s.) and amount of damaged units ($H(3)$=2.97, n.s.) did not differ significantly.

Test	Measurement	Treatment Group	M	SD	N
psycho-motor	performance	no warning strategy	0.93	0.08	8
		random warning strategy	0.91	0.11	8
		SENSATION warning strategy	0.91	0.10	8
	productivity	no warning strategy	79.13	6.58	8
		random warning strategy	75.00	9.44	8
		SENSATION warning strategy	77.38	8.33	8
	errors	no warning strategy	6.63	8.83	8
		random warning strategy	7.63	9.50	8
		SENSATION warning strategy	7.63	8.96	8
divided attention	performance	no warning strategy	0.98	0.02	8
		random warning strategy	0.95	0.05	8
		SENSATION warning strategy	0.99	0.02	8
	productivity	no warning strategy	224.38	7.91	8
		random warning strategy	216.63	16.51	8
		SENSATION warning strategy	220.42	7.87	8
	damaged units	no warning strategy	4.38	4.17	8
		random warning strategy	10.00	10.00	8
		SENSATION warning strategy	3.13	5.30	8

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.3.: Descriptive Statistics for Differences Between Treatment Groups in Evening Test; $N = 24$

6.3.1.3. Differences Between Treatment Groups in the Morning Test

In contrast to the evening experiment, differences were expected to be found between the treatment groups after a night of sleep deprivation. For the psycho-motor test the variables performance, productivity, and amount of errors were analyzed. For the divided attention test, performance, productivity, amount of damaged units, amount of damages tools, and number of GAUs were analyzed.

It was expected that the Sensation warning group would be superior to the no warning group:

$$H_0 : \mu_{Sensation\ warning} = \mu_{no\ warning} \tag{6.6}$$
$$H_1 : \mu_{Sensation\ warning} > \mu_{no\ warning} \tag{6.7}$$

Moreover, the Sensation warning group was expected be superior to the random warning group:

$$H_0 : \mu_{Sensation\ warning} = \mu_{random\ warning} \tag{6.8}$$
$$H_1 : \mu_{Sensation\ warning} > \mu_{random\ warning} \tag{6.9}$$

Finally, the random warning group should be superior the no warning group:

$$H_0 : \mu_{random\ warning} = \mu_{no\ warning} \tag{6.10}$$
$$H_1 : \mu_{random\ warning} > \mu_{no\ warning} \tag{6.11}$$

Descriptive statistics of the relevant variables are shown in table 6.4. The number of GAUs occurred is not included in this table: Participants who executed the experiment without having caused a GAU were assigned a GAU-score of zero and participants who caused one GAU were assigned a score of one. Two participants in the random warning group and two participants in the Sensation warning group caused a GAU. No GAU was caused in the no warning group.

Again, the data was non-parametric. Therefore, the hypotheses were tested with Mann-Whitney-tests. The Mann-Whitney-test is the non-parametric equivalent of the t-test for independent samples and is used for testing differences between groups when there are two conditions (i.e., Sensation warning strategy vs. no warning strategy, Sensation warning strategy vs. random warning strategy and random warning strategy vs. no warning strategy) and different participants have been used in each condition. An overview over the results is given in table 6.5. The number of GAUs was analyzed with a χ^2-test.

No significant results were found for the Mann-Whitney-tests. The χ^2-Square test for the GAUs was not significant either. The Sensation warning group did not create significantly more GAUs than the no warning group ($\chi^2(1) = 0.57$, n.s.). The same counts for the difference between the Sensation warning group and the random warning group ($\chi^2(1) = 0.33$, n.s.). The random warning group did not create significantly more GAUs than the no warning group either ($\chi^2(1) = 0.57$, n.s.).

Test	Measurement	Treatment Group	M	SD	N
psycho-motor	performance	no warning strategy	0.95	0.06	8
		random warning strategy	0.90	0.09	8
		Sensation warning strategy	0.87	0.18	8
	productivity	no warning strategy	297.38	24.93	8
		random warning strategy	284.88	47.55	8
		Sensation warning strategy	289.75	47.61	8
	errors	no warning strategy	18.13	26.47	8
		random warning strategy	32.25	28.26	8
		Sensation warning strategy	52.13	84.20	8
divided attention	performance	no warning strategy	0.98	0.03	8
		random warning strategy	0.97	0.03	8
		Sensation warning strategy	0.96	0.05	8
	productivity	no warning strategy	863.13	60.76	8
		random warning strategy	871.75	91.33	8
		Sensation warning strategy	866.75	64.02	8
	damaged units	no warning strategy	20.63	26.65	8
		random warning strategy	25.00	35.36	8
		Sensation warning strategy	31.88	45.90	8
	damaged tools	no warning strategy	0.50	0.93	8
		random warning strategy	0.00	0.00	8
		Sensation warning strategy	0.25	0.71	8

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.4.: Descriptive Statistics for Differences Between Treatment Groups in Morning Test; $N = 24$

Test	Measurement	Comparison	U	p	r
psycho-motor	performance	Sensation wrn. vs. no wrn.	22.0	.29	-.26
		Sensation wrn. vs. random wrn.	31.0	.92	-.03
		random wrn. vs. no wrn.	19.0	.17	-.34
	productivity	Sensation wrn. vs. no wrn.	30.5	.88	-.04
		Sensation wrn. vs. random wrn.	29.5	.79	-.07
		random wrn. vs. no wrn.	30.0	.84	-.05
	errors	Sensation wrn. vs. no wrn.	22.5	.32	-.25
		Sensation wrn. vs. random wrn.	31.0	.92	-.03
		random wrn. vs. no wrn.	21.0	.25	-.29
divided attention	performance	Sensation wrn. vs. no wrn.	31.0	.91	-.03
		Sensation wrn. vs. random wrn.	28.0	.67	-.11
		random wrn. vs. no wrn.	32.0	1.00	.00
	productivity	Sensation wrn. vs. no wrn.	31.0	.92	-.03
		Sensation wrn. vs. random wrn.	26.0	.53	-.16
		random wrn. vs. no wrn.	26.5	.56	-.14
	damaged units	Sensation wrn. vs. no wrn.	31.0	.91	-.03
		Sensation wrn. vs. random wrn.	28.0	.67	-.11
		random wrn. vs. no wrn.	30.5	.87	-.04
	damaged tools	Sensation wrn. vs. no wrn.	28.0	.54	-.16
		Sensation wrn. vs. random wrn.	28.0	.32	-.25
		random wrn. vs. no wrn.	24.0	.14	-.37

Note: U..Mann-Whitney-U, p..error probability, r..effect size, wrn. ..warning

Table 6.5.: Results of Mann-Whitney Tests for Differences Between Treatment Groups in the Morning Test

6.3.1.4. Characteristics of the Participants

Although there were no significant differences between the treatment groups, some variables such as productivity and the amount of errors in the psycho-motor tests showed SDs that were nearly three times higher in the Sensation warning group compared to the other two groups (see table 6.4): Some participants performed much better than the best participants in the no warning group, others performed much worse than the worst participants in the no warning group.

It was hypothesized that the effectiveness of the Hypovigilance-Management-System depends on certain characteristics of participants. Therefore, an explorative data analysis was conducted with respect to sub-groups of sex, age, and chronotype.

Effect of Sex Only the Sensation warning group was included in this analysis. The productivity and amount of errors at the psycho-motor test and the number of damaged units at the divided attention test had a large SD and, therefore, were investigated.

It was assumed that women use the information of the Hypovigilance-Management-System more sensible than men:

$$H_0 : \mu_{male} = \mu_{female} \tag{6.12}$$
$$H_{1a} : \mu_{male} > \mu_{female} \text{ for errors and damaged units} \tag{6.13}$$
$$H_{1b} : \mu_{male} < \mu_{female} \text{ for productivity} \tag{6.14}$$

Descriptive statistics for the variables with respect to sex for the morning test are provided in table 6.6

Test	Measurement	Sex	M	SD	N
psycho-motor	productivity	male	286.00	43.92	4
		female	293.25	57.63	4
	errors	male	30.25	120.22	4
		female	74.00	28.50	4
divided attention	damaged units	male	46.25	57.93	4
		female	17.50	31.75	4

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.6.: Descriptive Statistics for Effect of Sex on Factory Task; $N = 8$

Because the data was non-parametric, it was analyzed with a Mann-Whitney-test. None of the differences were significant. The productivity at the psycho-motor test did not differ between men ($M = 286$) and women ($M = 293$, $U = 7.00$, n.s.). The same applied to the difference in amount errors made between men ($M = 30.25$) and women ($M = 74.00$, $U = 8.00$, n.s.). The difference in the number of damaged units between men ($M = 46.25$) and woman ($M = 17.50$) did not differ significantly either ($U = 6.50$, n.s.).

Effect of Age The effect of age was analyzed in the same way and with the same variables as it was done for the effects of sex. Therefore, the participants were divided into two categories: from 22 to 24 years old and from 25 to 31 years old.

It was expected that the older participants performed better than the younger participants because it is assumed that they would show a higher compliance with the warning messages:

$$H_0 \; : \; \mu_{22-24\ years} = \mu_{25-31\ years} \tag{6.15}$$

$$H_{1a} \; : \; \mu_{22-24\ years} > \mu_{25-31\ years} \text{ for errors and damaged units} \tag{6.16}$$

$$H_{1b} \; : \; \mu_{22-24\ years} > \mu_{25-31\ years} \text{ for productivity} \tag{6.17}$$

The descriptive statistics are listed in table 6.7.

Test	Measurement	Age	M	SD	N
psycho-motor	productivity	22-24 years	285.33	54.97	6
		25-31 years	303.00	16.97	2
	errors	22-24 years	61.50	97.28	6
		25-31 years	24.00	14.14	2
divided attention	damaged units	22-24 years	31.67	50.27	6
		25-31 years	32.50	45.96	2

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.7.: Descriptive Statistics for Effect of Age on Factory Task; $N = 8$

A Mann-Whitney test was used for the analysis, because the data was non-parametric. The difference in productivity at the psycho-motor test between the 22-24 year olds ($M = 285$) and 25-31 year olds ($M = 303$) was not significant ($U = 6.00$, n.s.). Likewise, the 25-31 year old participants ($M = 24.00$) did not made significantly more errors at the psycho-motor test than the 22-24 year old participants ($M = 61.50$, $U = 5.00$, n.s.). For the divided attention test, the difference in number of damaged units was not significant ($U = 6.00$, n.s.) for the 22-24 years olds ($M = 31.67$) and the 25-31 years olds ($M = 32.50$).

6.3.2. Karolinska Sleepiness Scale (KSS)

The KSS was applied before and after both the evening and morning experiment, i.e., four times. The following analyses were conducted with the respective data.

6.3.2.1. Difference in Rating Between Evening and Morning Test

First, it was analyzed if there was a difference in evaluation between the evening and the morning experiment. It should support the assumption that the total sleep deprivation and early start time of the experiment had an effect on the subjective sleepiness of the participants. For this purpose, the rating at the beginning of the evening test is compared to the rating at the beginning of the morning test for all participants.

An increase in sleepiness is expected resulting from the sleep deprivation.

$$H_0 : \mu_{evening} = \mu_{morning} \quad (6.18)$$
$$H_1 : \mu_{evening} < \mu_{morning} \quad (6.19)$$

See table 6.8 for the according descriptive statistics.

Measurement	M	SD	N
before evening test	5.04	2.01	24
before morning test	7.33	0.82	24

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.8.: Descriptive Statistics for Difference in Rating Between Evening and Morning Test: $N = 24$.

The data was non-parametric and, therefore, the Wilcoxon signed-rank test was selected. The subjective sleepiness before the morning test ($M = 7.33$), was significantly higher than the one before the evening test ($M = 5.04$, $T = 2.00$, $p < .05$).

6.3.2.2. Differences Between Treatment Groups in Evening Test

Here, the change in sleepiness during the evening test is analyzed. Therefore, a difference value of the KSS score measured after the factory test and the one measured before the factory test is computed:

$$\Delta_{KSS} = KSS_{after} - KSS_{before} \quad (6.20)$$

A positive score indicates that the participants became more tired during the test.

For the evening test, no difference between the treatment groups was expected to be found because all participants worked under the same conditions:

$$H_0 : \mu_{no\ warning} = \mu_{random\ warning} = \mu_{Sensation\ warning} \quad (6.21)$$
$$H_1 : \text{at least two means are unequal} \quad (6.22)$$

The according descriptive statistics are shown in table 6.9

The Kruskal-Wallis test was used for the statistical analysis, because the data was non-parametric. No significant differences were found between the treatment groups in the evening experiment ($H(2) = 1.99$, n.s.). This confirms the assumption that the participants in the different treatment groups were equal with respect to their subjective sleepiness degradation.

6.3.2.3. Differences Between Treatment Groups in Morning Test

The change in sleepiness during the morning test is analyzed for the three treatment conditions. A difference value was computed like in the case of the evening experiment.

Treatment Group	M	SD	N
no warning strategy	-0.13	1.89	8
random warning strategy	-0.38	0.92	8
Sensation warning strategy	0.38	1.30	8

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.9.: Descriptive Statistics for Difference Between Treatment Groups in Evening Test; $N = 8$.

For the morning experiment, differences were expected to be found due to the different warning strategies:

It was expected that participants in the Sensation-group rated themselves more awake than the participants in the no warning group.

$$H_0 : \mu_{Sensation\ warning} = \mu_{no\ warning} \tag{6.23}$$
$$H_1 : \mu_{Sensation\ warning} < \mu_{no\ warning} \tag{6.24}$$

In addition, it was expected that the participants in the Sensation warning group rated themselves more awake than the participants in the random warning group:

$$H_0 : \mu_{Sensation\ warning} = \mu_{random\ warning} \tag{6.25}$$
$$H_1 : \mu_{Sensation\ warning} < \mu_{random\ warning} \tag{6.26}$$

Moreover, it was expected that the participants in the random warning group rated themselves more awake than the participants in the no warning group:

$$H_0 : \mu_{random\ warning} = \mu_{no\ warning} \tag{6.27}$$
$$H_1 : \mu_{random\ warning} < \mu_{no\ warning} \tag{6.28}$$

The according descriptive statistics are listed in table 6.10

Treatment Group	M	SD	N
no warning strategy	0.13	0.99	8
random warning strategy	0.50	0.76	8
Sensation warning strategy	1.13	0.83	8

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.10.: Descriptive Statistics for Difference Between Treatment Groups in Morning Test; $N = 24$

The data was non-parametric and, therefore, analyzed with the Mann-Whitney-test. The difference in rating between the Sensation warning group ($M = 1.1250$) and the no warning group ($M = 0.13$) only curtly missed significance ($U = 14.50$, $p = .052$). The

Sensation warning group became more sleepy during the experiment than the no warning group. Moreover, no significant difference was found between the Sensation warning group ($M = 1.13$) and the random warning group ($M = 0.50$, $U = 19.50$, n.s.). Finally, the difference in the sleepiness rating between the random warning group and the no warning group was not significant either ($U = 24.50$, n.s.).

6.3.3. Tests of Attentional Performance (TAP)

Two test batteries of the TAP-M were used at the experiment: alertness and executive control. The alertness test measured reaction times. The executive control test measured reaction times for correct answers, number of responses to non-critical stimuli $Q_{false\ positive}$ and number of missing responses to critical stimuli $Q_{missing}$. These last two measures were transformed into an accuracy rate A. It is to be added that the test included 40 critical and 40 non-critical stimuli.

$$A = 1 - \frac{Q_{false\ positive} + Q_{missing}}{80} \tag{6.29}$$

The outcome is a rate between zero and one. A low rate means a low accuracy and a high rate means a high accuracy.

6.3.3.1. Difference in Performance Between Evening and Morning Test

It was analyzed if there was a difference in performance between the evening and the morning experiment. It was expected that attention decreased from evening to morning as a result of the total sleep deprivation. Therefore, the data of all participants at the beginning of the evening experiment was compared to one at the begin of the morning experiment.

$$H_0 : \mu_{evening} = \mu_{morning} \tag{6.30}$$

$$H_1 : \mu_{evening} < \mu_{morning} \tag{6.31}$$

The descriptive statistics are shown in figure 6.11

Test	Measurement	M	SD	N
alertness	before evening test	252.96	22.70	24
	before morning test	263.46	24.16	24
executive control (reaction times)	before evening test	561.92	80.80	24
	before morning test	537.50	85.75	24
executive control (accuracy rate)	before evening test	0.98	0.03	24
	before morning test	0.98	0.03	24

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.11.: Descriptive Statistics for Difference Between Treatment Groups in Morning Test; $N = 24$

The Wilcoxon signed-rank test was used to analyze the data, because it was not parametric. The difference for the alertness test between the evening ($M = 252.96$) and morning test ($M = 263.46$) only curtly missed significance ($T = 75.00$, $p = .055$), i.e., the participants reacted slower in the morning than in the evening.

A significant difference was found for the reaction times at the executive control test between the evening ($M = 561.92$) and morning test ($M = 537.50$, $T = 51.50$, $p = 0.05$). The participants were faster in the morning experiment which is assumed to be due to a learn effect. The mean reaction times of the participants in the four attention trials were: 562 ($SD = 80.80$), 533 ($SD = 70.35$), 538 ($SD = 85.75$) and 541 ($SD = 103.43$) milliseconds respectively. Thus, it could be assumed that the influence of the learning effect were eliminated first for the measurement after the evening experiment.

However, the finding for the reaction times of the executive control test is not supported by the according accuracy rate as the difference between the respective evening and morning tests were not significant ($T = 5.00$, n.s.).

6.3.3.2. Differences Between Treatment Groups in Evening Test

Here, the change in reaction time and accuracy during the evening test were analyzed separately. Therefore, according difference values ΔV_i were computed:

$$\Delta V_i = V_{i;after} - V_{i;before} \tag{6.32}$$

No differences were expected to be found, because all treatment groups worked under the same conditions:

$$H_0 : \mu_{no\ warning} = \mu_{random\ warning} = \mu_{Sensation\ warning} \tag{6.33}$$

$$H_1 : \text{at least two means are unequal} \tag{6.34}$$

The according descriptive statistics are shown in table 6.12.

The data was non-parametric. Therefore, the Kruskal-Wallis test was used. None of the results were significant. This confirmed the assumption that all treatment groups were equal.

No significant difference was found for the reaction times in the alertness test ($H(2) = 0.59$, n.s.). Neither was a significant difference in reaction times found for the executive control test ($H(2) = 2.26$, n.s.). Moreover, the accuracy rate of the three treatment groups did not differ significantly ($H(2) = 1.03$, n.s.).

6.3.3.3. Differences Between Treatment Groups in the Morning Test

In contrast to the evening experiment, differences in reaction time and accuracy were expected to be found between the treatment groups for the morning test as these were supported by different warning strategies in the factory test.

It was expected that the Sensation warning group was superior to the no warning group:

Test	Measurement	Treatment Group	M	SD	N
alertness	reaction times	no wrn. strategy	3.88	22.46	8
		random wrn. strategy	7.63	14.88	8
		Sensation wrn. strategy	2.25	23.96	8
executive control	reaction times	no wrn. strategy	-36.63	42.28	8
		random wrn. strategy	-39.25	51.96	8
		Sensation wrn. strategy	-9.88	33.19	8
	accuracy rate	no wrn. strategy	0.01	0.04	8
		random wrn. strategy	0.02	0.05	8
		Sensation wrn. strategy	-0.00	0.03	8

Note: M..mean value, SD..standard deviation, N..number of participants, wrn. ..warning

Table 6.12.: Descriptive Statistics for Difference Between Treatment Groups in Evening Test; $N = 24$

$$H_0 : \mu_{Sensation\ warning} = \mu_{no\ warning} \quad (6.35)$$
$$H_a : \mu_{Sensation\ warning} < \mu_{no\ warning} \quad (6.36)$$

In addition, it was expected that the Sensation warning group was superior to the random warning group:

$$H_0 : \mu_{Sensation\ warning} = \mu_{random\ warning} \quad (6.37)$$
$$H_a : \mu_{Sensation\ warning} < \mu_{random\ warning} \quad (6.38)$$

Moreover, it was expect that the random warning group was superior to the no warning group:

$$H_0 : \mu_{random\ warning} = \mu_{no\ warning} \quad (6.39)$$
$$H_a : \mu_{random\ warning} < \mu_{no\ warning} \quad (6.40)$$

The according descriptive statistics are shown in table 6.13.

Because the data was non-parametric, the Mann-Whitney test was used for the analysis. An overview of the results is given in table 6.14

Only one result was significant. The level of alertness of the no warning group ($M = 0.38$) decreased less over time than that of the Sensation warning group ($M = 15.57$, $U = 10.00$, $p < 0.05$).

6.3.4. Additional Analysis

In this section, the difference in the level of sleepiness as determined by the rater and the duration of the breaks made by the participants is analyzed for the morning experiment.

The level of sleepiness was defined on a scale from 0 to 2 (0=awake, 1=moderate sleepy and 2=very sleepy). The duration of the breaks was measured in seconds. Because several breaks could be made, the duration of all breaks was summed up.

Test	Measurement	Treatment Group	M	SD	N
alertness	reaction times	no warning strategy	0.38	39.70	8
		random warning strategy	18.13	32.74	8
		Sensation warning strategy	15.57	12.33	7
executive control	reaction times	no warning strategy	20.25	23.65	8
		random warning strategy	18.88	43.25	8
		Sensation warning strategy	-46.29	119.49	8
	accuracy rate	no warning strategy	-0.02	0.04	8
		random warning strategy	-0.01	0.04	8
		Sensation warning strategy	-0.05	0.05	7

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.13.: Descriptive Statistics for Difference in the TAP-M Test Between the Treatment Groups in the Morning Test; $N = 23$ and 24, respectively

Test	Measurement	Comparison	U	p	r
alertness	reaction time	Sensation wrn. vs. no wrn.	10.00	.04	-.52
		Sensation wrn. vs. random wrn.	25.00	.73	-.09
		random wrn. vs. no wrn.	21.00	.25	-.29
executive control	reaction time	Sensation wrn. vs. no wrn.	18.50	.27	-.28
		Sensation wrn. vs. random wrn.	22.00	.49	-.17
		random wrn. vs. no wrn.	29.00	.75	-.08
	accuracy rate	Sensation wrn. vs. no wrn.	19.50	.32	-.25
		Sensation wrn. vs. random wrn.	13.00	.08	-.44
		random wrn. vs. no wrn.	25.00	.43	-.20

Note: U..Mann-Whitney U, p..error probability, r..effect size, wrn. ..warning

Table 6.14.: Result of Mann-Whitney test for the Difference Between Treatment Groups in Morning Test

To analyze if there were differences between the treatment groups, the following hypothesis were be tested:

$$H_0 \quad : \quad \mu_{no\ warning} = \mu_{random\ warning} = \mu_{Sensation\ warning} \tag{6.41}$$
$$H_1 \quad : \quad \text{at least two means are unequal} \tag{6.42}$$

An overview of the descriptive statistics is given in table 6.15.

Measurement	Treatment Group	M	SD	N
sleepiness	no warning strategy	0.63	0.92	8
	random warning strategy	0.63	0.74	8
	Sensation warning strategy	0.63	0.71	8
duration of breaks	no warning strategy	591.38	475.48	8
	random warning strategy	635.63	678.01	8
	Sensation warning strategy	677.75	376.37	8

Note: M..mean value, SD..standard deviation, N..number of participants

Table 6.15.: Descriptive Statistics for Difference Between Treatment Groups in Morning Test; $N = 24$

The data was not parametric. Therefore, two Kruskal-Wallis tests were used to analyze the difference between the groups.

No significant difference for sleepiness (as determined by the rater) was found ($H(2) = 0.12$, n.s.). In the same way, no difference in the duration of breaks between the three groups was detected ($H(2) = 0.78$, n.s.).

6.3.5. Results of the Usability and Acceptance Questionnaire

In this section the results of the usability and acceptance questionnaire are shown and discussed. For general issues of usability and acceptance, all 16 participants using the system were included in the analysis. For issues of usability and acceptance with respect to hypovigilance warnings, only the eight members of the Sensation-group were included in the analysis.

6.3.5.1. Usability

Most participants found the Hypovigilance-Management-System easy to use (12/13). The functions were easy to learn (12/14) and were easy to remember (12/13). However, all of the participants of the Sensation-group found that the Hypovigilance-Management-System was somehow disturbing during the test.

The status indicator of the wristwatch like device was easy to understand (12/15). More than half of the participants were satisfied with the level of sleepiness displayed by the status indicator (11/15). Opinions about the location of the status indicator were mixed: Many were satisfied (7/15), some others were dissatisfied (2/15). The number and size of LEDs was rated as sufficient (12/14).

More than half of the participants were satisfied with the positions (9/14) and the sizes (11/13) of the buttons. Reactions about the feedback and the required operation force of the buttons were mixed. Five out of thirteen found the required force needed to operate the buttons acceptable. However, three out of thirteen complained because the work gloves made it difficult to press the button correctly. Three out of thirteen participants were satisfied about the feedback while five of out of thirteen participants were dissatisfied. The last group declared that they did not know when the button was pressed correctly. This supports the above finding in respect of the feedback on pressing the feedback button.

All participants found it easy to understand the speech messages (13/13). The content was clear (12/13) and easy to remember (12/13). Two out of six participants in the random warning group declared that they followed the warning message(s). In the Sensation warning group, five out of seven participants declared that they have followed the instructions. A high compliance to the warnings of the Hypovigilance-Management-System can be deduced.

The factory test did not become easier or more difficult when the warning strategy was prominent (4/11). Eight out of eleven participants found it easier to stay awake when the Hypovigilance-Management-System was activated. This underlines the usefulness of such a system in order to help hypovigilant people safely stopping their dangerous work task.

Some individuals were satisfied with the place of attachment of the vibrotactile device (3/11), others were not satisfied (3/11). The largest group was undecided (5/11).

Half of the participants experienced their mobility impaired by the Hypovigilance-Management-System (9/18). Clear advantages of a wireless system can be deducted.

The participants were undecided about the influences of design (10/19) and size (10/20), and many (12/20) participants were satisfied with the weight of the Hypovigilance-Management-System.

6.3.5.2. Acceptance

No participant refused to use the Hypovigilance-Management-System at all (0/24). Consequently, they are most likely to use a Hypovigilance-Management-System when it warns them in case of extreme sleepiness (23/24). This is supported by the finding that half of the participants would like to get insight in real time data about their own sleepiness level (12/24). Only a few (5/24) would be willing to provide the employer with real time data of their sleepiness level. However, when sleepiness data was revealed on a group level (one value for a group of persons), most participants would be willing to share their data (18/23).

6.3.5.3. Motivation

A forth of the participants (6/22) had a high productivity as their main goal, another fourth of the participants had a low number of errors as goal. The others (11/22) tried to find a combination between both a high productivity and a low number of errors.

6.4. Discussion

Two hypotheses were formulated in chapter 4 which formed the basis of the work presented. The according results are discussed in this section.

6.4.1. Discussion of the System Development

The first hypothesis of this work claimed that it is possible to design a Hypovigilance-Management-System which fulfills all of the requirements presented in chapter 3. A novel hybrid design approach has been chosen in order to develop such a system. By the nature of its design, the system designed inherently fulfills the defined requirements and, thus, the first research hypothesis is corroborated.

Usability testing showed that the system, overall, was well designed. The data showed that it was easy to use, and the interaction with the system was clear and easy to learn. The mechanical properties of the wrist-worn device were rated well. Optimization potential was identified, as the data indicates that the central button might be difficult to press with gloves on, and a feedback about pressing the button would enhance the usability. The system did not disturb the users in conducting their main task, which is a prerequisite for its applicability. As a result, the users showed a high compliance with the system which is especially important for its practical usefulness: It has been shown earlier in this work that the effectiveness of a Hypovigilance-Management-System strongly depends on the users compliance with the system.

6.4.2. Discussion of the System Evaluation Experiments

The second hypothesis of this work claimed that a system which fulfills the above requirements would enhance safety by reducing errors and might maintain one's individual performance level. In order to investigate if this hypothesis could be corroborated, the Hypovigilance-Management-System designed was tested in a practical experiment. An industrial work task was analyzed and mapped to a practical laboratory task. By doing so, it was possible to control most influencing factors. A sample of participants was chosen in a way that it was most homogeneous, so inter-personal variance was minimized and the sample could be comparably small. The experiments included a training session, a baseline measurement in the evening, and, after a night of sleep deprivation, the actual data measurement in the morning.

6.4.2.1. Experimental Sample

A prerequisite for the validity of the measurements is that the three experimental groups show no difference in the dependent variables under the same experimental conditions. In order to achieve this, participants were randomly assigned to the different treatment groups. However, the groups were controlled for sex and chronotype as these are known as main influencing factors.

The baseline measurement, in which all of the participants faced the same conditions, did not show any significant differences in any of the dependent variables. It can be concluded that there was no systematic difference between the treatment groups.

6.4.2.2. Design of the Experiment

In order to meaningfully test a Hypovigilance-Management-System, the participants need to suffer from hypovigilance. Therefore, it was intended to simulate the effects of night shift work on vigilance by experimentally induced sleep deprivation. All of the participants showed a significant increase in hypovigilance from the evening to the morning experiment. Moreover, all of the participants reported a very high level of hypovigilance before the morning test (represented by a mean KSS-value of 7.3 on a scale with nine indicating “nearly falling asleep”). It can be concluded that the experimental induction of hypovigilance was successful.

Moreover, for the purpose of comparing the effects of a Hypovigilance-Management-System on hypovigilant individuals, the dependent variables need to be sensitive to hypovigilance. This is inherently the case for the KSS; it can be concluded from the literature for the subtest of TAP-M, and it is to be assumed for the factory task, for which it needed to be proven. The results of the experiments show a significant decrease in productivity from the evening experiment to the morning experiment for the “neutral” group, i.e., the no-warning group. The other dependent variables of the factory test, however, do not show a significant difference between the vigilant and the hypovigilance trials. This finding is explained by the speed-accuracy-trade-off, which indicates the negative correlation of the speed at which a task is conducted and the accuracy that is reached: In the experiment, the participants were aware of their hypovigilant state and worked slower in order to still work precisely. Single participants who did not show a decrease in productivity did show an increase in errors what supports the finding.

In the same way, a significant decrease in alertness was measured by means of TAP-M. No consistent result was found for executive control test. This finding is attributed to learning effects: although two learning sessions were conducted before the baseline measurement in order to rule out these effects, the results for the executive control task became stable after the evening experiment only.

Therefore, it can be concluded that the dependent variables were chosen meaningfully and the experimental design was done well, resulting in a valid test set-up. The dependent variables proved to be sensitive to hypovigilance which is a prerequisite for the meaningful conduction of the actual measurements.

6.4.2.3. Evaluation of the HMI

The effect of the Hypovigilance-Management-System was not large and only few significant results have been found.

No significant differences between the treatment groups have been fond for the factory test. However, for the Sensation warning group, a large variance has been found that was three times higher than the ones of the other two groups: Some participants in the Sensation warning group performed better than the best participants in the no warning group and some performed worse than the worst performing participant in the no warning group. This difference indicates that the Hypovigilance-Management-System is helpful for some persons and might be disturbing for others. A small variance within the group was expected, and, therefore, no further potentially moderating variables were measured. Still, this strikingly large variation within the Sensation-group was investigated with respect to sex and age, but no significant cause for the variation could be found; a hint is given though, as some individuals of the older group made profoundly more errors in the psycho-motor task than the younger group.

Although the difference was not significant, a tendency was observed, indicating that the individuals in the Sensation warning group rated themselves more sleepy than the ones in the no warning group. It is highly likely that this rating is caused by the system, reminding the participants of the Sensation-group about their (low) vigilance state, leading to higher *subjective* hypovigilance level. This finding supports the opinion that Hypovigilance-Management-Systems can increase safety by making its users more aware of their true vigilance state, thus encouraging them to take according safety measures when necessary.

No significant differences with respect to the TAP-M were found but a lower vigilance decrease for the no warning group compared to the Sensation-group.

6.4.2.4. General Observations

During the experiment, the participants were observed by the test leaders. Unusual behavior was recorded and discussed with each participant in a short interview after the factory test.

The participants in the random warning group often ignored the warning messages and kept working, although they did not know that the warnings were administered on a random basis. Moreover, they reported that the messages were experienced as annoying. Thus, it can be concluded that the effectiveness of hypovigilance warnings depends on the coherence of the warnings with the subjective hypovigilance evaluation. Therefore, a proper timing of hypovigilance warnings seems to be crucial in order to reach high compliance of the user to the warnings.

Moreover, it was observed that some participants had the ability to plan their breaks at suitable moments: Without technical assistance, they were able to accurately detect when they were getting sleepy while others did not have this ability and interrupted their task too early (which is inefficient) or kept working too long (which represents an increased risk of an error). This finding supports the assumption that Hypovigilance-Management-Systems can be an effective means to train users to find the most efficient time for a break.

It can be concluded that many individuals do not know when and how to take a break most efficiently. For them, a Hypovigilance-Management-System could be a very helpful device, on the one hand, to learn to correctly judge the own hypovigilance level, and on the other hand, to learn the most efficient break time pattern with respect to hypovigilance.

6.5. Conclusions

The experimental setup worked as planned, all prerequisites could be fulfilled. However, the research question and corresponding hypotheses could not be confirmed by this experiment. The Sensation warning group did not perform significantly better than the no warning group. Likewise, the random warning group did not perform significantly better than the no warning group and the Sensation warning group did not perform significantly better than the random warning group. The variance within the test groups was higher than expected; consequently, the power of the statistical tests was reduced, and the probability of a β-error increased, i.e., the probability of accepting the absence of effects while effects do exist. Although the sample size has been carefully chosen, a larger sample size might have been useful.

Moreover, three hours of testing time seemed to be too short: Most participants planned to take a break in the middle of the test. This was also the part of the experiment at which most participants became sleepy, resulting in a comparable break behavior for all groups.

However, actual workers fulfill a comparable task for eight hours and making it more difficult to plan optimal breaks. Here, a Hypovigilance-Management-System presumably could increase the break efficiency and, thus, increase safety and help maintaining the personal performance level.

Furthermore, a video camera was located in front of the psycho-motor device to enable the rater to observe the facial expressions of the participants. The camera might frequently have reminded the participants that they were being observed. It can not be ruled out that the participants wanted to avoid being recorded while showing extreme signs of sleepiness causing them to decide to take their breaks a bit earlier than they normally would have done.

The participants were highly motivated and knew they were under supervision. Both of these facts can counteract hypovigilance (compare to section 2.3.1.2). It is possible that these effects, in the present case, militate the valid conduction of short term validation experiments, as they will fade out only over longer working periods, therefore, calling for long-term experiments.

An increase in sleepiness often has a negative influence on the quality of the work of an industrial worker. The experiment indicates that the use of the Hypovigilance-Management-System could solve this problem for some persons. However, it should be pointed out that technical assistance should only be provided when other countermeasures against sleepiness such as proper shift cycle design proved being ineffective.

In other fields of application which include more monotonous tasks with less physical activation, e.g., the transportation sector, the effectiveness of the Hypovigilance-Management-System is probably higher. Due to the amount of movement in the psycho-motor task, physical activation could (partly) have counteracted the effects of the sleep deprivation.

Overall, short term effects of Hypovigilance-Management-Systems could not be measured, especially with respect to performance maintenance or even performance increase. Since Hypovigilance-Management-Systems can be conceptualized as a means of risk management, their effectiveness might be perceivable over longer periods only, comparable to the Electronic Stability Program (ESP)-system in a car: Driving a car with and without this system, each one for 3 hours, presumably might not indicate any safety increase by the ESP-system. However, in the rare situations in which the car starts to slide, the system does save lives.

An increase in safety by Hypovigilance-Management-Systems is assumed to be reached twofold: On the one hand, the system helps the user to learn to better judge his/her own level of sleepiness by getting objective vigilance feedback. On the other hand, if the user complies with the system (which is very likely by the above results), and stops his/her dangerous work task such as working on a dangerous machine or driving a car, the risk of an accident is obviously reduced.

The system developed in this work is universal in the discussed sense, i.e., it can be utilized in most of the potential application scenarios. Therefore, it is assumed that it has the potential to enhance work safety on a broad basis. However, still, further research is needed.

6.5.1. Outlook on Further Research

The experiment conducted in this work had a high face validity. The experiment closely mapped a typical task of an industrial worker. Still, only minor direct improvements of safety and performance could be observed. This finding might be explained by the constant physical activation and, thus, arousal, of the participants. It is concluded that, for these tasks, the main danger is not a constant degradation of performance, but more a general degradation of alertness, which might, e.g., lead to accidents such as falling down a stair or not seeing a fork lift passing by. These situations could not be tested in the laboratory. Thus, it would be wishful to test the Hypovigilance-Management-System in a real life setting over a long period of time.

The participants were allowed to take breaks during the morning test under the condition that each break would take ten minutes maximum. For participants who wanted to take a nap, ten minutes were a bit too short as the participants needed some time to reach a comfortable sleeping position. The remaining time was often too short to get into the first stage of sleep (muscle relaxation) which recovers the participant. Therefore, the break time needs to be increased, e.g. to about fifteen or twenty minutes. Moreover, the adjustment of the break time according to the actual sleep stage of the user could improve the system and should be investigated in further research.

The Hypovigilance-Management-System has been tested for a repetitive positioning task, which is a typical task of an industrial worker. It could also be interesting to test the Hypovigilance-Management-System for other kinds of industrial tasks, like operating a milling machine. The task is not as monotonous as the positioning task, but it is much more dangerous. Moreover, for this task, it is more difficult to protect the industrial worker against injuries and a single mistake can lead to severe accidents.

Furthermore, acceptance issues need to be investigated. It is important to know under which conditions the participants would like to use the Hypovigilance-Management-System. Personal privacy could be violated, if hypovigilance data is shared with other persons. In the same way, a Hypovigilance-Management-System could be used to control the status of single workers, which is represented in the concern of the participants about giving their individual hypovigilance data to a potential employer. Before introducing such systems to real work systems, these ethical issues need to be considered and discussed.

7. Summary

In this work, the development and evaluation of a universal, multimodal HMI for Hypovigilance-Management-Systems is described. In principles, Hypovigilance-Management-Systems measure the state of vigilance of the respective user and take according measures if a critical state of hypovigilance with respect to the work task of the user is reached, i.e., warn the user on different levels of urgency and might try to keep the user awake for a short period.

Hypovigilance is steadily increasing in the western societies and, in consequence, the risk of hypovigilance related accidents. Different factors contribute to the increase in hypovigilance in the western societies, such as, e.g., globalization and high automation standards: Globalization with increased concurrence and increased work intensity causes many individuals to sacrifice sleep in favor of other activities. The need for highly automated process in order to be competitive requires shift work. Both factors lead to sleep deficits and, hence, to hypovigilance. This situation is aggravated by the steady increase in sleep disorders.

Hypovigilance, however, is a key cause for severe accidents in various application scenarios, among them the transportation sector and the shift working industry. Clearly, countermeasures are to be considered. Primary measures, such as the proper design of shift cycles, intend to prevent the creation of hypovigilance itself. Where this is not possible, technical countermeasures, so called Hypovigilance-Management-Systems can support the user and increase safety.

In order to be able to develop such a system, basic characteristics of hypovigilance were discussed. First, it was pointed out that, in the current literature, there is a confusion of different terms. Therefore, basic terms were defined; a new definition of the term *vigilance* introduced, which summarized different cognitive constructs which are important for a successful and safe conduction of work tasks. On the basis of the two-process model of Borbély (1982), a simple model was deduced that explains the hypovigilance level of a person as a result of the two counteracting forces *sleep drive* and *wake drive* which are moderated by circadian effects. The main influencing factors for sleep drive and wake drive were discussed in detail. It was pointed out that the only truly effective countermeasure against hypovigilance is sleeping. Hence, it was concluded that Hypovigilance-Management-Systems should cause the user to stop his/her dangerous work task and go to sleep or, at least, take a power nap. Other countermeasures, however, might be useful for short term purposes.

A requirements analysis with respect to Hypovigilance-Management-Systems has been conducted in which, first users of the system were categorized by their mobility relative to their work system as well as by the dynamic of this work system. Moreover, specific interaction possibilities were investigated with respect to private and professional users. It was concluded that a universal Hypovigilance-Management-System needs to be mobile, should have predictive warning capabilities and aim for a high compliance of the user with the system. Then, general requirements for the interaction strategy, i.e., the warning strategy, were deduced. It was pointed out that, in order to be effective, a warning must first draw the attention of the user, then inform the user about the nature, consequences and countermeasure of the hazard and, finally, require a user feedback. The need for a device to draw attention, a device to inform the user and a feedback device was derived. Additionally, the need for a status indicator as well as a vigilance maintenance device was affiliated. Basic design guidelines for such devices were summarized on the basis of the current psychological and human factors literature. In the same way, usability and personalization issues were discussed and the benefit of designing a most universal system was pointed out.

On the basis of the requirements for a Hypovigilance-Management-System, existing Hypovigilance-Management-System were investigated. Therefore, 18 systems were analyzed. It was concluded that none of these systems fulfills the requirements both for the warning strategy and the HMI-elements. However, it was claimed that it is principally possible to generate a Hypovigilance-Management-System setup that fulfills all of the requirements. Furthermore, it was claimed that, by fulfilling these requirements, this system would effective in terms of the reduction of errors and the enhancement of performance in real working tasks. It was emphasized that both the development of such a system as well as its validation in a real work environment never has been done before and, therefore, can be considered an innovation.

Consequently, the development of such a system was pursued. The requirements defined so far formed a solid basis for this development but needed to be detailed with data from the final application sites. The difficulties in getting reliable requirements data from these sites was discussed, and, as a result, a new hybrid-development approach was followed:

First, on the basis of the requirements described, a basic warning strategy was developed and according basic HMI-elements were deduced. Then, a set of representative application scenarios was chosen.

The specific requirements of these application scenarios were collected by means of a questionnaire survey. The data was analyzed with the aim to identify requirements clusters which enabled the development of one solution that suits all application scenarios. In this way, it was found, e.g., that most of the applications scenarios require a vigilance maintenance system and that a watch-like device can be utilized in all application scenarios.

On the basis of these refined requirements, the final warning strategy and the according HMI were developed following a methodical approach. Active principles both for the communication strategy and the HMI-elements were collected in an interdisciplinary brain storming work shop. They were summarized in morphological boxes and solution variants were developed on their basis.

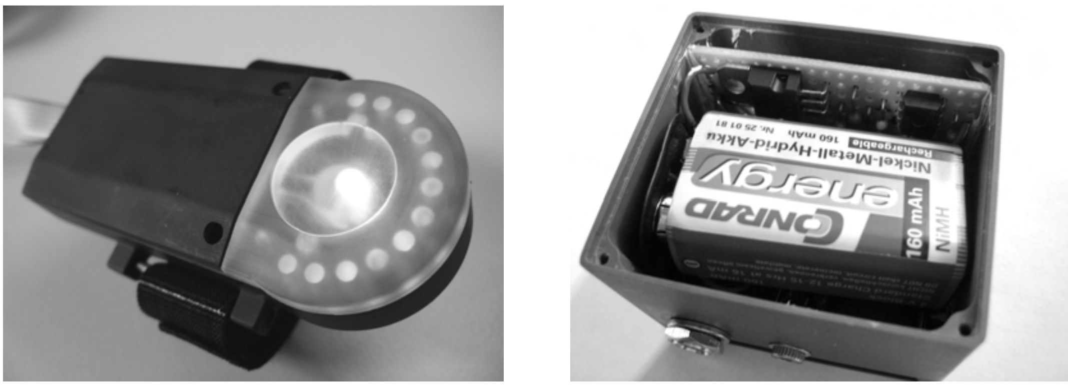
First, the solution variants for the warning strategy were compared by means of a value benefit analysis and the best solution was chosen: It features a continuous display of the actual vigilance state of the user. In case of a warning, it attracts attention multimodally by a vibrotactile signal combined with a static light and a melody. For imminent warnings, the signals are intensified by a shorter vibration interval, a blinking flashlight and a higher sound volume. Complex information about the warning is provided by speech messages which is to be confirmed by a finger input. The vigilance maintenance system provides Landström Sounds combined with pulsed vibrations. Data for the personalization is externally stored. Should the system fail, an error message is given through speech output.

Then, the solution variants for the HMI-elements were compared in the same way. The best solution was characterized as follows: It uses an earphone for acoustic output, LEDs for visual output, a vibration unit included in accessories such as a chest band or belt and a button as a feedback device. The vigilance state is displayed by three LEDs. All other adjustments are done by means of buttons and personal information is stored on a smart card.

On this basis, the final warning strategy and HMI-elements were constructed. A detailed warning strategy resulted which features three warning modes, a *normal mode* in which the actual vigilance state is displayed, a *cautionary mode* in which the user is warned early before dangerous vigilance degradations occur, and an *imminent mode* in which the user is intensively warned that a very dangerous vigilance level has been reached. The latter mode is augmented by a vigilance maintenance mode. Moreover, the system takes the vigilance history of the user into account in order to reliably warn early enough. This warning strategy was implemented in the software system SwitchBoard.

In the same way, the final HMI-elements were developed. The center of the physical HMI-setup is represented by a watch-like device. The border ring of the "clock-face" is used as a status indicator; it is lighted green, yellow or red, according to the detected user state. The center of the "clock-face" flashes white in case of an imminent alarm and acts as a push-button for the user feedback at the same time. The device also includes buttons for the adjustment of the audio volume, and for the repetition of voice messages. In addition, a vibration device was developed to present haptic stimuli. As a result of a usability study, this device is installed on a belt at the side of the hip. Finally, a specific headphone was chosen to display audio signals.

The resulting prototypes are depicted in figure 7.1a and figure 7.1b respectively.



(a) Final Wrist Worn Device

(b) Final Belt Unit

Figure 7.1.: Final HMI-Elements

By the way of methodological construction, the developed Hypovigilance-Management-System inherently fulfills the requirements defined above, proving that it is indeed possible to construct a system which fulfills these requirements.

Usability testing showed that the system, overall, was well designed. It proved to be easy to use, the interaction with the system was clear and easy to learn. The system did not disturb the users in conducting their main task, which is a prerequisite for its applicability. As a result, the users showed a high compliance with the system.

However, it was still to prove that the system developed enhances safety by reducing errors and, additionally, might help maintain one's individual performance level. Therefore, the Hypovigilance-Management-System constructed was tested in a practical experiment. An industrial work task was analyzed and mapped to a practical laboratory task in order to control most influencing factors. It consisted of a repetitive manual task, combined with a divided attention task, which were amended by subjective sleepiness scales as well as by selected tests of a neuro-psychological test battery. A homogeneous sample was chosen and randomly divided into three groups, a control group with no intervention, a treatment group using the system developed and a positive control group using a system with random output. The experiments included a training session, a baseline measurement in the evening, and, after a night of sleep deprivation, the actual data measurement in the morning.

It could be shown that the dependent variables were chosen meaningfully and that the experimental design was well done, resulting in a valid test set-up. The dependent variables proved to be sensitive to hypovigilance which is a prerequisite for the meaningful conduction of the actual measurements.

Anyhow, the research hypotheses could not be confirmed. The treatment group did not perform significantly better than the control group and the positive control group. Overall, short term effects of Hypovigilance-Management-Systems could not be measured, especially with respect to performance maintenance or even performance increase. Different influencing factors were discussed that could have moderated the effects. However, none of them by itself could explain that the Null-Hypothesis could not be rejected. It was concluded that, as Hypovigilance-Management-Systems are a means of risk management, their effectiveness might be perceivable over longer periods only.

An increase in safety by Hypovigilance-Management-Systems was assumed to be reached twofold: On the one hand, the system could help the user to learn to better judge his/her own level of sleepiness by getting objective vigilance feedback. On the other hand, if the user complies with the system (which is very likely by the above results), and stops his/her dangerous work task such as working on a dangerous machine or driving a car, obviously, the risk of an accident would be reduced.

In consequence, further investigation is needed. It was suggested to conduct a long term study in the field. Moreover, it was supposed to investigate the effects of the adjusting the generated break durations to the actual individual sleep stage development as well as to utilize the system in further industrial tasks.

Finally, the ethical implications of introducing Hypovigilance-Management-Systems were discussed. Although Hypovigilance-Management-Systems might profoundly enhance work safety and subjective well being, they could also be used to monitor individuals and, therefore, increase work induced strain.

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A. Overview and Analysis of Existing Hypovigilance-Management-Systems

	Universality			Warning Modes			Structure of the Warning							HMI						Usability			Personalization		
Product	Mobility-Index	Predictive Warning	Universality Index	Normal Mode	Vigilance Maintenance Mode	Communication Quality Index	Attracting Attention	*Providing Hazard Information*	*Providing Consequences Information*	*Providing Behavior Recommendations*	Providing Complex Warning Information	System Requires User Feedback	Warning Quality Index	Multimodality of the Warning Signal	Choice of Sensory Channels Adequate to (Main) Application Scenario	Increase in Warning Intensity Possible	Localization of Warning Display	Warning is Not Masked	HMI Quality Index	Situation is Not Endangered by the Warning	Non-Obtrusiveness of the System	Usability Quality Index	Personalization of WS possible	Personalization of Output Characteristics Possible	Personalization Quality Index
Engine Driver Vigilance Telemetric Control (EDVTCS)	◐	◐	◐	●	○	◐	●	○	○	○	○	●	◐	◐	◐	●	◐	●	◐	◐	◐	◐	○	○	○
Micro Nod Detection System (MINDS)	○	○	○	○	○	○	●	○	○	○	○	◐	◐	◐	◐	●	●	●	●	◐	●	◐	○	○	○
Eye Tracking Alertness Monitor	○	○	○	○	○	○	●	○	○	○	○	◐	◐	○	◐	○	--	◐	○	●	●	●	○	○	○
ABM Drowsiness Monitoring Device	◐	○	○	○	○	○	●	○	○	○	○	○	○	○	○	○	--	◐	○	●	◐	◐	○	○	○
Vehicle Drivers Anti Dozing Aid (VDADA)	●	○	◐	○	◐	○	●	○	○	○	○	○	○	●	●	●	●	●	●	◐	◐	◐	○	○	○
Driver Fatigue Monitor DD850	○	◐	○	◐	○	○	●	●	○	○	○	●	◐	◐	●	●	●	●	●	●	●	●	●	●	●
SafeTRAC	○	○	○	●	○	◐	●	○	○	●	○	○	○	◐	◐	○	●	◐	◐	●	●	●	●	●	●
Advisors System for Tired Drivers (ASTiD)	○	●	◐	●	○	◐	●	◐	○	◐	○	○	○	◐	◐	○	●	◐	◐	●	○	◐	●	○	◐
SAM G-3	○	○	○	○	○	○	●	○	○	○	○	◐	◐	◐	●	●	--	●	◐	◐	●	◐	●	○	◐
TravAlert	○	○	○	○	○	○	●	○	○	○	○	◐	◐	○	◐	○	--	●	○	●	●	●	●	○	◐
ARRB Fatigue Monitoring Device	○	●	◐	○	●	◐	●	●	●	●	●	●	●	◐	●	●	●	●	●	●	◐	◐	●	○	◐
Actiwatch Alert	●	○	◐	○	●	◐	●	○	○	○	○	●	◐	○	◐	○	--	◐	○	●	◐	◐	●	○	◐
Doze Alert	●	○	◐	○	●	◐	●	○	○	○	○	◐	◐	○	◐	○	--	●	○	●	◐	◐	●	○	◐
Stay Alert	●	○	◐	○	○	○	●	○	○	○	○	○	○	◐	◐	○	--	◐	○	●	○	◐	○	○	○
Nissan Safety Drive Advisor	○	◐	○	○	○	○	●	○	○	●	○	●	◐	◐	●	○	●	●	◐	●	●	●	○	○	○
Photo Driven Alert System	●	○	◐	○	○	○	●	○	○	○	○	○	○	○	◐	○	--	◐	○	●	○	◐	○	○	○
Driver Attention System	○	◐	○	○	○	○	●	○	○	○	○	○	○	◐	●	◐	--	◐	◐	●	●	●	○	○	○
AWAKE Hypovigilance-Management-System	○	◐	○	●	○	◐	●	●	●	●	●	●	●	●	●	●	◐	◐	●	●	●	●	●	●	●

○ criterion not satisfied ◐ criterion partially satisfied ● criterion fully satisfied

Table A.1.: Analysis of the Existing Hypovigilance-Management-Systems

A.1. Legend to table A.1 "Analysis of the existing Hypovigilance-Management-Systems"

The existing Hypovigilance-Management-Systems presented in section 3.4 have been analyzed on the basis of their description and by means of the criteria presented in table 3.1. Like throughout the whole work, the focus is laid on the HMI only. The according results are depicted in table A.1.

An empty circle indicates that the according criterion is not or nearly not satisfied. A semi-circle indicates that the criterion is only partly satisfied and a full circle indicates that the criterion is fully satisfied. With respect to the example of the mobility index, an empty circle indicates that the system can be used stationary only, a semi-circle indicates that the system can be used within a restricted area only (e.g., around a machine) and a full circle indicates that the system can be used anywhere, i.e., that it is truly mobile.

From the single ratings, summarizing indexes for the categories have been computed where the category *Structure of the warning* includes a subindex *Providing complex warning information* summarizes information about the presentation of information with respect to *hazard*, *consequences* and *behavior recommendations*. These three sub-criteria are depicted in italics in table A.1.

Therefore, the according criteria have been "added" for each category: an empty circle was defined to have the value 0, a semi-circle was defined to have the value 0.5 and a full circle was defined to have the value 1. Table A.2 shows the mapping of category sums Σ to category ratings in terms of circles.

Category	○	◖	●
Universality	$\Sigma \leq 0.5$	$0.5 < \Sigma < 2.0$	$\Sigma \geq 2.0$
Communication Quality	$\Sigma \leq 1.0$	$1.0 < \Sigma < 2.0$	$\Sigma \geq 2.0$
Complex Information	$\Sigma \leq 1.0$	$1.0 < \Sigma < 2.5$	$\Sigma \geq 2.5$
Warning Quality	$\Sigma \leq 1.0$	$1.0 < \Sigma < 2.5$	$\Sigma \geq 2.5$
HMI Quality	$\Sigma \leq 1.5$	$1.5 < \Sigma < 4.0$	$\Sigma \geq 4.0$
Usability Quality	$\Sigma \leq 0.5$	$0.5 < \Sigma < 2.0$	$\Sigma \geq 2.0$
Universality	$\Sigma \leq 0.5$	$0.5 < \Sigma < 2.0$	$\Sigma \geq 2.0$

Table A.2.: Mapping of Category Sums Σ to Category Ratings

B. Questionnaire for the Requirements Analysis for the HMI

The questionnaire included in this appendix has been used for the requirements analysis of the HMI. It has been designed as an interactive word document in which most of the answers could be either given by means of a check box or chosen from a pull down menu. For a better understanding, the respective menus have been “opened” in the depiction below.

INFORMATION SOCIETY TECHNOLOGIES (IST) PROGRAMME

SENSATION

507231

Title Technical pilots requirements questionnaire

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Summary This questionnaire addresses the responsible persons for the pilot sites. It aims to gather the information needed for the process of requirements engineering.

Status: D

Distribution: Responsible persons for technical pilots (i.e. WP4.6 pilots)

Document ID USTUTT_WP4_5-Rep2-Ver3

Pretext

This questionnaire addresses the persons responsible for the pilot sites. It aims to gather the information needed for the design of the hypovigilance management systems, with special focus on the warning strategy and the user interfaces.

Being the responsible for your pilot and, thus, being informed about the physical setup and the work task within the pilot, filling in the questionnaire will be easy for you. However, some pilots might include different work places. For example in a chemical factory, there could be workers dealing directly with the machines and others which are only doing monitoring tasks. If, at this time, you are not sure which of the potential users in your pilot will be involved in the pilot, or if several different types of users will be involved, please fill in one questionnaire for each user type.

The questionnaire might contain questions to which you may not have the exact answer. In this case, please give your "best guess" and chose the "do not know" only in case you really do not have any clue. Thank you very much in advance!

Technical remark:

This Questionnaire works with the MS Word form options. The fields for data input are highlighted in grey color. Boxes ☐ can be check marked, ... fields require a text input. The grey fields in the tables of section 3 are pull down menus. Please click on the field and choose the appropriate answer.

Please send the questionnaire back to Lorenz.Hagenmeyer@iao.fhg.de **latest by 7 April.**

If you encounter any problems or difficulties or if you have any questions, please feel free to contact me at any time.

Email: Lorenz.Hagenmeyer@iao.fhg.de

Tel: +49 711 970 2196

Thank you very much in advance, for your time spent on filling in the questionnaire

Questionnaire

1. Description of task

1.1. Please describe the over all **work task** of the user in a few sentences:

.....

Identify the **subtasks** and their **proportion** relative to the whole work task:
(e.g. watching at a display 50%, talking on the phone 10%, documentation 30%)

.....

1.2. **Mobility** of the **user** within the work task

- ☐ None: User is fixed on his seat, line of sight predestined (e.g. car driver)
- ☐ Little: User is sitting on one chair / staying at one desk, various lines of sight (e.g. monitoring task)
- ☐ Limited: User is mobile within a small radius (e.g. around a machine)
- ☐ Mobile: User is mobile within a lager area (e.g. walking around the whole plant)

1.3. **Mobility** of user's **working place** relative to the environment

- ☐ Immobile (e.g. office, plant)
- ☐ Mobile (e.g. car)

1.4. How many **hours a day** does the user **usually spend** on the work task?

.....

1.5. In which **time of day** is the work task normally executed?

- ☐ day
- ☐ night
- ☐ both

1.6. Can the **task** be **aborted** when hypovigilance reaches a critical level?

- ☐ No, because .....
- ☐ Yes, immediately
- ☐ Yes, within some time delay
  » Reason for time delay (e.g. reaching a parking place):
  ....
  Estimated duration of time delay: min
- ☐ Do not know

1.7. Can the **user** be **replaced** when hypovigilance reaches a critical level?

- ☐ No
- ☐ Yes » What is the time until the second person is ready? (e.g. woken up, reached the workplace): min
- ☐ Do not know

1.8. Please attach **photos** of the users working place. If available please include in addition a photo(s) from the perspective of the user (showing the user's field of vision).

It is <u>not</u> possible to insert photos here. Please **attach the photos to the email** when sending back the Questionnaire.

Please write here the **name** of the attached files:
.....

1.9. Which **limitations** imposed **by the system** will be **acceptable** with respect to the work task?

a) Necessary **user interaction**

- ☐ Interaction must not be necessary (e.g. For a private car driver the system must get automatically activated, when he starts the engine.)
- ☐ Interaction necessary (e.g. The user has actively to apply the sensors)

b) If the user is mobile, will he/she **accept** specific **restriction of this mobility**?
(E.g., if the user is moving around a machine he/she is working on, will he/she accept to move only in a specified area?)

- ☐ Yes
- ☐ No

2. HMI-output-components

2.1. Is there a possibility to **install** the following **HMI-output-components** in the **field of vision**?

- ☐ Yes, display
- ☐ Yes, flashing lights
- ☐ No, because .....

2.2. Is there any kind of **display** at the workplace? (e.g. computer monitor, machine display)

- ☐ Yes
- ☐ No

If Yes, what **kind of information** does the display show? (e.g. process data of a machine, radar output, video control films, etc.)
.....

2.3. With respect to the work task, could this display be **used** to show warning information?

- ☐ Yes
- ☐ No, because .....

2.4. Does the user frequently use one or several of the following **communication devices** at the workplace?

	Yes	No	Do not know
Mobile phone	☐	☐	☐
Walkie-talkie	☐	☐	☐
Handheld	☐	☐	☐
other:			

2.5. Are there any **modes of communication** or **devices** explicitly **forbidden** in the workplace? (e.g. mobile phone in an aeroplane)
.....

2.6. Are there any known **sources of electrical interference** in the workplace or **communication black spots**? (Places with no mobile coverage for example.)
.....

2.7. Does the work task **allow** the user **to wear**:

	Yes	No	Do not know
Wristwatch	☐	☐	☐
Finger Ring	☐	☐	☐
Ear- clip	☐	☐	☐
Head Phone	☐	☐	☐
Cap / Hat	☐	☐	☐
Headband	☐	☐	☐
Helmet	☐	☐	☐
Chest band	☐	☐	☐

2.8. Does the work task **force** the user to wear **protective equipment**?

	Yes	No	Do not know
Is protection required at all?	☐	☐	☐
Helmet	☐	☐	☐
Protective glasses	☐	☐	☐
Protective mask	☐	☐	☐
Gloves	☐	☐	☐
Heat protection suit	☐	☐	☐
Protection against chemical burn	☐	☐	☐
Protection against cold	☐	☐	☐
Other:			

2.9. With **respect to the work task**, which **output device** do you consider being **useful**,

a) to **continually indicate** the **hypovigilance level** of the user (user feedback)?

- ☐ Traffic light-like scale (green, yellow, orange, red, purple)
- ☐ analogue display (bar plot: down = ok, up= very sleepy)
- ☐ other ....

location of a respective indicator?

(Multi response is possible.)

- ☐ device worn by the user (e.g. at wrist)
- ☐ included into the work environment (line of sight)
- ☐ at supervisor's place
- ☐ other ....

b) to **catch the user's attention** prior to a more detailed warning information?

(Multi response is possible.)

- ☐ visual indicator: e.g. flashing lamp
- ☐ sound cue (e.g. beep)
- ☐ speech output
- ☐ sound of increasing intensity
- ☐ vibration device at .... (part of the body)
- ☐ other ....

c) to **provide** further **information** to the user?

(multiple answers possible)

- ☐ speech output
- ☐ text displayed on a screen
- ☐ other ....

2.10. Does the work task/work place provide **other assistance systems**, which could **be integrated** into the warning strategy? (e.g. lane departure warning system in a car)

- ☐ No
- ☐ Yes, kind of assistance system: ....

3. Description of possible hazards

The following section of the questionnaire is divided into two parts, one for daytime conditions and one for night-time conditions. Please fill in the sections related to the time(s) at which the work task is performed (compare to question 1.5 on page 3).

The following **Questions 3.1.1 – 3.1.8** are related to **daytime** conditions. If the work is only performed at night-time, please continue with question 3.2.1 on page 11.

3.1.1 What is your guess of **how many times** the hypovigilance management system will have to **warn** the user due to fatigue? (**daytime** conditions)

- ☐ Several times a working shift
- ☐ Once a working shift
- ☐ Every second / third working shift
- ☐ Once a week
- ☐ Once or twice a month
- ☐ Once or twice a year
- ☐ other: ....
- ☐ Do not know

The next 5 questions intend to investigate the risk and the consequences of hazards which appear at the work place **on the average**. Please do not answer for the worst case only.

3.1.2 How do you judge the risk of the user to **endanger him/herself** ? (**daytime** conditions)

Please use the pull down menu by clicking on the grey shadowed field

Kind of hazard	Risk Level	
	Normal conditions	Under hypovigilance
Injury	please select risk level	please select risk level
Death	please select risk level	
.....	please select risk level	

please select risk level
no risk
risk
high risk
unavoidable hazard

3.1.3 How do you judge the risk of the user to endanger **other persons**? (**daytime** conditions)

Please use the pull down menu by clicking on the grey shadowed field

Kind of hazard	Maximum number of affected individuals	Risk Level	
		Normal conditions	Under hypovigilance
Injury	affected individuals	please select risk level	please select risk level
Death		please select risk level	please select risk level
.....		please select risk level	please select risk level

affected individuals
1-2 persons
3-100 persons
100 - 1000 persons
more than 1000

3.1.4 How do you judge the risk of the user to cause **material damage**? (**daytime** conditions)

Please use the pull down menu by clicking on the grey shadowed field

Property owner	Amount of damage	**Risk Level**	
		Normal conditions	Under hypovigilance
Own property	amount	please select risk level	please select risk level
Companies property		please select risk level	please select risk level
Property of thirds		please select risk level	please select risk level
.....		please select risk level	please select risk level

amount
hunderts of €
thousands of €
millions of €

3.1.5 How do you judge the risk of the user to **endanger the environment**? (**daytime** conditions)

Risk level
Please use the pull down menu by clicking on the grey shadowed field

Element	**Risk level**	
	Normal conditions	Under hypovigilance
Air	please select risk level	please select risk level
Water	please select risk level	
Ground	please select risk level	
.....	please select risk level	

please select risk level
no risk
risk
high risk
unavoidable hazard

Consequences of contamination
Please use the pull down menu by clicking on the grey shadowed field

Element	**Consequences of contamination**		
	Affected area	Durability	Consequences
Air	affected environment	durability	consequences
Water			
Ground			
.....			

affected environment
local
regional
global

durability
hours
days
years

consequences
illness
injury
death

3.1.6 Which **exogenous factors** additionally **influence** the **risk** of a hazard? (**daytime** conditions)

Please checkmark where applicable (X)

Factor	No influence	Increasing risk	Decreasing risk	Do not know
Very bright light conditions (e.g. sunshine)	☐	☐	☐	☐
Dim light conditions	☐	☐	☐	☐
Bad weather conditions (e.g. rain, snow, storm)	☐	☐	☐	☐
Light car traffic	☐	☐	☐	☐
Heavy car traffic	☐	☐	☐	☐
.....	☐	☐	☐	☐

3.1.7 **At which level** of hypovigilance do you think that the user has to get **feedback** or has to be **warned** in order to avoid additional danger? (**daytime** conditions)

Please checkmark where applicable (X)

Level of Hypovigilance	No warning	Feedback necessary	Warning necessary	Do not know
Level 1: first signs of inattention / fatigue	☐	☐	☐	☐
Level 2: strong fatigue	☐	☐	☐	☐
Level 3: nearly falling asleep (including micro sleep)	☐	☐	☐	☐
Level 4: sleeping	☐	☐	☐	☐

3.1.8 Do you believe a immediate **warning** prior to a hypovigilant state **would be of any use regarding safety** in context with the work task? (**daytime** conditions)

☐ Yes
☐ No, because ....
☐ Do not know

The following 8 Questions (3.2.1 – 3.2.8) are related to the risk level of the work task during **night-time** conditions.
If the work task is not performed at night, please continue with section 4 on page 14.

3.2.1 What is your guess of **how many times** the hypovigilance management system will have to **warn** the user due to fatigue? (night-time conditions)

- ☐ Several times a working shift
- ☐ Once a working shift
- ☐ Every second / third working shift
- ☐ Once a week
- ☐ Once or twice a month
- ☐ Once or twice a year
- ☐ other: ....
- ☐ Do not know

The next 5 questions intend to investigate the risk and the consequences of hazards which appear at the work place **in average**. Please do not answer for the worst case only.

3.2.2 How do you judge the risk of the user to **endanger him/herself**? (**night-time** conditions)

Please use the pull down menu by clicking on the grey shadowed field

Kind of hazard	**Risk Level**	
	Normal conditions	Under hypovigilance
Injury	please select risk level	please select risk level
Death	please select risk level	
.....	please select risk level	

please select risk level
no risk
risk
high risk
unavoidable hazard

3.2.3 How do you judge the risk of the user to endanger **other persons**? (**night-time** conditions)

Please use the pull down menu by clicking on the grey shadowed field

Kind of hazard	Maximum number of affected individuals	**Risk Level**	
		Normal conditions	Under hypovigilance
Injury	affected individuals	please select risk level	please select risk level
Death		please select risk level	please select risk level
.....		please select risk level	please select risk level

affected individuals
1-2 persons
3-100 persons
100 - 1000 persons
more than 1000

3.2.4 How do you judge the risk of the user to cause **material damage**? (**night-time** conditions)

Please use the pull down menu by clicking on the grey shadowed field

Property owner	Amount of damage	**Risk Level**	
		Normal conditions	Under hypovigilance
Own property	amount	please select risk level	please select risk level
Companies property		please select risk level	please select risk level
Property of thirds		please select risk level	please select risk level
.....		please select risk level	please select risk level

amount
hunderts of €
thousands of €
millions of €

3.2.5 How do judge the risk of the user to **endanger the environment**? (**night-time** conditions)

Risk level
Please use the pull down menu by clicking on the grey shadowed field

Element	**Risk level**	
	Normal conditions	Under hypovigilance
Air	please select risk level	please select risk level
Water	please select risk level	
Ground	please select risk level	
.....	please select risk level	

please select risk level
no risk
risk
high risk
unavoidable hazard

Consequences of contamination
Please use the pull down menu by clicking on the grey shadowed field

Element	**Consequences of contamination**		
	Affected area	Durability	Consequences
Air	affected environment	durability	consequences
Water			
Ground			
.....			

affected environment
local
regional
global

durability
hours
days
years

consequences
illness
injury
death

3.2.6 Which **exogenous factors** additionally **influence** the **risk** of a hazard? (**night-time** conditions)

Please checkmark where applicable (X)

Factor	No influence	Increasing risk	Decreasing risk	Do not know
Very bright light (e.g. headlights)	☐	☐	☐	☐
Dim light conditions	☐	☐	☐	☐
Bad weather conditions (e.g. rain, snow, storm)	☐	☐	☐	☐
Light car traffic	☐	☐	☐	☐
Heavy car traffic	☐	☐	☐	☐
.....	☐	☐	☐	☐

3.2.7 **At which level** of hypovigilance do you think that the user has to get feedback or has to be **warned** in order to avoid additional danger? (**night-time** conditions)

Please checkmark where applicable (X)

Level of Hypovigilance	No warning	Feedback necessary	Warning necessary	Do not know
Level 1: first signs of inattention / fatigue	☐	☐	☐	☐
Level 2: strong fatigue	☐	☐	☐	☐
Level 3: nearly falling asleep (including micro sleep)	☐	☐	☐	☐
Level 4: sleeping	☐	☐	☐	☐

3.2.8 Do you believe a immediate **warning** prior to a hypovigilant state **would be of any use regarding safety** in context with the work task? (**night-time** conditions)

- ☐ Yes
- ☐ No, because ....
- ☐ Do not know

4. Workplace environment

Noise

4.1. Are there unavoidable **noises**?

- ☐ No
- ☐ Yes
- ☐ Sometimes

If there are unavoidable noises, **how loud** are they at ear level?

- ☐ silent → <55dB(A)
- ☐ noticeable → 55 dB(A) to 85 dB(A)
- ☐ You can hardly understand your own words → >85 dB(A)
- ☐ Do not know

4.2. Where does the noise **come from**?

- ☐ Machinery
- ☐ Driving sounds (wind, engine, …)
- ☐ other: ....
- ☐ Do not know

4.3. The noise can be **characterized** as...

- ☐ Homogeneous noise (same loudness during the task)
- ☐ Impulse sounds (sounds appearing suddenly and lasting only short time)
- ☐ Do not know

4.4. Is **ear protection** worn at the workplace?

- ☐ Yes
- ☐ No
- ☐ Do not know

If yes, **which kind** is used frequently?

- ☐ Ear muffs
- ☐ Ear plugs
- ☐ other: ....
- ☐ Do not know

4.5. Does the user listen to **radio/music** during the task?

- ☐ Yes
- ☐ No
- ☐ Do not know

If yes, can it be automatically **muted**?

- ☐ Yes
- ☐ No

Climate

4.6. Are there **extreme temperatures** during the task at the workplace?

Heat (more than 30°C)	☐ Yes	☐ No	☐ Do not know
Cold (less than 10°C)	☐ Yes	☐ No	☐ Do not know

4.7. Please describe the **average humidity** in the application field .

- ☐ Low (0% ... 30%)
- ☐ Normal (30% ... 70%)
- ☐ High (70% ... 100%)
- ☐ Do not know

4.8. Is the user during the work task **exposed** to

- ☐ Splash water
- ☐ Rain
- ☐ Do not know

Vibrations

4.9. Does the user face **vibrations**?

- ☐ Yes
- ☐ No
- ☐ Do not know

If yes, what is the **source** of the vibrations?
.....

Where is the vibration introduced to the user? (e.g. hands, feet, buttocks…)

.....

Limitations due to specific sensor characteristics

4.10. Does the application environment show any **restrictions** regarding the following aspects? (If yes, please give a short description of the restrictions)

Bio-compatibility (e.g. sterility) .....

Electrical-compatibility (e.g. electrical interference) .....

Other: .....

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Light

Light conditions at **<u>daytime</u>**
If the work is not performed at day-time conditions, please continue with question 4.11.2 on lower on this page.

4.11.1 **Lighting conditions** at the **workplace** are:

- ☐ Very bright (e.g. direct sunshine, operation field illumination)
- ☐ Intermediate (e.g. normal office illumination)
- ☐ Dim
- ☐ Do not know

4.12.1 **Lighting conditions** in the workplace **surroundings** (e.g. outside the car, around the desk) are:

- ☐ Very bright (e.g. direct sunshine, operation field illumination)
- ☐ Intermediate (e.g. normal office illumination)
- ☐ Dim
- ☐ Changing with daytime (natural illumination, dependent of weather conditions)
- ☐ Do not know

4.13.1 Can the illumination cause **glare**?

Directional glare	☐ Yes	☐ No	☐ Do not know
Reflection glare	☐ Yes	☐ No	☐ Do not know

Light conditions at **<u>night-time</u>**
If the work is not performed at night-time conditions, please continue with section 5 on the next page.

4.11.2 **Lighting conditions** at the **workplace** are:

- ☐ Very bright (e.g. direct sunshine, operation field illumination)
- ☐ Intermediate (e.g. normal office illumination)
- ☐ Dim
- ☐ Do not know

4.12.2 **Lighting conditions** in the workplace **surroundings** (e.g. outside the car, around the desk) are:

- ☐ Very bright (e.g. direct sunshine, operation field illumination)
- ☐ Intermediate (e.g. normal office illumination)
- ☐ Dim
- ☐ Changing with daytime (natural illumination, dependent of weather conditions)
- ☐ Do not know

4.13.2 Can the illumination cause **glare**?

Directional glare	☐ Yes	☐ No	☐ Do not know
Reflection glare	☐ Yes	☐ No	☐ Do not know

5. Personality of User

5.1. May the user suffer from one of the following **disabilities**?

(Multi response is possible.)

- ☐ Hardness of hearing
- ☐ Deafness
- ☐ Blindness
- ☐ Color-blindness
- ☐ Paralysis
- ☐ Epilepsy
- ☐ Other .....
- ☐ Do not know

5.2. What is the **professional qualification** of standard user?

(Multi response is possible.)

- ☐ Untrained
- ☐ Semi trained
- ☐ Trained
- ☐ Academic personnel
- ☐ Do not know

5.3. What is the ability of **comprehension** of standard user?

(Multi response is possible.)

- ☐ Low
- ☐ Medium
- ☐ High
- ☐ Do not know

5.4. How do you judge the **motivation** of the user to comply with the warning system?

- ☐ Low
- ☐ Medium
- ☐ High
- ☐ Do not know

Please give reasons for your answer: .....

5.5. Which possibilities do you see to **force** the user to use a warning system?

- ☐ Not possible at all
- ☐ Instructions in combination with punishment by the employer
- ☐ Law
- ☐ Do not know
- ☐ other: .....

Please do not forget to attach the photos mentioned in question 1.8.

Thank you for your cooperation!

C. Requirements List for the Design of the HMI

F/W	No.	Requirements fixed (F), wish (W)	Descriptions & Dimensions
F	1	draw attention	simple information, signal
F	2	giving information to the user about the current situation	complex information
F	3	giving information to the user about potential consequences	complex information
F	4	giving recommendations to the user	complex information
F	5	understand ability of the giving information to every point of time	
W	6	plausibility of the giving information	for all user groups
F	7	no output of information provoke the user to a dangerous behavior	
F	8	no confusion of the user	
F	9	informational reliability	
F	10	no obstruction of the main task of the user	
W	11	handicapped accessible	
W	12	age-based	old persons
F	13	concept of operation plausible	easy to keep in mind
W	14	short concept of operation	short expenditure of time by operation
W	15	displaying the current state	to every point of time
W	16	clear definition of the states	in each situation
F	17	possibility of giving input	for user feedback
F	18	feedback clearly in time	
F	19	feedback clearly in content	
W	20	feedback to the user after giving feedback	
F	21	feedback to user clearly in content and time	in case of a response to the user
F	22	possibility of volume control by the user	
F	23	stepped intenseness of warning	
F	24	repeat of warning by non-confirmation of the user	

F/W	**No.**	**Requirements** fixed (F), wish (W)	**Descriptions & Dimensions**
F	25	regard of the main task by intenseness of warning	
F	26	possibility of repeat of a warning	by the user
F	27	output of error warning	
F	28	consider possible misuse of the user	by programming
W	29	message to the user by errors of operation	
F	30	explanation of the function	user manual and introduction
F	31	existing of an internal power source	
F	32	long capacity of the power source	> 8 hours
W	33	reliability of the power source	
W	34	renewable power source	
F	35	deactivating	on software level
F	36	activating	on software level
W	37	possibility of reset	
W	38	self-explanation of the user interface	
W	39	comfort	no fatigue of the user
F	40	clear recognizability of operation and use	
F	41	universal applicable	10 professions
F	42	consider the ergonomics of man and woman	5^{th} percentile woman to 95^{th} percentile man
F	43	positioning in view field of the user	vertical: 105°, horizontal: 120°
F	44	positioning in reaching area of the user	ergonomics
F	45	no exceeding stress of the user's senses	
W	46	consistence with the working environment	
W	47	optic equivalence with the social position of the user	
F	48	consider social, cultural and international differences	
F	49	consistence in the system and the system environment	
F	50	low weight	$m < 184$g
W	51	low space	
W	52	smooth running buttons	$F_{max} < 60$N
F	53	protection against external use	
W	54	low costs	
F	55	low flammability of the used materials	fire resistance class
F	56	no dangerous substances in the used materials	
F	57	no discharge of dangerous vapours by heating	
W	58	scratch resistance of the surface	
W	59	shock resistance of the surface	
W	60	dust and splash water proof	
F	61	possibility of personalization	3 chronotypes

F/W	**No.**	**Requirements** fixed (F), wish (W)	**Descriptions & Dimensions**
F	62	prevention against opening a device by a user	
F	63	correct functionality	to every point of time

Table C.1.: Requirements List for the HMI

D. Morphological Boxes for the Design of the HMI

In general, a morphological matrix depicts the solution space for a technical problem by listing the technical subfunctions in the first column and according solution principles in rows. In this way, a systematic approach to defining new solutions can be taken, avoiding the arbitrary selection of a solution to the problem which often results in neglecting unusual but efficient solution variants.

Variants selected can be depicted by a spline layed through the matrix with dots indicating the solution principles chosen. These variants are compared by means of a value-benefit-analysis in order to filter out the best solution.

D.1. Morphological Boxes for Informational Aspects of the HMI

function \ solution		1	2	3	4	5	6	7	8	9	10
Attracting attention	**haptic**	vibrotactil	cool air / venting the room	no haptic							
	acoustic	simple audio signal	random melody	melody	bang	vary the ambient noise	short speech message	no acoustical			
	visual (also state)	flashlight / blinking light	static light	change in state of the user interface	vary the ambient lighting	vary the ambient color	display action (animation / light)	change in state of the HMI interface	no visual		
	others	olfactory	alarm other persons	no others							
Giving information		speech message from loudspeakers	speech message from ear speakers	text message in display	animation in display	pictograms in display	flapping board with text				
User giving feedback		speech input	clapping	input with fingers	input with hand	input with foot	gestical input				
Feedback after User Feedback		simple audio signal	snap in the speakers	change in state of the HMI interface	speech message	display action (animation / light)	no				
Keeping awake		playing music	offer some diversion (games, ...)	mathematical questions	change in state as diversion	Landström sounds	do several actions as diversion	confirmation with an extra key	demand a second feedback later	olfactory	cool air
Increase for imminent warning	**haptic**	vibrate stronger	shorter vibrating interval	demand an extra feedback	no haptic						
	acoustic	faster melody	getting louder	playing higher audio signals	fast formation of audio signals	no acoustical					
	visual	brighter light	blinking light	no visual							
Personalization		internal saving of personal settings	external saving of personal settings	modify personal settings at the system							
Error warning		flashlight	text message	speech message	discreet beep	snap in the speakers					

Figure D.1.: Morphological Box for Informational Aspects

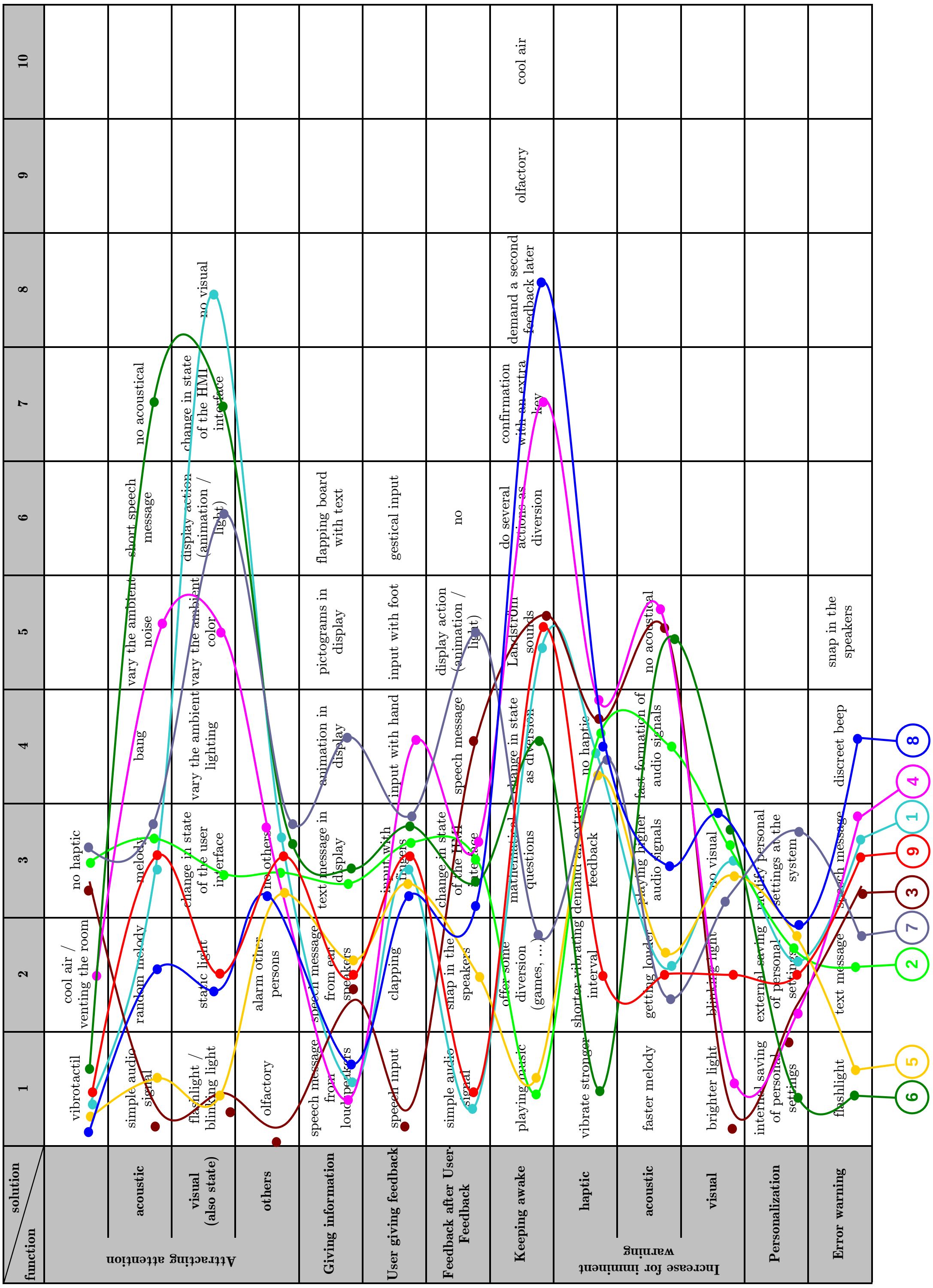

Figure D.2.: Depiction of All Informational Variants

function		solution 1	2	3	4	5	6	7	8	9	10
Attracting attention	haptic	vibrotactil	cool air / venting the room	no haptic							
	acoustic	simple audio signal	random melody	melody	bang	vary the ambient noise	short speech message	no acoustical			
	visual (also state)	flashlight	static light	change in state of the user interface	vary the ambient lighting	vary the ambient color	display action (animation / light)	change in state of the HMI interface	no visual		
	others	olfactory	alarm other persons	no others							
Giving information		speech message from loudspeakers	speech message from car speakers	text message in display	animation in display	pictograms in display	flapping board with text				
User giving feedback		speech input	clapping	input with fingers	input with hand	input with foot	gestical input				
Feedback after User Feedback		simple audio signal	snap in the speakers	change in state of the HMI interface	speech message	display action (animation / light)	no				
Keeping awake		playing music	offer some diversion (games, ...)	mathematical questions	change in state as diversion	Landström sounds	do several actions as diversion	confirmation with an extra key	demand a second feedback later	olfactory	cool air
Increase for imminent warning	haptic	vibrate stronger	shorter vibrating interval	demand an extra feedback							
	acoustic	faster melody	getting louder	playing higher audio signals	fast formation of audio signals						
	visual	brighter light	blinking light								
Personalization		internal saving of personal settings	external saving of personal settings	modify personal settings at the system							
Error warning		flashlight	text message	speech message	discreet beep	snap in the speakers					

Figure D.3.: Depiction of the Best Informational Variant

D.2. Morphological Boxes for Hardware Aspects of the HMI

function \ solution	1	2	3	4	5	6	7	8	9
Acoustic output	earphone	head set	use a hearing aid	loudspeaker / horn	use multimedia devices	no acoustical			
Visual output	display	flashlight lamp	lamp / LED	indirect ambient lighting	lighting of chassis	background lighting of user interface	no visual		
Haptic output	vibration in accessories	vibration integrated in clothing	vibration of the interface / steering wheel	vibration of an existing mobile phone	vibration of seat	vibration of floor	vibration of the HMI device	ventilator	no haptic
Other output	olfactory output	no other							
Feedback device	microphone for speech input	key control	button / switch	touch pad	touch screen	foot pedal	video camera for physical input		
Displaying of state	3 warning lamps / 3 LED	1 tri-colour LED	background lighting of the user interface	3 lighted pictogrammes	display	speech message	accommodation of the ambient lighting	background lighting of the HMI interface	
Personalisation device	smartcard / memory card input device	three-step switch for chronotypes	saving of settings in device	setting over display	RFID	fingerprint scan			
On/Off device	button control	control with throwing	push control	key control					
Reset device	button control	push control	speech input with microphone	touch screen	key control				
Repeat device	press button / press sensor	push control	speech input with microphone	touch pad	touch screen				
Volume control	control with throwing	push control	button control	touch screen					

Figure D.4.: Morphological Box for Hardware Aspects

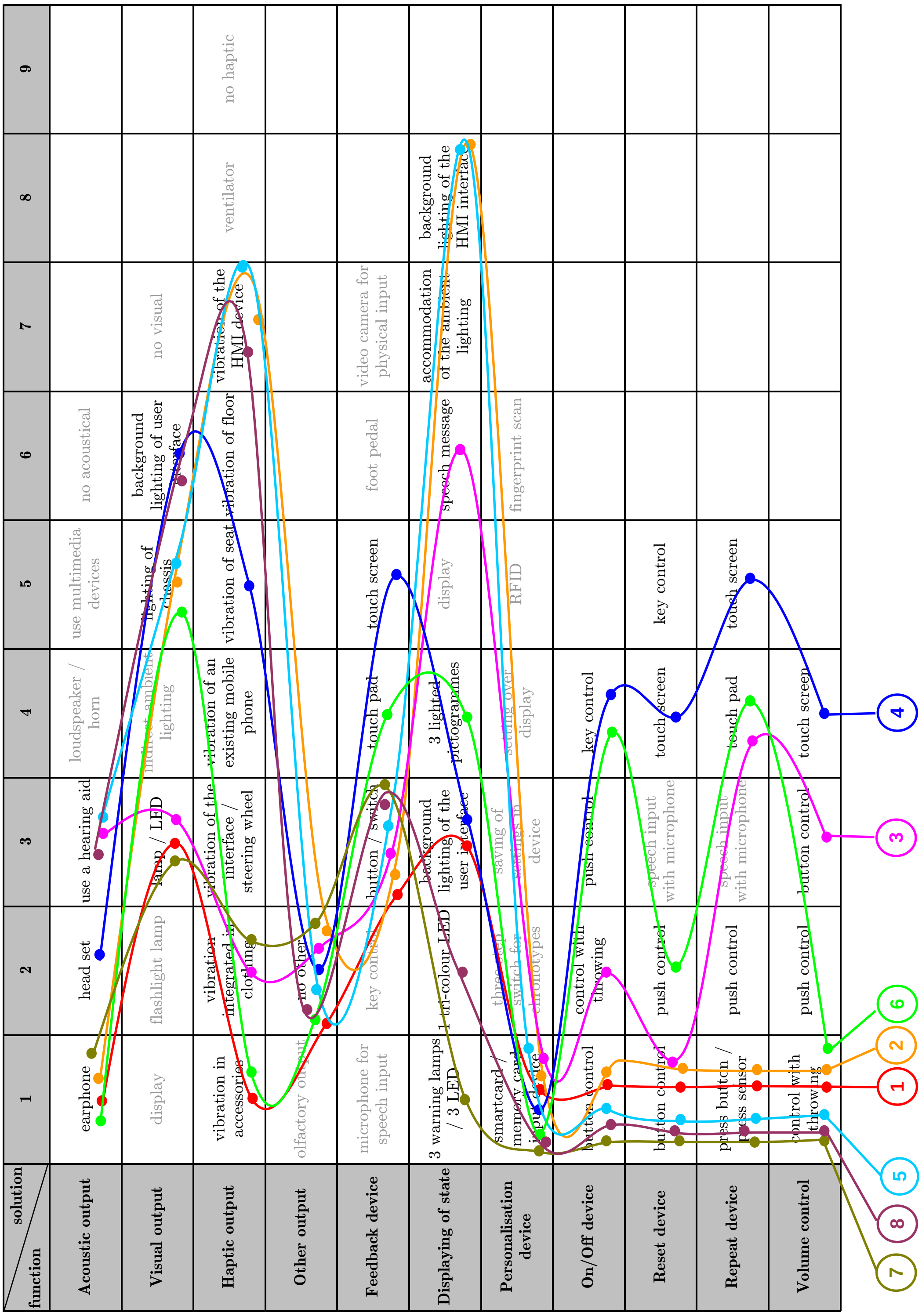

Figure D.5.: Depiction of All Hardware Variants

function \ solution	1	2	3	4	5	6	7	8	9
Acoustic output	earphone	head set	use a hearing aid	loudspeaker / horn	use multimedia devices	no acoustical			
Visual output	display	flashlight lamp	lamp / LED	indirect ambient lighting	lighting of chassis	background lighting of user interface	no visual		
Haptic output	vibration in accessories	vibration integrated in clothing	vibration of the interface / steering wheel	vibration of an existing mobile phone	vibration of seat	vibration of floor	vibration of the HMI device	ventilator	no haptic
Other output	olfactory output	no other							
Feedback device	microphone for speech input	key control	button / switch	touch pad	touch screen	foot pedal	video camera for physical input		
Displaying of state	3 warning lamps / 3 LED	1 tri-colour LED	background lighting of the user interface	3 lighted pictogrammes	display	speech message	accommodation of the ambient lighting	background lighting of the HMI interface	
Personalisation device	smartcard / memory card input device	three-step switch for chronotypes	saving of settings in device	setting over display	RFID	fingerprint scan			
On/Off device	button control	control with turning	push control	key control					
Reset device	button control	push control	speech input with microphone	touch screen	key control				
Repeat device	press button / press sensor	push control	speech input with microphone	touch pad	touch screen				
Volume control	control with turning	push control	button control	touch screen					

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Figure D.6.: Depiction of the Best Hardware Variant

E. Value Benefit Analysis of the Design Variants

A value benefit analysis is a means to compare different variants with respect to a chosen set of validation criteria. First, these criteria are chosen. They are weighted against each other in a pairwise comparison. To each criterion, a weighting factor is assigned with all of the weighting factors accumulating to 100%. Then, the fulfilment of each criterion is judged for each variant. The sum of the multiplications of the fulfilment factors of a variant for a specific criterion and the weighting factors of this criterion results in the value of the variant.

E.1. Informational Aspects

main criteria		criteria		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Sum	Weight (G) [%]
1	informational requirements	quality of drawing attention	**1**		1	1	1	1	2	1	2	2	1	2	1	2	2	2	2	23	**9,6%**
		quality of user activating	**2**	1		1	1	2	1	1	2	2	2	2	2	1	2	1	2	23	**9,6%**
		understandability of information	**3**	1	1		1	1	1	1	2	2	2	2	2	1	2	1	1	21	**8,8%**
		plausibility of information	**4**	1	1	1		1	1	1	1	2	1	2	1	1	2	1	1	18	**7,5%**
		obviousness of information	**5**	1	0	1	1		1	0	1	2	1	2	1	1	2	1	1	16	**6,7%**
		cognitive strain on user	**6**	0	1	1	1	1		1	1	2	1	2	1	2	1	1	2	18	**7,5%**
		concept of operation plausible for typical user	**7**	1	1	1	1	2	1		1	1	1	1	0	0	1	1	0	13	**5,4%**
		operation steps fast to perform (without many steps)	**8**	0	0	0	1	1	1	1		1	0	1	0	1	1	0	0	8	**3,3%**
		length of starting and installing the system	**9**	0	0	0	0	0	0	1	1		1	0	1	0	0	0	0	4	**1,7%**
		feedback clearly in content and time	**10**	1	0	0	1	1	1	1	2	1		1	2	1	0	0	1	13	**5,4%**
		short response to user after giving feedback	**11**	0	0	0	0	0	0	1	1	2	1		1	0	0	0	0	6	**2,5%**
		warning intenseness adaptable to working task and situation	**12**	1	0	0	1	1	1	2	2	1	0	1		1	1	1	1	14	**5,9%**
		utilisability for mobile people	**13**	0	1	1	1	1	0	2	1	2	1	2	1		1	1	1	16	**6,7%**
		grade of personalisation and simpleness of personalisation	**14**	0	0	0	0	0	1	1	1	2	2	2	1	1		0	1	12	**5,0%**
		grade of affright	**15**	0	1	1	1	1	1	1	2	2	2	2	1	1	2		1	19	**7,9%**
		saving of privacy	**16**	0	0	1	1	1	0	2	2	2	1	2	1	1	1			15	**6,3%**
																				239	**100,0%**

Figure E.1.: Pairwise Comparison of the Criteria

main criteria		No.	criteria	Weight (G) [%]	variant 1 Compliance Factor (E)	variant 1 Points (GxE)	variant 2 Compliance Factor (E)	variant 2 Points (GxE)	variant 3 Compliance Factor (E)	variant 3 Points (GxE)	variant 4 Compliance Factor (E)	variant 4 Points (GxE)	variant 5 Compliance Factor (E)	variant 5 Points (GxE)
1	informational requirements	1	quality of drawing attention	**9,6%**	4	38	3	29	4	38	2	19	5	48
		2	quality of user activating	**9,6%**	4	38	3	29	5	48	4	38	5	48
		3	understandability of information	**8,8%**	4	35	4	35	5	44	4	35	5	44
		4	plausibility of information	**7,5%**	5	38	5	38	5	38	5	38	5	38
		5	obviousness of information	**6,7%**	5	33	5	33	5	33	5	33	5	33
		6	cognitive strain on user	**7,5%**	3	23	4	30	4	30	5	38	5	38
		7	concept of operation plausible for typical user	**5,4%**	5	27	4	22	3	16	3	16	4	22
		8	operation steps fast to perform (without many steps)	**3,3%**	5	17	5	17	4	13	3	10	5	17
		9	length of starting and installing the system	**1,7%**	3	5	4	7	2	3	4	7	3	5
		10	feedback clearly in content and time	**5,4%**	5	27	4	22	4	22	3	16	5	27
		11	short response to user after giving feedback	**2,5%**	5	13	4	10	2	5	3	8	5	13
		12	warning intenseness adaptable to working task and situation	**5,9%**	4	23	3	18	3	18	4	23	4	23
		13	utilisability for mobile people	**6,7%**	5	33	3	20	4	27	5	33	4	27
		14	grade of personalisation and simpleness of personalisation	**5,0%**	5	25	5	25	3	15	5	25	5	25
		15	grade of affright	**7,9%**	3	24	4	32	4	32	3	24	3	24
		16	saving of privacy	**6,3%**	2	13	4	25	5	31	1	6	4	25
				100,0%		**413**		**391**		**414**		**371**		**456**

Figure E.2.: Evaluation of the Variants (ctd. in figure E.3)

main criteria			criteria	Weight (G) [%]	variant 6		variant 7		variant 8		variant 9	
					Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)
1	informational requirements	1	quality of drawing attention	**9,6%**	3	29	3	29	5	48	5	48
		2	quality of user activating	**9,6%**	4	38	4	38	5	48	5	48
		3	understandability of information	**8,8%**	4	35	2	18	4	35	5	44
		4	plausibility of information	**7,5%**	5	38	3	23	5	38	5	38
		5	obviousness of information	**6,7%**	5	33	5	33	5	33	5	33
		6	cognitive strain on user	**7,5%**	4	30	3	23	4	30	4	30
		7	concept of operation plausible for typical user	**5,4%**	4	22	3	16	4	22	5	27
		8	operation steps fast to perform (without many steps)	**3,3%**	4	13	4	13	4	13	5	17
		9	length of starting and installing the system	**1,7%**	4	7	4	7	4	7	3	5
		10	feedback clearly in content and time	**5,4%**	4	22	4	22	5	27	5	27
		11	short response to user after giving feedback	**2,5%**	3	8	5	13	4	10	5	13
		12	warning intenseness adaptable to working task and situation	**5,9%**	2	12	3	18	5	29	5	29
		13	utilisability for mobile people	**6,7%**	2	13	2	13	5	33	4	27
		14	grade of personalisation and simpleness of personalisation	**5,0%**	3	15	1	5	5	25	5	25
		15	grade of affright	**7,9%**	4	32	4	32	4	32	4	32
		16	saving of privacy	**6,3%**	5	31	4	25	3	19	4	25
				100,0%		**378**		**327**		**450**		**468**

Figure E.3.: Evaluation of the Variants (ctd.)

E.2. Hardware Aspects

main criteria		criteria		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Sum	Weight (G) [%]
1	technical requirements	high coverage of required user groups	**1**		2	1	2	2	0	1	2	1	2	1	2	2	1	2	21	**10,0%**
		anthrompometric adaptability	**2**	0		1	0	2	0	1	2	1	1	0	1	1	0	1	11	**5,2%**
		physical strain on user	**3**	1	1		0	2	0	1	2	1	1	1	1	1	0	2	14	**6,7%**
		quality of displaying the states	**4**	0	2	2		2	1	1	2	2	1	1	2	1	1	2	20	**9,5%**
		optically integratable in the existing work environment	**5**	0	0	0	0		0	0	1	0	1	0	1	0	0	2	5	**2,4%**
		no interefering with the main task of the user	**6**	2	2	2	1	2		1	2	1	2	1	2	1	2	2	23	**11,0%**
		unobtrusiveness of the device	**7**	1	1	1	1	2	1		2	1	2	1	1	0	1	2	17	**8,1%**
		possibility of outsourcing of tasks to existing components	**8**	0	0	0	0	1	0	0		0	0	0	1	0	1	2	5	**2,4%**
		ergonomic operation possible (reaching area, viewing field)	**9**	1	1	1	0	2	1	1	2		2	1	1	1	1	2	17	**8,1%**
		simpleness of personalization	**10**	0	1	1	1	1	0	0	2	0		1	2	1	1	2	13	**6,2%**
		protection of privacy	**11**	1	2	1	1	2	1	1	2	1	1		2	1	1	2	19	**9,0%**
		protection against external use	**12**	0	1	1	0	1	0	1	1	1	0	0		0	1	2	9	**4,3%**
		clear operation modalities	**13**	0	1	1	1	2	1	2	2	1	1	1	2		1	2	18	**8,6%**
		grade of mobility of the user	**14**	1	2	2	1	2	0	1	1	1	1	1	1	1		2	17	**8,1%**
		simpleness of implementation	**15**	0	1	0	0	0	0	0	0	0	0	0	0	0	0		1	**0,5%**
																			210	**100,0%**

Figure E.4.: Pairwise Comparison of the Criteria

main criteria			criteria	Weight (G) [%]	variant 1		variant 2		variant 3		variant 4	
					Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)
1	technical requirements	1	high coverage of required user groups	10,0%	5	50	5	50	4	40	3	30
		2	anthrompometric adaptability	5,2%	5	26	4	21	5	26	5	26
		3	physical strain on user	6,7%	4	27	4	27	3	20	5	33
		4	quality of displaying the states	9,5%	4	38	5	48	2	19	4	38
		5	optically integratable in the existing work environment	2,4%	4	10	5	12	4	10	4	10
		6	no interefering with the main task of the user	11,0%	4	44	5	55	3	33	3	33
		7	unobtrusiveness of the device	8,1%	2	16	3	24	2	16	2	16
		8	possibility of outsourcing of tasks to existing components	2,4%	2	5	1	2	3	7	4	10
		9	ergonomic operation possible (reaching area, viewing field)	8,1%	5	40	5	40	5	40	3	24
		10	simpleness of personalization	6,2%	5	31	5	31	5	31	5	31
		11	protection of privacy	9,0%	3	27	4	36	1	9	3	27
		12	protection against external use	4,3%	3	13	3	13	4	17	5	21
		13	clear operation modalities	8,6%	5	43	5	43	3	26	4	34
		14	grade of mobility of the user	8,1%	3	24	5	40	3	24	2	16
		15	simpleness of implementation	0,5%	4	2	5	2	3	1	2	1
				100,0%		**396**		**445**		**320**		**351**

Figure E.5.: Evaluation of the Variants (ctd. in figure E.6)

main criteria			criteria	Weight (G) [%]	variant 5		variant 6		variant 7		variant 8	
					Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)	Compliance Factor (E)	Points (GxE)
1	technical requirements	1	high coverage of required user groups	**10,0%**	4	40	5	50	5	50	4	40
		2	anthrompometric adaptability	**5,2%**	4	21	5	26	5	26	4	21
		3	physical strain on user	**6,7%**	4	27	4	27	4	27	4	27
		4	quality of displaying the states	**9,5%**	5	48	5	48	5	48	4	38
		5	optically integratable in the existing work environment	**2,4%**	5	12	5	12	5	12	5	12
		6	no interefering with the main task of the user	**11,0%**	5	55	4	44	4	44	5	55
		7	unobtrusiveness of the device	**8,1%**	3	24	4	32	4	32	5	40
		8	possibility of outsourcing of tasks to existing components	**2,4%**	1	2	2	5	2	5	1	2
		9	ergonomic operation possible (reaching area, viewing field)	**8,1%**	5	40	4	32	5	40	5	40
		10	simpleness of personalization	**6,2%**	5	31	5	31	5	31	5	31
		11	protection of privacy	**9,0%**	4	36	4	36	4	36	4	36
		12	protection against external use	**4,3%**	3	13	4	17	3	13	3	13
		13	clear operation modalities	**8,6%**	5	43	3	26	5	43	5	43
		14	grade of mobility of the user	**8,1%**	5	40	5	40	5	40	4	32
		15	simpleness of implementation	**0,5%**	5	2	4	2	3	1	5	2
				100,0%		**435**		**428**		**449**		**433**

Figure E.6.: Evaluation of the Variants (ctd.)

F. Summary of the Communication Strategy

F.1. Thresholds of the State Transitions

Start State	End State	Vigilance Value V Measured
1	2	$3 \leq V \leq 4$
1	3	5
2	4	1
2	3	5
3	5	$2 \leq V \leq 4$
3	7	1
4	1	1 for 10 min
4	6	$2 \leq V \leq 4$
4	3	5
5	3	5
5	7	1
6	4	1
6	3	5
7	5b	$2 \leq V \leq 4$
7	3	5
7	1	1 for 30 min
5b	3	5
5b	7	1

Table F.1.: Thresholds of the State Transitions

F.2. Summary of System Actions

State No.	Status Indicator	Acoustics	Vibration	Speech Messages	Feedback Required	Vigilance Maintenance System
1	green	—	—	—	—	—
2	yelow	Beep 2x	Vibration pulse 2x	You are sleepy. Your safety is endangered, so please take a break. Please confirm by pressing the confirmation button.	—	—
3	red	Alarmclock Signal	Pulsed Vibrations untill Feedback	You're extremely sleepy. There is a high risk for an accident. Please take a break immediately and sleep for at least 10 minutes. Please confirm by pressing the confirmation button. *After confirmation:* The vigilance maintenance system is activated now. It is intended to increase your alertness for a short time only. It is not a compensation for sleep.	yes	activate after feedback is given
4	green	Beep 1x	—	—	—	—
5	red	In combination with the vigilance maintaining function		—		on
5b	red	Beep 2x	Vibration pulse 1x	You are very sleepy. There is an increased risk of an accident. Please take a break immediately and sleep at least 10 minutes. Please confirm by pressing the confirmation button.	yes	on
6	yellow	Beep 2x	Vibration pulse 1x	You are very sleepy. There is an increased risk of an accident. Please take a break immediately and sleep at least 10 minutes. Please confirm by pressing the confirmation button. *After confirmation:* The vigilance maintaining system is activated again. It is intended to increase your alertness for a short time only. It is not a compensation for sleep.	yes	—

State No.	Status Indi-cator	Acoustics	Vibration	Speech Messages	Feedback Re-quired	Vigilance Mainte-nance System
7	yellow	Beep 1x	—	Sleepiness is not detected anymore. The vigilance maintaining system will be deactivated.	—	deactivate

Table F.2.: Summary of System Actions

G. Usability Questionnaire of the Vibration Experiment

Vibrations-Erkennungs-Versuch

Bitte füllen Sie folgende Felder aus:

VP-Nr.: ___ Geschl.: ___ Alter: ____ Gewicht: ______kg Größe: ______cm

Bitte kreuzen Sie Zutreffendes in den unten aufgeführten Feldern an:

1) Wie intensiv wurde die Vibration von Ihnen empfunden?

	sehr intensiv	stark	mittelmäßig	schwach	sehr schwach
Handinnenseite					
Unterarm					
Oberarm					
Gürtelschnallenbereich					
Hüftenseite					

2) An welchem Versuchspunkt war für Sie die Vibration am …

a. … angenehmsten ?

- ☐ Unterarm
- ☐ Oberarm
- ☐ Gürtelschnallenbereich
- ☐ Hüftenseite

b. … unangenehmsten ?

- ☐ Unterarm
- ☐ Oberarm
- ☐ Gürtelschnallenbereich
- ☐ Hüftenseite

3) An welchem Versuchspunkt könnten Sie sich eine Sekundenschlaf –WARNUNG mittels Vibrations-Einheit vorstellen?

- ☐ Unterarm
- ☐ Oberarm
- ☐ Gürtelschnallenbereich
- ☐ Hüftenseite

H. Questionnaire for Demographic and Chronobiological Data

Persönliche Daten

Datum

Bitte füllen Sie die Fragebögen zu den persönliche Daten und zum Chronotyp aus. Am Ende dieses Dokumentes gibt es ein Button mit dem Sie Ihre Antworten direkt an mich senden können. Ihre Eingaben werden selbstverständlich vertraulich behandelt.

Falls Sie Fragen oder Anmerkungen haben können Sie mir gerne ein E-Mail senden oder mich anrufen:

Lorenz Hagenmeyer

E-Mail : lorenz.hagenmeyer@iao.fraunhofer.de
Telefon : 0711/970-2196

Nachname

Vorname

E-Mail

Telefon   Mobil

Bank*

Kontonummer*   Bankleitzahl*

** Die Vergütung wird auf dieses Konto überwiesen*

Alter

Geschlecht

Händigkeit

Bildungsgrad   Studienrichtung

Folgen Sie einem normalen Schlafrhythmus?**

*** Normale Schlafrhythmus: 7 bis 9 Stunden Schlaf zwischen 22:00 und 10:00 Uhr*

Haben Sie innerhalb der letzten 2 Monate Flüge über 2 Zeitzonen absolviert?

Fragebogen zum Chronotyp

Dieses Dokument hat als Ziel, aufzuzeigen, zuwelcher Uhrzeit Sie am produktivsten sind.

<u>Anweisungen:</u>

- Bitte lesen Sie jede Frage sorgfältig durch, bevor Sie antworten.
- Beantworten Sie bitte alle Fragen, auch dann wenn Sie sich bei einer Frage unsicher sind.
- Beantworten Sie die Fragen in der vorgegebenen Reihenfolge.
- Beantworten Sie die Fragen so schnell wie möglich. Es sind die ersten Reaktionen auf die Fragen, die uns mehr interessieren als eine lange überlegte Antwort.
- Beantworten Sie jede Frage ehrlich. Es gibt keine richtige oder falsche Antwort.

1. Wenn es nur nach Ihrem eigenen Wohlbefinden ginge und Sie Ihren Tag völlig frei einteilen könnten, wann würden Sie dann aufstehen ?

   ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○

   5 6 7 8 9 10 11 12

2. Wenn es nur nach Ihrem eigenen Wohlbefinden ginge und Sie Ihren Abend völlig frei gestalten könnten, wann würden Sie dann zu Bett gehen ?

   ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○

   20 21 22 23 24 1 2 3

3. Wie sehr sind Sie von Ihrem Wecker abhängig, wenn Sie morgens zu einer bestimmten Zeit aufstehen müssen ?

   ○ Überhaupt nicht abhängig
   ○ Etwas abhängig
   ○ Ziemlich abhängig
   ○ Sehr abhängig

4. Wie leicht fällt es Ihnen üblicherweise morgens aufzustehen ?

- ○ Überhaupt nicht leicht
- ○ Nicht sehr leicht
- ○ Ziemlich leicht
- ○ Sehr leicht

5. Wie wach fühlen Sie sich morgens in der ersten halben Stunde nach dem Aufwachen ?

- ○ Überhaupt nicht wach
- ○ Ein bisschen wach
- ○ Ziemlich wach
- ○ Sehr wach

6. Wie ist Ihr Appetit in der ersten halben Stunde nach dem Aufwachen ?

- ○ Sehr gering
- ○ Ziemlich gering
- ○ Ziemlich gut
- ○ Sehr gut

7. Wie müde fühlen Sie sich morgens in der ersten halben Stunde nach dem Aufwachen ?

- ○ Sehr müde
- ○ Ziemlich müde
- ○ Ziemlich frisch
- ○ Sehr frisch

8. Wenn Sie am folgenden Tag keinerlei Verpflichtungen haben, wann gehen Sie dann - verglichen mit Ihrer üblichen Schlafenszeit - zu Bett ?

- ○ Selten oder nie später
- ○ Weniger als eine Stunde später
- ○ 1 - 2 Stunden später
- ○ Mehr als 2 Stunden später

9. Sie haben beschlossen, sich körperlich zu betätigen. Ein Freund rät Ihnen, zweimal wöchentlich eine Stunde zu trainieren; für ihn sei die beste Zeit zwischen 7 und 8 Uhr. Ausgehend von Ihrem eigenen Wohlbefinden, wie schätzen Sie Ihre Leistungsfähigkeit zu dieser Zeit ein ?

- ○ Ich wäre gut in Form
- ○ Ich wäre ziemlich in Form
- ○ Es wäre ziemlich schwierig für mich
- ○ Es wäre sehr schwierig für mich

10. Um wieviel Uhr werden Sie abends müde und haben das Bedürfnis, schlafen zu gehen ?

○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○ ○

20 21 22 23 24 1 2 3

11. Sie möchten für einen zweistündigen Test, von dem Sie wissen, dass er mental sehr beansprucht, in Bestform sein. Wenn es nur nach Ihrem eigenen Wohlbefinden ginge und wenn Sie Ihren Tag völlig frei einteilen könnten, welchen der vier Test-Zeiträume würden Sie wählen ?

- ○ 8 - 10 Uhr
- ○ 11 - 13 Uhr
- ○ 15 - 17 Uhr
- ○ 19 - 21 Uhr

12. Wenn Sie um 23 Uhr zu Bett gehen sollten, wie müde wären Sie dann?

- ○ Überhaupt nicht müde
- ○ Etwas müde
- ○ Ziemlich müde
- ○ Sehr müde

13. Aus irgendeinem Grund sind Sie einige Stunden später als gewöhnlich zu Bett gegangen. Es besteht jedoch keine Notwendigkeit, am nächsten Morgen zu einer bestimmten Zeit aufzustehen. Welcher der folgenden Fälle wird bei Ihnen am ehesten eintreten ?

- ○ Ich werde zur üblichen Zeit wach und schlafe nicht wieder ein
- ○ Ich werde zur üblichen Zeit wach und döse danach noch ein wenig
- ○ Ich werde zur üblichen Zeit wach, schlafe dann aber wieder ein
- ○ Ich wache erst später als üblich auf

14. In einer Nacht müssen Sie für eine Nachtwache zwischen 4 und 6 Uhr wach sein. Am darauffolgenden Tag haben Sie keine weiteren Verpflichtungen. Welche der nachfolgenden Alternativen sagt Ihnen am ehesten zu ?

- ○ Ich werde erst nach der Nachtwache zu Bett zu gehen
- ○ Ich werde vorher ein Nickerchen machen und nach der Nachtwache schlafen
- ○ Ich werde vorher richtig schlafen und hinterher noch ein Nickerchen machen
- ○ Ich werde nur vorher schlafen

15. Sie müssen zwei Stunden körperlich schwer arbeiten und können sich Ihren Tag völlig frei einteilen. Wenn es nur nach Ihrem eigenen Wohlbefinden ginge, welche der folgenden Zeiten würden Sie wählen ?

- ○ 8 - 10 Uhr
- ○ 11 - 13 Uhr
- ○ 15 - 17 Uhr
- ○ 19 - 21 Uhr

16. Sie haben sich zu einem anstrengenden körperlichen Training entschlossen. Ein Freund rät Ihnen, zweimal wöchentlich eine Stunde zu trainieren; für ihn sei die beste Zeit zwischen 22 und 23 Uhr. Ausgehend von Ihrem eigenen Wohlbefinden, wie schätzen Sie Ihre Leistungsfähigkeit zu dieser Zeit ein ?

- ○ Ich wäre gut in Form
- ○ Ich wäre ziemlich in Form
- ○ Es wäre ziemlich schwierig für mich
- ○ Es wäre sehr schwierig für mich

17. Angenommen, Sie können Ihre Arbeitszeit frei wählen und Ihre Arbeitszeit beträgt 5 Stunden pro Tag (einschließlich der Pausen), die Tätigkeit ist interessant und wird nach Erfolg bezahlt. Welche 5 aufeinanderfolgenden Stunden würden Sie wählen ?

☐ ☐
24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

18. Zu welcher Tageszeit fühlen Sie sich Ihrer Meinung nach am besten ? *(Bitte nur 1 Feld ankreuzen !)*

○ ○
24 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

19. Man spricht bei Menschen von 'Morgen-' und 'Abendtypen'. Zu welchem der folgenden Typen zählen Sie sich ?

- ○ Eindeutig 'Morgentyp'
- ○ Eher 'Morgen-' als 'Abendtyp'
- ○ Eher 'Abend-' als 'Morgentyp'
- ○ Eindeutig 'Abendtyp'

Haben Sie alle Fragen beantwortet?

Wenn ja, bitte senden Sie mir dann Ihre Antworten durch Klick auf folgende Button.

Bitte stellen Sie sicher, daß Sie eine funktionierende Verbindung zum Internet haben! Bei Problemen mit dem Datenversand versuchen Sie zunächst, die Datendatei zu speichern und diese als Attachment mit einer normalen Mail zu senden (nach Klick auf obigen Button "Sonstiges" auswählen und der Anleitung folgen). Sie können das Formular aber auch ausdrucken und mir zufaxen oder es am Empfang des IAO abgeben.

Vielen Dank!

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I. Usability and Acceptance Questionnaire of the Evaluation Study

Gebrauchstauglichkeit und Akzeptanz

Bitte bewerten Sie das Schläfrigkeitswarnsystem (Fachausdruck: Hypovigilanz-Management-System, HVMS) anhand folgender Fragen. Kreuzen Sie bitte jeweils die am besten zutreffende Antwort an.

Das System soll später drahtlos (per Funk) betrieben werden. Versuchen Sie daher bitte, sich bei der Beantwortung die event. störenden Kabel “wegzudenken“.

1. Allgemein

1.1. Wie einfach/schwierig fanden Sie es, dieses HVMS zu bedienen?
↙ sehr einfach ①------- ②------- ③------- ④------- ⑤ sehr schwierig ↘

1.2. Wie einfach/schwierig fanden Sie es, die Funktionen dieses HVMS zu lernen?
↙ sehr einfach ①------- ②------- ③------- ④------- ⑤ sehr schwierig ↘

1.3. Wie einfach/schwierig fanden Sie es, die Funktionen dieses HVMS zu erinnern?
↙ sehr einfach ①------- ②------- ③------- ④------- ⑤ sehr schwierig ↘

1.4. Wie sehr hat dieses HVMS bei der Fabrikaufgabe geholfen/gestört?
↙ sehr geholfen ①------- ②------- ③------- ④------- ⑤ sehr gestört ↘

2. Statusindikator (Grüne/Gelbe/Rote LEDs)

2.1. Wie beurteilen Sie die Verständlichkeit des Statusindikators?
↙ sehr verständlich ①------- ②------- ③------- ④------- ⑤ nicht verständlich ↘

2.2. Wie zufrieden sind Sie mit der Anzahl der Stufen des Statusindikators?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

2.3. Wie zufrieden sind Sie mit der Anordnung der LEDs des Statusindikators?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

2.4. Wie zufrieden sind Sie mit der Anzahl und der Größe der LEDs des Statusindikators?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

3. Bedienung

3.1. Wie zufrieden sind Sie mit der Anordnung der Taster?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

3.2. Wie zufrieden sind Sie mit den Größen der Taster?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

3.3. Wie zufrieden sind Sie mit der Bedienkraft der Taster?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

3.4. Wie zufrieden sind Sie mit der Rückmeldung des Systems auf einen Tastendruck?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

4. Sprachmitteilung

4.1. Wie einfach/schwierig fanden Sie es, die Sprachmitteilungen zu verstehen?
↙ sehr einfach ①------- ②------- ③------- ④------- ⑤ sehr schwierig ↘

4.2. Wie zufrieden sind Sie mit dem Inhalt der Sprachmitteilungen?
↙ sehr zufrieden ①------- ②------- ③------- ④------- ⑤ nicht zufrieden ↘

4.3. Wie einfach/schwierig fanden Sie es, die Sprachmitteilungen zu erinnern?
↙ sehr einfach ①------- ②------- ③------- ④------- ⑤ sehr schwierig ↘

4.4. Wie oft sind Sie den Ratschlägen der Sprachmitteilungen gefolgt?
↙ immer ①------- ②------- ③------- ④------- ⑤ nie ↘

5. Auditive und vibrotaktile Warnsignale

5.1. Wie einfach/schwierig fanden Sie es, die Fabrikaufgabe auszuführen, wenn Warnsignale aktiviert waren?

↙ sehr einfach — sehr schwierig ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

5.2. Wie einfach/schwierig fanden Sie es, wach zu bleiben, wenn die Warnsignale aktiviert waren?

↙ sehr einfach — nicht schwierig ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

5.3. Wie zufrieden sind Sie mit der Befestigungsstelle der Vibrationeinheit?

↙ sehr zufrieden — nicht zufrieden ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

6. Bewegungsfreiraum

Bitte versuchen Sie, sich die Kabel "wegzudenken".

6.1. Wie beschränkend war die Befestigung dieses HVMS für Ihren Bewegungsfreiraum?

↙ sehr beschränkend — Überhaupt nicht beschränkend ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

6.2. Wie zufrieden sind Sie mit der Formgebung dieses HVMS?

↙ sehr zufrieden — nicht zufrieden ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

6.3. Wie zufrieden sind Sie mit den Abmessungen dieses HVMS?

↙ sehr zufrieden — nicht zufrieden ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

6.4. Wie zufrieden sind Sie mit dem Gewicht dieses HVMS?

↙ sehr zufrieden — nicht zufrieden ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

7. Akzeptanz

7.1. Wären Sie bereit, der Firma für die Sie arbeiten Zugang zu Ihren Daten über Erschöpfung und Müdigkeit auf Gruppenlevel (also z.B.: wie ist der Mittelwert der Schläfrigkeit der Gruppe) zu geben?

- ☐ Ja
- ☐ Nein
- ☐ Unsicher

7.2. Unter welchen Bedingungen wären Sie bereit, das HVMS zu benutzen?

- ☐ Um Ihnen Echtzeit-Kontrolldaten ihrer Erschöpfung und Schläfrigkeit zu liefern
- ☐ Um dem Arbeitgeber Echtzeit-Kontrolldaten Ihrer Erschöpfung und Schläfrigkeit zu liefern
- ☐ Um im Fall von extremer Erschöpfung und Müdigkeit zu alarmieren
- ☐ Unter keiner Bedingung

7.3. Denken Sie, dass das HVMS in einer Fabrik zum Erkennen von und zum Warnen vor Erschöpfung und Schläfrigkeit gebraucht wird?

- ☐ Ja
- ☐ Nein
- ☐ Unsicher

8. Bemerkungen

8.1. Wie war Ihre Motivation während der Fabrikaufgabe?

8.2. Was war Ihr Ziel während der Fabrikaufgabe, produzieren von vielen Einheiten oder vermeiden von Fehlern?

↙ hohe Stückzahl　　　　kein Fehler ↘

① ------- ② ------- ③ ------- ④ ------- ⑤

8.3. Bitte beschreiben Sie, was Sie an diesem HVMS als besonders negativ empfunden haben:

8.4 Bitte beschreiben Sie, was Sie an diesem HVMS als besonders positiv empfunden haben: