On Studying Human Factors in Complex Cyber-Physical Systems

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Abstract

Deep penetration of modern information and communication technology in manufacturing companies (*vertical integration*) and across supply chains (*horizontal integration*) leads to an increasing amount and complexity of information that needs to be perceived, filtered, processed, and reacted to. Yet, the human factors that influence performance are insufficiently understood. This article outlines that *individual* factors, *interface* factors, and *system* factors affect overall performance and it presents two complementary research methodologies for identifying and quantifying these factors. On one side, we show that controlled laboratory experiments with singular decision tasks can precisely identify and quantify factors contributing to performance. On the other side, we use business simulation games with realistic decision tasks that can quantify the complexity of the underlying system. Our studies show that information amount, complexity, and presentation affect performance and that Decision Support Systems can increase performance and decrease error rates if and only if they are designed correctly. The article concludes with a research agenda to specifically understand which factors influence performance and how humans in the loop can be supported.

Keywords: Human Factors, Cyber-Physical Systems, Industrial Internet, Decision Making

1 Introduction

Today's manufacturing companies are facing tremendous changes through increasing competition in globalized markets, growing customer demands in regard to delivery times, product variety, and product quality. At the same time, the so called "*fourth industrial revolution*" or "*Industry 4.0*" is transforming manufacturing companies through deep penetration of all processes with modern information and communication technology under the label "*Internet of Things*" and "*Industrial Internet*" (Lee, 2008). One aspect of this revolution is the synthesis of physical systems (e.g., robots, production machinery, and production and inventory control systems) and cybernetic elements (smart information technology, autonomous, and self-optimizing computing systems), forming novel and increasingly complex "*Cyber Physical Systems*" (CPS)". The role of human decision makers

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in the loop of this mélange of increasingly complex data and better support through smart IT is insufficiently understood. In order to develop suitable support tools, we must carefully identify, evaluate, and quantify the factors that influence efficiency, effectivity, and user satisfaction in these complex environments. This article presents a glimpse on the factors that need to be considered and our research methodology for understanding human factors in the context of CPSs.

2 Background and A Glimpse at the Factors Space

In the Cluster of Excellence "Integrated Production Technologies for High Wage Countries" researchers investigate how the deep penetration of information and communication technology affects the flow of material and information through and across companies and how the growing amount of information can be handled efficiently. Within this project we focus on the flow of materials and information between several companies of a supply chain.

Although managerial systems at this stage are increasingly automated, human operators in the loop still need to verify the system's functioning or react to situations not modeled in the software system (Wickens et al., 2013). Hence, the interfaces must aid human deciders in data perception, choosing of alternatives and response entry. To support this process, we need to understand which factors influence efficiency, effectivity, and user-satisfaction.

We divided the possible factors in three distinct domains: *Individual factors, interface factors,* and *system factors,* as illustrated in Figure 1. In the following we present a list of possible factors and related studies will be presented in the subsequent section.

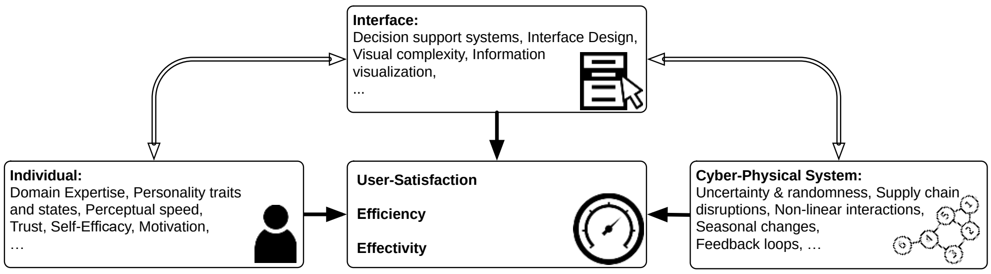

Figure 1: Overview of the factor space of human factors in cyber-physical systems.

2.1 Individual factors

In a supply chain context, individual decision makers manage the cooperation between multiple companies and they need to integrate information from multiple sources into their decision process. From perspective of the individual, multiple user factors can influence the attained performance. For example, *perceptual speed* influences how fast an individual processes information (Ekstrom, French, & Harman, 1979). Deriving the correct conclusions from the presented data is shaped by *domain knowledge, motivation,* and *self-efficacy believes*

(Bandura, 1982; Pardee, 1990). The cultural dimension is increasingly recognized for management and planning tasks (Hofstede, 1984). Consequently, culture may also shape performance in CPS. In regard to decision support systems, *obedience* may also play a role, as more obedient individuals may be more willing to follow wrong or even harmful suggestions of a DSS. As supply chains across multiple companies require communication and negotiation skills, *openness* and *communication skills* may also be relevant factors, as well as the perception of feedback (Djamasbi et al. 2008).

2.2 Interface factors

The domain of interface factors relates to the general usability of the software system that acts as an interface to the underlying system. It is evident that high usability is necessary to correctly sense and perceive data, infer the correct reactions, and communicate the planned action to the software system. To understand which aspects of an interface contribute to performance, it is necessary to more closely understand the role of the human in the loop and how the interface communicates information and translates interaction (Calero Valdez et al., 2015) without increasing complexity. An interface is composed of several different factors, such as *readability of presented alpha-numerical data*, its *visualization*, the *interaction patterns*, which all need to be aligned with the users' mental model to work effectively. Not only *availability* but also *design of information dashboards* (Few, 2006) or *decision support systems* have been shown to influence the attained performance. Furthermore, the *modality* of the provided information or even the *grade of user-centered design* could influence the interfaces contribution to performance (Lim et al. 2005; Ben-Tvi 2012).

2.3 System factors

The last domain of factor relates to the underlying cyber-physical system itself. In the case of inter-company flow of goods and information, numerous aspects influence the overall performance. One of the first prominent examples is the Beer Distribution Game (Forrester, 1958) that is used to investigate the effect of the position within the supply chain, on the so called Bullwhip-Effect – an effect that describes the self-reinforcing resonance of order-placements through the supply chain, at cost to the end of the supply chain (i.e. the manufacturer). Furthermore, the supply chain may be prone to disruptions cause by unexpected delays, variances in quality or amount of a supplier.

Additional complexity arises from feedback loops in the underlying system: Feedback loops emerge if decisions, which are usually based on the state of the system, again react upon the system (Senge, Kleiner, Roberts, Ross, & Smith, 1994). As such, each decision has an indirect and often delayed influence on the system or the considered metrics. Furthermore, these systems are often tainted with randomness and uncertainty. This adds additional complexity to the job of the decision makers.

2.4 Interactions

The difficulty of understanding human factors in complex cybernetic cyber-physical systems is further increased by the fact, that the three factor domains might interact: A specific user factor may only show its distinctive effect under specific interface or system factors. But uncovering these interacting effects is difficult, as exploring a larger factor space leads to a "combinatorial explosion" (Ware, 2004) that could easily blast the practicability of the experimental paradigm. As we will show at the end of the following section, a holistic consideration of all three factor domains is necessary.

3 Research Methodology and Empirical Findings

User factors, interface factors, and system factors relate to an individual's performance in managerial tasks in the cross company flow of materials and information. To identify, evaluate, and quantify these factors, we used a two-fold multi-methodological approach with strictly controlled laboratory experiments with conventional usability metrics, such as *performance* and *error*, and studies with *business simulation games* with profit of the simulated company as performance benchmark (Brauner & Ziefle, 2016). The former focusses on individual and interface factors (e.g., perceptual speed, font sizes, contrast, visual grouping), whereas the latter is more suitable to capture the complexity of the underlying system and the influence of tools to balance this complexity (e.g., supply chain disruptions, decision support systems). For the former, we usually consider conventional usability metrics (*performance* and *error*).

3.1 Baseline Experiments

As outlined above, we assume that the three described factors influence the overall performance in interacting with complex cyber-physical systems. In multiple laboratory experiments we identified and quantified factors influencing efficiency and effectivity of human decision tasks in interacting with cyber-physical systems in the production domain.

In a first experiment the influence of amount of data entities (factor: <u>lines</u>), length of the presented data (factor: <u>length</u>), and the concreteness of the presented information (factor: <u>label</u>; abstract or concrete products) was weighted (Ziefle, Brauner, & Speicher, 2015). The study‘s task resembled a simple material disposition tasks: Given an inventory, the participants had to decide whether new material needs to be procured. The study found that all factors increased the efficiency, but that accuracy remains largely unaffected. Furthermore, higher perceptual speed had a positive influence on efficiency, but not on accuracy. Thus, the study showed that individual user factors and system factors must be considered for the design of interfaces for cyber-physical systems.

In a second experiment, we used the same decision task to further integrate the influence of the interface in our research (Mittelstädt, Brauner, Blum, & Ziefle, 2015). The number of items in the inventory (factor: <u>lines</u>) and the complexity of the decision task (factor: <u>complexity</u>) were varied as the factors stemming from the underling system. Furthermore, the usability of the interface to the cyber-physical system was varied (factor: usability); in this case operationalized through regular and tiny font sizes. All factors influenced reaction times. Surprising though, is the significant interaction between lines and complexity. It indicates that complexity comes at an extra cost in environments with higher information density. Strikingly, we also learnt that the originally small influence of perceptual speed unfolds its large and perfidious effect in decision tasks with increased complexity and information density. Concluding, this study has shown that all three factors need to be considered.

As we have learned that factors from each domain influence efficiency and effectivity in interacting with CPS a follow-up study investigated if human decision making could be supported by suitable decision support systems. In this experiment with a similar decision task the effect of no DSS, a correctly working DSS, and a defective DSS with 50% correctness (factor DSS) were compared in regard to efficiency and effectivity (Brauner, Calero Valdez, Philipsen, & Ziefle, 2016). The DSS was presented and introduced as an additional redundant visual indicator to support the decision task. The participant's task was to read tabulated stock levels for a changing number of products (factor: information amount) and to decide if new products need to be ordered (factor: procurement decision). As expected, the correctly working decision support system had a positive influence on reaction times and accuracy, whereas the defective system is even worse than no decision support. But, if only limited information needs to be considered, the effect of the correctly working DSS on efficiency and effectivity is marginal. This changes if large tables are considered: The correct DSS increases the performance, whereas the defect DSS has limited or no influence on performance compared to the baseline condition. In regard to accuracy the correct DSS is beneficial compared to the baseline condition. However, the defect DSS yields in significantly lower accuracy compared to the baseline. The conclusion is that adequately designed interfaces can support decision makers in CPS and help to achieve higher performance and higher accuracy. However, these interfaces can also have detrimental effects if they are not working correctly, as deciders seem to be easily deflected by defective systems.

3.2 Business Simulation Games

The previously presented studies focused on singular decision tasks and each single decision task was unrelated to others. As reality is more complex, dynamic, tightly coupled, and involves delayed and hidden feedback loops (Senge et al., 1994) these laboratory experiments will neither be able to identify and quantify the influence of the underlying system, nor can they be used to study respective interacting effects in regard to individual and interface factors. To address this limitation, we are using business games as a research framework (Brauner & Ziefle, 2016). These games are built on a sound model of the underlying cyber-physical system (Stiller et al., 2014) and allow precise manipulation of the game's user interface and the system's complexity in experimental or quasi-experimental environments. As the complexity of experiment rises, so does the performance or accuracy metric: Instead of considering *correct* or *wrong* answers, the performance metric is calculated as the cumulated profit over several rounds of the business simulation games. If players interact well with the underlying system, they attain higher profits. We used this methodology in several studies to show that interface refinements and decision support systems have a positive influence on performance. We further have argued that this methodology can also be used an assessment tool to identify the best candidates for a managerial job, to identify training potentials, or as a fun and entertaining learning environment.

The first study showed that the underlying system has a tremendous influence on the attained performance (Brauner, Runge, Groten, Schuh, & Ziefle, 2013). The participants had a random position in a four-tier supply chain (factor: position) and the supply chain disruption was found to have a larger impact on the average performance the farer away from the customer. Hence, the underlying system influences overall performance. Surprisingly, the average decision times were neither related to performance, nor to position.

A second study more closely investigated the complexity of the underlying system (Philipsen, Brauner, Stiller, Ziefle, & Schmitt, 2014a). In a simulated company setting the internal production quality and / or the supplier's quality felt randomly (factor: disruption) and the participants could react by higher investments in quality assurance in the respective domain. The condition without unexpected drops in supplier's quality and production quality yielded in the highest performance, whereas a drop in both the supplier's quality and the production quality yielded in the lowest performance. Also, a drop in own production quality yielded in lower performance than a drop in supplier's quality, indicating an external attribution.

A third study addressed the interface's ability to support human decision makers (Philipsen, Brauner, Stiller, Ziefle, & Schmitt, 2014b). For this study, we integrated decision support systems and used a process-oriented visual layout of the on-screen elements (factor: interface). In a randomized-control trial the refined interface yielded in significantly higher profit. Thus, a suitable design of interfaces to cyber-physical systems can leverage the overall performance.

In summary (see Figure 2), the studies on the business simulation games have shown that *interface* and *system* factors have a tremendous influence on the attaint performance. Surprisingly, the studies found only smaller influence of *individual* factors on the performance.

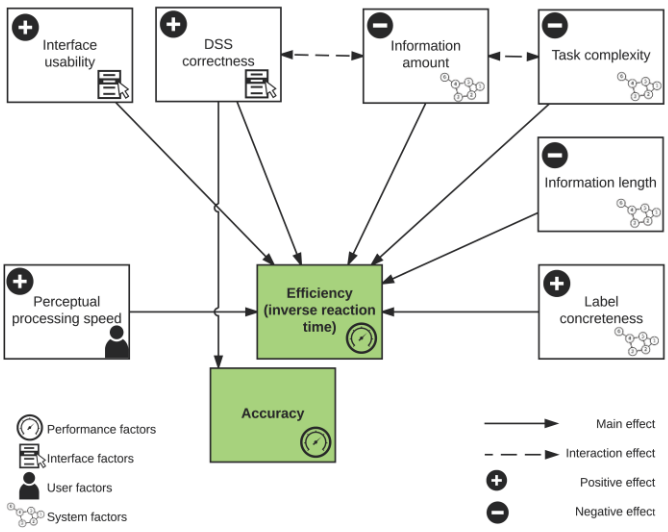

Figure 2: Summary of all effects from all studies grouped by user, interface and system effects.

3.3 Conclusion and Convergence

Both presented methodologies yielded in important findings on performance in cyber-physical systems in the production domain. We showed that *individual*, *interface*, and *system* factors influence human performance in interfacing with CPS. Surprisingly, these factors mostly affect the reaction times and not the accuracy in laboratory settings, whereas accuracy and not the reaction times were effected in the business simulation games. The question arises, what causes this shift in the time-accuracy tradeoff. Also, we need to learn how the findings from the strictly controlled laboratory environments transfer to more complex or real-life scenarios.

For example, we look at the baseline experiment on a table-reading task in the material disposition context. In this task we found that poor usability only has a marginal negative influence of efficacy and efficiency in decision tasks. However, a deeper investigation uncovered a three-way interaction of perceptual speed as individual factor, usability as interface factor, and data amount as system factor: The combination of these three factors leads to tremendously lower performance. Yet, discovering these many-way interactions requires a significant number of subjects and test trials and it is rather difficult to incorporate further *individual* (e.g., trust), *interface* (e.g., decision support systems), and *system* factors (e.g., supply chain disruptions) into the research model.

4 Future Research Agenda

On the basis of the presented findings we conclude with a research agenda for understanding the role of human factors in complex cybernetic cyber-physical systems.

Relationship between efficiency and effectivity: When is which factor important? How strong is the influence of context on this trade-off? In which scenarios is this not a trade-off?

Understanding the role of errors: The presented studies have shown that decision support systems, business analytics, information visualizations, and similar concepts have an evident benefit, as they increase the overall efficiency and effectivity. Yet, the study on defective decision support systems showed that incorrect suggestions are likely to be followed. Hence, we must understand if and how human operators can be enabled to consider the underlying data and not only blindly follow the DSS’s suggestions. The same applies for higher degrees of automation, ranging from suggested presets up to almost fully automated processes in which the human operators only have supervisory roles. We assume that the inhibition threshold of overruling automated decisions will increase with the level of automation. Therefore, the level of automation as additional system factor has to be taken into account in future research.

User-satisfaction: Our current studies focused on efficiency and effectivity as target metrics. Of course, work satisfaction and motivation plays an important role for human performance and must also incorporated in holistic models of human performance in complex cyber-physical systems.

Validation in the field: The presented findings must be validated in the field, despite the additional factors that must be taken into account (e.g., distractions at the workplace, from co-workers, the effect of noise, interruptions of the workflow). We speculate that some of the weaker individual and interface factors might fade into the background in real life scenarios, whereas others may gain in importance.

Development of guidelines for practitioners: The presented studies have shown that numerous factors need to be considered in order to develop effective and usable interfaces for decision makers in complex cyber-physical systems. Therefore, the overarching goal of researchers in academia must be to provide a weighted comprehensive list of the influencing factors and practical guidelines how these factors can be balanced.

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