Scoping Review on Human-Machine Interaction and Health and Safety at Work

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Abstract. Continuous technological developments are ongoing challenges in the design of safe and healthy workplaces. Concepts of human-machine interaction (HMI) are an essential part of these developments which have to be examined constantly with regard to their influence on humane work. In order to map the existing knowledge on relations and design, a scoping review on human-machine interaction in production systems was conducted. Focussing on findings concerning physical and mental health as well as performance and job satisfaction, an extensive selection- and review-process led to the inclusion of 102 studies into the scoping review. The results were split content-based into three subcategories: function allocation, interface and interaction design as well as operation and supervision of machines and systems.

The results on function allocation stress the meaning of a task-oriented assignment of degrees and levels of automation, which both have an influence on workload and performance. Nevertheless, questions of trust and human involvement play an important role, too, and a global optimal balance of performance, workload and subjective feelings has not been found yet. Conclusions concerning the effects of human-machine interaction on mental health cannot be drawn from the studies of the scoping review. The studies dealing with interface and interaction design point to a confirmation of existing guidelines on ergonomic design. Yet, questions concerning mental health and work satisfaction remain broadly unanswered. A successful operation and supervision process is mainly determined by machine and system characteristics such as reliability. The concept of technological coupling may be used to describe the interaction of humans and machines. Studies using this framework indicate a tendency towards a poorer mental health and less intrinsic job satisfaction in cases of tight technological coupling.

Further research should address the relation between mental health and human-machine interaction. Additionally, existing knowledge and guidelines need to be revised with regard to the demands of new technologies and new ways of interaction such as human-robot collaboration.

Keywords: Human-machine interaction · Function allocation · Interface design · Safety and health at work

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1 Human-Machine Interaction in Future Production Work

Industrial work is an important economic factor in a high-wage country such as Germany. Statistics show that a considerable number of jobholders are working in the manufacturing sector which offers jobs for a quarter of the working population [1].

Furthermore, developments like industry 4.0 stress the integration of physical and computer-based processes into cyberphysical systems where new forms of interaction and knowledge demands hold challenges for the design of industrial working systems.

Past and present technological developments thus emphasize the meaning of human-machine interaction which is highly important for humane work. Human-machine interaction that is insufficiently designed can be seen as a risk factor: the increasing complexity of technologies, working processes and human-machine interfaces may in these cases increase emotional and mental stress for machine operators [2]. In order to investigate these assumptions, the presented scoping review was prepared.

The research question to be answered was whether human-machine interaction effects outcomes such as (mental) health, wellbeing, job satisfaction and performance considering the moderating influence of age and gender.

2 Method

2.1 Scoping Review as a Means to Prepare Reviews

A scoping review is a review method that aims towards a broad mapping of knowledge. In general, a scoping review does not exclude sources based on their origin, study design and quality, thus offering a broader scope for research questions. The scoping review may be used to disseminate and summarize research findings so that research gaps can be identified [3]. [4] find that scoping studies may set "the scene for a future research agenda" (p. 75). Additionally, a scoping review is used to assess whether further insights into the topic should be gained by the preparation of a systematic review [3].

[3] propose five steps for conducting a scoping review: (1) identification of the research question, (2) identification of relevant studies, (3) study selection, (4) charting of data, (5) collation, summary and report of the results.

Some critics of narrative review forms have been summarized by [4]. Critical aspects include insufficient quality of the texts, reasons for in- and exclusion of material are not discussed or contrary views are not reflected. To answer these critics the present scoping review included an extensive documentation of inclusion and exclusion criteria. Furthermore, the depiction of contrary and conflicting evidence on one topic was seen as an important aspiration leading to a holistic picture of the current state of research.

2.2 Study Selection Process

A complex search algorithm was developed and applied in the databases EBSCOhost and Pubmed. The search algorithm was composed of four parts: (a) a set of terms like human-machine interaction, man-machine systems and supervisory control was used to

describe and capture aspects of human-machine interaction; (b) outcome variables of interest allocated to the categories (mental) health (e.g. depression, depressive symptoms, musculoskeletal diseases, pain), wellbeing (e.g. complaints, headache, well-being, happiness), job satisfaction (e.g. sick leave, absenteeism, intention to leave, work satisfaction) and performance-variables (e.g. organizational effectiveness, quality of service) which were completed HMI-specific terms such as error and accident; (c) terms such as production, conveyor belt and industry were intended to focus on industrial working systems; (d) the search algorithm was concluded by a Boolean Not-operation in order to exclude subject areas such as military, education and service industries.

In July 2014 the search algorithm was applied in the databases leading to 21.075 hits. In order to edit the hits a software program for reference management was used. There, a first reduction of hits could be accomplished by searching for not-suiting terms within titles and keywords. A lot of articles didn't address the targeted content, as keywords such as genome, pharmacology or protein show. Moreover, the titles of the references were analysed according to the search terms. This procedure led to the exclusion of 16.941 hits. The next step within the selection process was the analysis of the remaining 2086 articles based on their abstracts. Again, the main part of articles could be excluded (1.779) because the abstracts didn't address the aspects in question. Finally, 269 articles were chosen to be analysed fully.

In their article on the advancement of scoping reviews, [5] emphasize the iterative character of the study selection process (step 3 according to [3]) which should be as transparent as possible. In order to ensure both transparency and quality within the study selection process a second reviewer who accompanied the abstract review process was involved. Calculating the interrater-reliability according to [6] assured the quality of the selection process. Therefor a set of 50, randomly chosen abstracts was read by a second, independent rater, who was briefed according to the selection criteria. The computation of consensus between the two rater resulted in a coefficienct of concordance of $\kappa = .81$. Afterwards, there was a short feedback on the decisions and the criteria applied. Then another set of 50 randomly chosen abstracts was rated. The second rating generated a Cohen's Kappa of $\kappa = .89$. Both scores can be seen as highly concordant [7].

The next step of the selection process was the examination of full texts. Of the 269 firstly included studies another 167 were excluded. The reasons are manifold ranging from diverging contexts to an insufficient description of variables and methods. Finally, 102 studies were included into to the scoping review in order to be analysed in detail.

2.3 Study Characteristics

According to [3] a basic numerical analysis was performed prior to a content-based structuring. It includes study characteristics such as year of origin or the geographical distribution of the studies.

In order to gain a broad depiction of the studies no time limit had been set for the database search. The main part of the studies analysed originated from the years 2005 to 2015, as can be seen in Fig. 1.

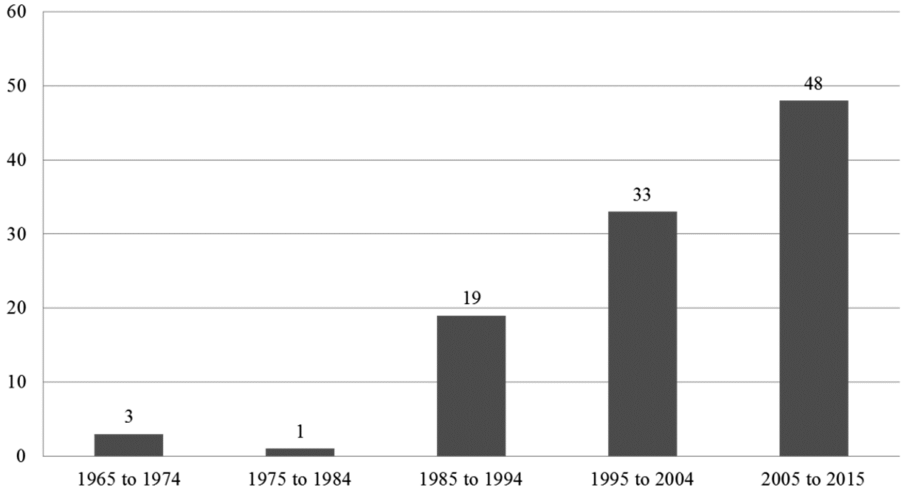

Fig. 1. Number of studies per decade

Furthermore, the countries of origin of the studies were considered. In Fig. 2, it can be seen that most of the studies were completed in Northern American countries.

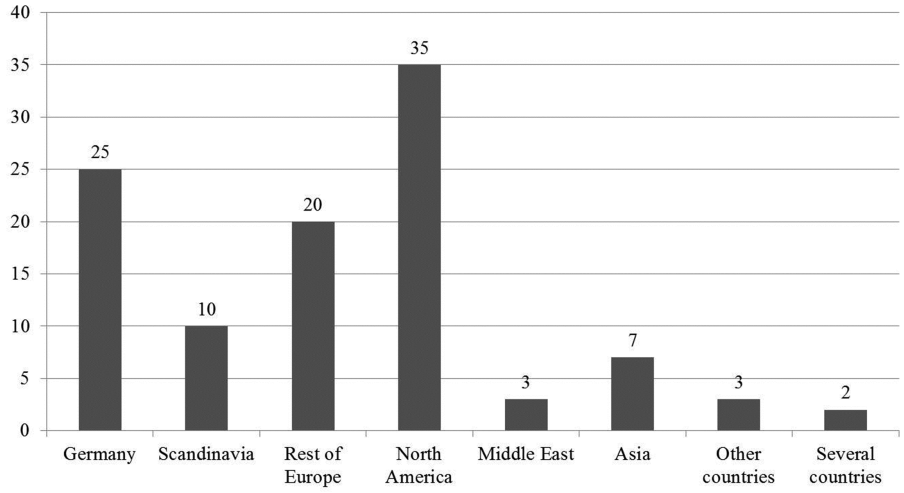

Fig. 2. Number of studies by country of origin

With 25 studies, Germany is the country that produced the second most contributions to the scoping review followed by other European countries (20 studies) and studies conducted in the Scandinavian region (10 studies).

2.4 Structuralizing the Studies

With respect to the manifold study focuses the material was assigned to three features of human-machine interaction namely function allocation, interface and interaction design as well as operation and supervision of machines and systems. The chosen classification is based on a theory-driven approach.

Function Allocation
The feature function allocation emphasizes the priority of working tasks that should determine the allocation of functions between humans and machines [8]. According to [9] function allocation plays an important role for the emergence of mental workload. A possible reason is described by [10] who state that function allocation influences cognitive functions.

Interface Design
Another important aspect to be considered when designing human-machine systems is the design of interfaces and interactions, which depicts the second feature of human-machine interaction within the scoping review. Aspects of interface design can be understood as input and output modalities of machines and systems [9]. This feature comprises depictions and displays, aspects of ergonomic design and forms of interaction. The latter was described by [11] as the regular exchange between human and (computerized) systems where different processes of feedback exist. An example of this interchange between human and systems are multiple forms and modalities of feedback.

Operation and Supervision of Machines and Systems
The last feature of human-machine interaction chosen for structuralizing the studies can be seen as the result of the prior features. Given a certain function allocation and interface design, employees have to work with machines considering certain machine and context characteristics. On an operational level cases of application are described.

3 Results

On a general level the scoping review shows that the main part of the studies was conducted within laboratorial settings. Laboratory studies often include characteristics of intervention studies meaning that there is a manipulation of conditions between two or more groups.

Considering the three features of human-machine interaction Fig. 3 shows that the main part of the analysed studies addresses aspects of interface design (41 studies). Studies dealing with operation and supervision of machines represent the second most observed content (33 studies). Within the scoping review studies covering function allocation are analysed the least (25 studies).

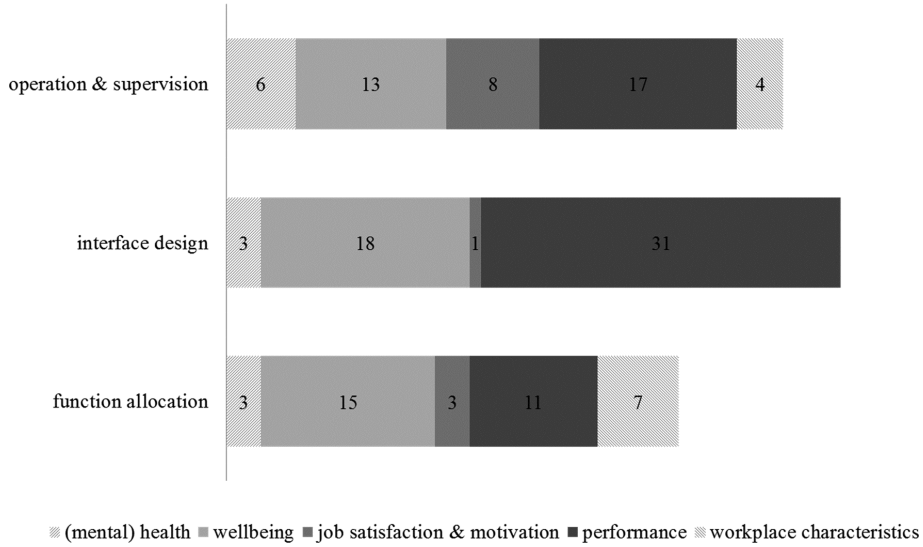

Fig. 3. Distribution of studies regarding features of human-machine interaction and outcome-categories

With regard to the set of dependent variables a strong focus on performance can be observed. Aspects of wellbeing which also include workload or user satisfaction have been examined frequently, too. Job satisfaction on a general level and aspects of work motivation didn't play a considerable role in the analysed studies. The same applies to (mental) health.

Since some studies describe changes in workplace that are related to the introduction of new machines and systems, workplace characteristics were identified as another set of independent variables. They include positive as well as negative perceived changes introduced by new technological facilities.

With the ongoing development of technologies a blend between human-machine interaction and human-computer interaction can be observed. Today, most machine control units are based on computer technology [12]. Since machines are endowed with computer-based processes, new challenges on human-machine interaction are imposed. Within this context [13] point out that computers and information systems connect humans and machines in manufacturing environments. In order to account for these similarities some results concerning human-computer interaction (HCI) are emphasized, too. The results concerning the three features of human-machine interaction are described in more detail within the next paragraphs.

3.1 Function Allocation

The study situation remains unclear for the relation between function allocation and (mental) health. Studies scatteredly touch this relation in very different contexts and with diverging methodological approaches, so that it seems difficult to come to verified

conclusions. The relation between function allocation and aspects of job satisfaction or motivation remains unclear, too. As can be seen in Fig. 3, both areas of dependent variables were examined by three studies respectively.

Stronger evidence for possible effects of function allocation can be observed for aspects of wellbeing. Studies show that degree of automation as well as level of automation exert influence on workload. Subjective workload decreases, as degree and level of automation increase [14]. However, there are complex interactions with other states of wellbeing such as trust and the desire for (manual) control [15].

Computer-based adaptive automation can be distinguished between event-based, performance-based and psychophysiological-based approaches as well as modelling-based strategies [16]. Within this context [17] could show that there was no clear picture between an event-based, performance-based and adaptable automation with regard to performance variables. However, subjective state measures such as workload and strain could benefit from a performance-based approach while measures referring to self-confidence yield advantageous results for an adaptable automation. An example of a psychophysiological-based automation can be found in [18]. The authors show that both variations of automation mode (EEG-based and a yoked version of EEG data) result in comparable level 1 situation awareness. With regard to subjective workload, a self-initiated usage of the support system induces higher workload ratings than a computer-based initiation [18].

Furthermore, the scoping review includes studies showing that there is a need to differentiate between routine and non-routine situations with regard to performance and operator workload. As was underlined by the analysis of [19], advantages of higher degrees of automation on performance cannot be maintained in non-routine situations often.

With regard to workplace characteristics it can be stated that the introduction of new technologies may be related with positive outcomes such as skill enhancement [20]. But rather negative effects such as a limitation in authority may also occur.

In short, strategies of automation design and function allocation should consider different trade-offs between aspects of performance and states of wellbeing or workload. Moreover, principles of function allocation can be acting as stressors or resources in changing workplace characteristics and aspects of job control. For the investigation of adverse or beneficial effects of human-machine interaction job control can be seen as a connective element. With the current state of research conclusions concerning long-term effects on strain cannot be drawn.

3.2 Interface and Interaction Design

Since most machines are equipped with displays representing computer-based processes in the background, aspects of interface and interaction design play an important role in HMI and HCI.

Within this context feedback design is an important factor. As new technologies enable the usage of several feedback modalities, [21] recommend bimodal feedback which can be related to decreased workload. The authors conclude that of several multimodal feedback variations, the most advantageous results could be obtained by the

combination of haptic and visual feedback. [22] demonstrate differences between men and women regarding their reaction on negatively framed feedback. This study undermines the importance of aspects such as individualization which is also entrenched by the norm ISO 9241-110 [23].

With regard to the usage of modern technologies such as head-mounted displays (HMDs) studies indicate a short term occurrence of physical complaints like headaches [24]. [25], using a test duration of 2×4 h, show that the use of the HMD does not cause impairments on the visual system. However, an increased muscular activity in the neck region and an increase in subjective complaints in the time course are detected. Yet, it is not possible to deduce long-term effects based on the studies included within in the scoping review.

The cooperation of humans and robots can be seen as a special form of human-machine interaction. The studies included in the scoping review suggest that visual features as well as the intended work domain must be taken into account when designing human-robot interaction [26]. Outcome variables that seem to be influenced by human-robot interaction are aspects of workload, user satisfaction, performance or feelings of safety [27].

In general, the studies dealing with interface and interaction design confirm existing findings on the advantages of ergonomic design so far. Concerning the examined outcome variables, especially user satisfaction, workload and performance benefit of ergonomic design principles such as redundant information representation. Results on job satisfaction and motivation have been found rarely so that there is an insufficient data base for conclusions.

3.3 Operation and Supervision of Machines and Systems

The studies in this feature of human-machine interaction descend from broad areas of application. A concept that was introduced within the context of advanced manufacturing technologies – namely technological coupling – finds evidence for negative health outcomes related to the occurrence of tight technological coupling [28]. The author also shows that tight coupling exerts negative influence on job satisfaction [28]. These results could be confirmed in later works [29]. Moreover, the operation and supervision of machines and systems affects workplace characteristics indicating a strong connection to task-related factors such as decision latitude. [30] show a negative correlation between tight coupling and timing as well as method control.

Additionally, several studies indicate that system characteristics hold an important meaning for the operation and supervision of systems and machines. Especially aspects of wellbeing such as workload and performance are affected by system characteristics such as reliability and error rate. On a general level it can be seen that reliable systems are related with higher trust ratings [31] and decreased workload [32]. Concerning performance variables, [33] find in their literature review that low reliability of systems ($\leq$0.7) erases possible performance benefits of the automated system.

Summarizing, the operation of systems is influenced by system characteristics and can change job structures as well as skills of jobholders which should be taken into account in the development of new systems. Situational (e.g. quantitative workload) and

individual (e.g. age) factors influence the interaction of humans and machines. For the supervision of systems the scoping review does not yield clear conclusions.

4 Discussion

The Scoping Review on human-machine interaction can be seen as a comprehensive appraisal of the literature. Within the review process a heterogeneous picture could be drawn reflecting the manifold areas of application, design and concepts that are examined within the context of human-machine interaction.

With regard to the method chosen, the scoping review allows a broad collection of knowledge. Nevertheless, a topic as extensive as human-machine interaction may have benefitted from a stronger focus. Even studies that were grouped within the same feature of human-machine interaction showed great content-related differences. As a consequence, a detailed comparison of studies was not feasible. However, a major advantage offered by the broad overview of a scoping review is the possibility to identify research gaps. The scoping review on human-machine interaction shows that there is a great need to intensify research activities on the relation between human-machine interaction and aspects of (mental) health. Changes in workplace and task characteristics induced by technological systems may be seen as a connective element which stresses the meaning of a task-focus within human factors research. Further research questions refer to the applicability of current concepts and design options on advanced technologies. As for human-robot interaction, existing knowledge has to be verified and broadened in order to meet future challenges such as fenceless collaboration. From a methodological point of view the scoping review encourages to conduct field studies as well as studies with the targeted population of employees since many findings results from laboratory studies with student samples. Moreover, it can be seen that a differentiation between age groups and gender is pursued only rarely. With demographic change at hand these considerations should be taken into account more strongly, thus leading to age-differentiated design principles that enable safe and healthy work. Additionally, long-term effects should be focussed more strongly by longitudinal studies.

However, the literature on human-machine interaction shows an abundance of design principles. Principles such as the arrangement of displays according to gestalt-laws or advisories concerning the density of information can be found in German regulatory documents. On an international level, ISO norms like ISO 6385 [34] point to a human-centred design of machines and systems. With regard to the design of dialogues ISO 9241-110 [23] names aspects such as suitability for the task, self-descriptiveness, controllability, conformity with user expectations, error tolerance, suitability for individualisation, and suitability for learning that stem mainly from human-computer interaction research. The application of these principles is a starting point for ergonomic design.

In conclusion, 102 analysed studies on human-machine interaction point out that mainly wellbeing and performance are affected by features of human-machine interaction. Nevertheless, the design of working tasks plays an essential role, too, because it determines the interactions between humans and machines. As was already described

by [10], a human-machine system is more than the sum of its parts. The design of future human-machine systems should account for the increasing complexity of machines and systems. Visions of industry 4.0 and cyberphysical systems contain new challenges for the design of human-machine interaction so that it becomes ever more central to ensure a transparent, comprehensible and ergonomic design of machines and systems. Therefore further research should focus on a detailed description of human-machine systems and outcome variables in order to gain a comprehensive understanding of their interactions. Thus, the identification of both detrimental and beneficial forms of human machine interaction can ensure safety and health at work.

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