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Crossing the boundaries of automation—Function allocation and reliability

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ABSTRACT

Two important automation characteristics are crucial when considering human performance consequences of automation support. One characteristic concerns the function allocation (FA) between human and automation. Adverse effects of automation seem to be most likely when the human operator is taken out-of-the-loop from active decision-making, excessing a boundary from information automation to decision automation. The second characteristic is the reliability of automation. Previous research suggests a critical reliability boundary around 70% below which automation support cannot be considered as helpful. This study explored differential effects of crossing both boundaries at the same time. Within a multi-task simulation consisting of a monitoring task and two concurrent tasks, participants were assigned to one of six groups, two manual control groups and four automation-supported groups. Automation support differed with respect to FA (stage 1 vs stage 4 automation) and reliability (68.75% vs 87.5%), both factors varied across the critical boundaries. Results suggest that reliability determines human operators' attention allocation and performance. When reliability was below the boundary, participants showed an increased attentional effort and a worse performance compared to fairly reliable support. Against the stated assumptions, FA did not reveal any impact. In combination with previous research this result might indicate that the FA boundary might rather be some kind of "function allocation valley" concerning decision-making automation (stage 3) in which negative consequences for human operators are most likely. Results are discussed in the context of recent automation research.

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1. Introduction

When considering human-automation interaction, two important automation characteristics are crucial to determine if automation support is beneficial or rather deteriorates performance compared with no automation support. One characteristic concerns the function allocation (FA) between human and automation, i.e. the tasks and functions that are assigned to and consequently carried out by automation. The second characteristic is the reliability of automation that determines to what extent the operator can rely on the proper functioning of the automated system. In recent years, two boundaries have been proposed regarding these two automation characteristics, which are assumed to be critical with respect to human performance consequences. For FA, a number of experimental results comprised in a meta-analysis by Onnasch et al. (2014b) revealed that negative consequences of automation, like loss of situation awareness and manual skills, are most likely when FA moves across a critical boundary from information automation to decision automation (Parasuraman et al., 2000). A second boundary was proposed by Wickens and Dixon (2007) and addresses a critical reliability level of an automated system below which the system cannot be considered beneficial anymore for human performance. Based on a thorough quantitative literature review they provided strong empirical evidence that automation only entails positive effects on joint human-automation performance if the automation's reliability is higher than 0.7 (70%). In case the reliability is lower, working with automation support was found to lead to even worse performance than working without automation support.

The current study builds up on these findings and aims to gain further insight on differential effects when the two previously identified boundaries are both crossed.

1.1. Function allocation between human and automation

Different framework models have been proposed to allow a standardised characterisation of automated systems with respect to the distribution of functions between human and automation (Endsley and Kaber, 1999; Endsley and Kiris, 1995; Milgram et al., 1995; Parasuraman et al., 2000; Riley, 1989; Sheridan, 2000). Common to all these models is the assumption that automation

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does not exist in an all-or-none fashion, but rather constitutes a continuum from no support to full automation of all functions. Accordingly, potential costs and benefits have to be considered as a function of more or less automation.

A well accepted framework model has been introduced by Parasuraman et al. (2000). They suggest a taxonomy, which characterises automation on two different dimensions: stages and levels. The stage component refers to the human information processing model (Wickens et al., 2013) and differentiates four different functions that can be reallocated to automation: information acquisition (stage 1), information analysis (stage 2), decision-making (stage 3), and action implementation (stage 4). The first two stages are often referred to as information automation (IA), whereas the latter two stages can be summarised by the term decision automation (DA). Additionally, defining the level of automation on each stage further specifies automation. Due to the two-dimensionality of the model, a system can be characterised according to the functions that are automated (stage dimension) and the level of automation on each stage (level dimension). This approach allows comparing various types of automation in a standardised manner and therefore outmatches other models that are only applicable to a certain kind of automation (e.g. Endsley and Kiris, 1995; Milgram et al., 1995; Riley, 1989; Sheridan, 2000).

Driven by the idea of potential costs and benefits in terms of human performance consequences as a function of more or less automation, the examination of the impact of FA on human-automation interaction has become one of the major interests in automation research. In particular, consequences of different stages of automation on human performance were examined (e.g. Endsley and Kiris, 1995; Kaber et al., 2000; Layton et al., 1994; Lorenz et al., 2002; Manzey et al., 2012). Results suggest that higher stages support human performance optimally by taking over certain parts of the task and thus reducing operators' workload. However, when automation is not perfectly reliable, a higher-stage automation has been shown to adversely affect operators' situation awareness and may also increase the risk of catastrophic failures due to operators' skill loss after a prolonged use of automation. As a consequence, it has been suggested that medium automation would represent the best compromise to maximise performance benefits of automation, and minimise possible new risks at the same time (e.g. Cummings and Mitchell, 2007; Endsley and Kiris, 1995; Kaber et al., 1999; Kaber and Endsley, 1997; Manzey et al., 2012). Applying these results to the automation taxonomy proposed by Parasuraman et al. (2000) the often stated recommendation to implement some kind of medium automation (Endsley and Kaber, 1999; Endsley and Kiris, 1995; Kaber et al., 1999; Manzey et al., 2012) can be specified. Comparing medium and high amounts of automation in those studies, the most critical difference of these gradations with respect to human performance consequences seems to be whether only information input functions are automated (information automation, stage 1 and 2) or additional output functions like decision-making or action implementation (decision automation, stage 3 and 4).

Direct empirical evidence for this assumption has been provided in a recent meta-analysis by Onnasch et al. (2014b). The meta-analysis was based on 18 experiments and examined the effects of human-automation FA on routine system performance, performance when the automation fails, workload, and situation awareness. Results indicated a clear automation benefit for routine system performance with increasing automation, as well as benefits for workload when automation functions properly. However, when automation does not function properly, i.e. when there is an automation breakdown, a negative impact of more complex automation on failure system performance and situation awareness was reported. This out-of-the-loop-unfamiliarity performance problem (OOTLUF; Wickens, 2000a, 2000b) seems to arise when cognitive functions related to active decision-making are resumed by automation in particular. Accordingly, Onnasch et al. (2014b) found negative consequences to be most likely when automation moves across a critical boundary between stage 2 and stage 3; the latter alleviating the human from active decision-making. When this boundary is crossed the risk of adverse effects on human performance is more likely, as well as potential catastrophic consequences when automation is unreliable or should suddenly fail (Wickens and Hollands, 2000).

1.2. Reliability of automation

The second aspect that is of crucial importance regarding effects of automation on human performance is its reliability (Lee and See, 2004). Depending on the realised stage of automation, reliability can be defined as the proportion of correctly indicated critical events (information automation), correctly given diagnoses, suggested decisions, or correctly executed actions (decision automation).

Several studies have addressed the impact of automation reliability on human performance in terms of complacency (e.g. Parasuraman et al., 1993), automation bias (for a systematic review see Goddard et al., 2012), situation awareness (e.g. Wickens, 2000a, 2000b), or attention allocation (Wickens et al., 2005). Comprising results of single studies, an overall picture of the impact of automation reliability on human performance was provided by a quantitative literature review conducted by Wickens and Dixon (2007). The analysis included data points from 20 different studies, which explicitly varied the reliability of diagnostic automation. They found a positive linear relation between automation's reliability and the joint human–automation performance. That is, even though operators may have tended to miss more critical events when working with highly reliable automation the overall number of jointly detected critical events was still higher compared to working with less reliable automation. However, when automation reliability was below approximately 70%, automation support yielded even worse performance compared to working with no automation. Thus, effective compensation for unreliability seems to be possible to a certain level only.

However, a drawback of most of the studies reported thus far and that were integrated in Wickens and Dixon's (2007) analysis is that they only compared relatively extreme reliability levels and missed to describe the characteristics of operators' adaptation to automation across a more complete range of reliability. To gain more insight into the proposed change from supportive automation to useless automation Onnasch et al. (2014a) examined the impact of five different reliability levels of alarm systems (the simplest form of information automation) on joint human–automation performance and visual attention allocation in a multi-task simulation. Alarm reliability was set to 68.75%, 75%, 87.5%, or 93.75% by varying the number of critical events that were missed by the alarm system. In comparison with a manual control group they found a clear automation benefit concerning human–automation performance that was independent of the level of automation reliability. Whereas the manual control group only detected around 70% of engine malfunctions, detection rates increased with alarm-support, even in the lowest reliability condition, up to 90%. This result revealed that all participants in the alarm-supported groups adapted to differing reliability levels in a very effective way. However, when reliability was below 70% the performance benefit was associated with an increased attentional effort, and a declined relative performance in a concurrent task compared to the other alarm-supported groups. In fact, when working with the least reliable alarm system, participants allocated as much visual attention to the supported task as the manual control group, i.e. behaved as if no automation support was available. Hence, automation below a

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