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# How operators make use of wide-choice adaptable automation: observations from a series of experimental studies

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**ABSTRACT**
The present paper is concerned with the design of adaptable automation. It analyses the aggregated data from five experiments ($N = 154$) to examine which automation levels operators prefer, how often they switch between them, and whether performance is associated with frequent switching or the automation levels being used. Using wide-choice adaptable automation (i.e. up to six levels were offered), the experiments were conducted using a PC-based simulation of a complex work environment. The results showed that about 95% of operators had a clearly preferred automation level, which they used for more than 50% of the time. They strongly preferred intermediate automation levels over levels at the higher and lower ends of the scale. Most operators switched rarely between levels and when they did, they usually made small adjustment rather than large changes. Several implications for the design of adaptable automation were derived from the empirical data.

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Adaptable automation; performance; automation design; operator preferences; operator strategies

## RELEVANCE TO ERGONOMICS/HUMAN FACTORS THEORY

The present work examined in what way operators made of use of adaptable automation that offered a large number of automation levels. It addresses the advantages and disadvantages of offering wide-choice adaptable automation using the theoretical framework of automation taxonomies.

## Introduction

### *Models and mains concepts in automation research*

Automation has become a major research topic in the field of ergonomics and human factors. The number of tasks that can be automated and the possibilities of how automation can be implemented have increased, but how operators actually use of these possibilities is often not taken into consideration during the design of technical systems. In order to make the best use of the rapid technological progress in this area, it is important to examine

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empirically the advantages and disadvantages of the different technological options, resulting in evidence-based advice on automation design. The empirical approach needs to be guided by solid theory and good models. In the present article, theoretical and empirical work in automation domain has been examined by focusing on adaptable automation (i.e. a human-centred form of automation which provides considerable latitude to operators about how to use the automatic system). The present research aimed to examine whether there are any preferences of operators for certain automation levels and to examine to what extent operators switch between automation levels during task completion.

In the field of automation, considerable theoretical work has been carried out over many years, which resulted in the development of many models, taxonomies and concepts. Automation taxonomies aim to describe in detail how the allocation of function between human and machine may look like. The first influential taxonomy was the 10-level model by Sheridan and Verplank (1978). It proposes levels of automation (LOAs) that range from full manual control (level 1) to full control by the machine (level 10), and also includes several intermediate levels, such as the machine suggesting a decision, but it needs to be approved by the operator (level 5) or the machine implementing its own recommendation and only informing the operator about it (level 7). There are several other models (e.g. Endsley and Kaber 1999; Endsley and Kiris 1995) that provide the same one-dimensional structure but differ in the number of levels or were applied to different domains (e.g. aviation, industrial manufacturing, generic models). These one-dimensional models were extended by adding a second dimension describing different information processing stages (i.e. information acquisition, information analysis, decision selection and action implementation), which can be automated to different degrees (Parasuraman, Sheridan, and Wickens 2000). More recent automation models have proposed the concept 'degree of automation', in which the two-dimensional automation levels and processing stages are mapped onto one continuum (Wickens et al. 2010; Onnasch et al. 2014). This helps us decide which of several technical systems is more highly automated. An overview of different automation taxonomies may be found in an article recently published by Vagia, Transeth, and Fjerdingen (2016).

While the automation taxonomies are primarily concerned with the question of allocation of function, other concepts have addressed the degree of flexibility in functional allocation and who is responsible for managing this flexibility (i.e. human or machine). A distinction may be made between three principal options of automation design: static automation, adaptive automation and adaptable automation (Kaber and Endsley 2004; Scerbo 2006). (a) In static automation, the allocation of function between human and automation is fixed whereas adaptable and adaptive automation allow some flexibility. (b) In adaptive automation, the machine takes the decision about a change in automation level (e.g. moving from LOA1 to LOA4). A further distinction between sub-types of adaptive automation may be made: performance-based, physiology-based and event-based (Endsley and Kaber 1999). Accordingly, the decision of the machine may either be based on performance levels shown by the operator (e.g. a slowing down of reaction time), on the psychophysiological state of the operator (e.g. increased levels of heart rate), or on a change in objective task load caused by a critical event (e.g. the appearance of thick fog is considered a critical event that makes task completion more difficult). (c) In adaptable automation, the decision of which automation level to choose is made by the human operator.

In automation design, an important task is to select the most suitable design options among all possible options (see Table 1). A number of criteria are suggested, which may be used to determine which of the principal automation design options should be implemented. An important criterion in practice is clearly the *ease of implementation* which is associated with constraints and technical feasibility. This naturally influences the frequency of the technical system being used in industry (i.e. the more easily a technical system can be implemented and the less costly it is, the more widely it is used). In addition to the technical criterion 'ease of implementation', there are four psychological criteria that refer to the responsiveness and adaptability of the system and to how users perceive and understand the system and its environment. *Adaptability to operator preferences* refers to the degree to which the automation takes into account different operator needs to which automation levels can be tailored (e.g. by changing or by allowing operators to change automation levels). *Responsiveness to changing situational circumstances* is an important criterion because it indicates how quickly automation can react to changing situational requirements (e.g. considerable increases or reductions in workload) by adjusting LOA. For example, a rapid reduction in operator workload may be needed if there was an impending risk of performance breakdown. Automation state awareness refers to the degree the operator of the current activities of the automatic system (notably the automation level it currently operates in). This criterion is related to the concept of situation awareness (Endsley 1995). *Perceived control over system* is concerned with the extent to which the operator believes that he/she is able to control the system. Perceived control is an important psychological concept in the domain of work (e.g. Spector 1986) and is likely to play a role here, too. The evaluation of the five criteria contained in Table 1 is based on a coarse assessment carried out by the authors. The results of the assessment show that adaptable automation provides a number of advantages over alternative automation design options (e.g. high score for responsiveness, automation state awareness and perceived control) even though it does not come out the best with regard to all evaluation criteria (e.g. ease of technical implementation).

## Design options for adaptable automation

For the design of adaptable automation, the system designer is also faced with the question of what kind of LOA should be offered to the operator. For example, the fine-grained model by Sheridan and Verplank (1978) or Endsley and Kaber (1999) suggests 10 different LOAs that may be offered to operators. This indicates that operators could be given considerable choice by system designers but the question is whether such a large choice

**Table 1.** Evaluation of principal automation designs based on a set of relevant criteria

| Principal automation designs | Ease of technical implementation | Adaptability to operator preferences | Responsiveness to changing situational circumstances | Automation state awareness | Perceived control over system |
|---|---|---|---|---|---|
| Static | High | No | none | very high | medium |
| Adaptive (performance-based) | Low | Yes | low | Low | low |
| Adaptive (physiology-based) | Low | Yes | medium | Low | low |
| Adaptive (event-based) | Medium | No | high | Medium | very low |
| Adaptable | Medium | Yes | high | High | high |

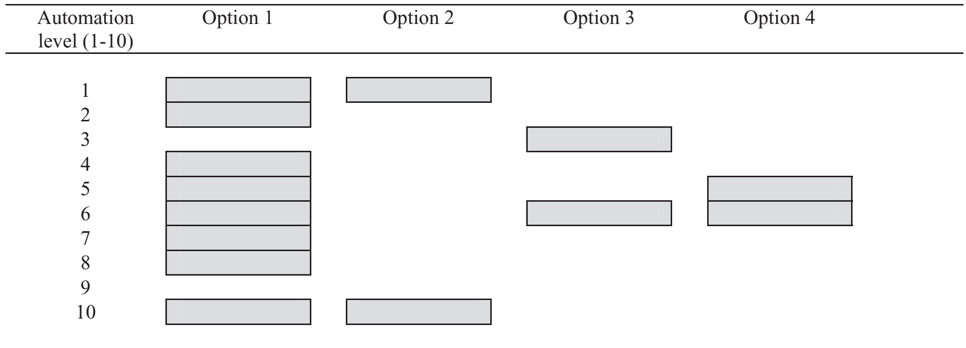


**Figure 1.** Design options for adaptable automation with four examples based on the 10-level model of Sheridan and Verplank (1978): option 1: very broad range (10 levels) and wide choice (8 levels); option 2: very broad range (10 levels) and very limited choice (2 levels); option 3: narrow range (4 levels) and very limited choice (2 levels); option 4: very narrow range (2 levels) and very limited choice (2 levels)

would actually be beneficial. There are many different options of how such a system could be designed. Figure 1 provides some examples of the different options available. It shows that design options can differ with regard to the two dimensions: number of LOAs and range of LOAs. For example, design option 1 is characterised by wide choice and a broad range whereas option 4 offers little choice and a narrow range. The two dimensions are also quantifiable with regard to the number of LOAs to choose from and the range of LOAs being covered. Using terms such as 'limited-choice automation' or 'broad-range automation' may be helpful to pinpoint the essence of the design options available in adaptable automation (Sauer and Chavaillaz 2017). Clearly, these two dimensions are not independent from each other since it is impossible to have 'narrow-range automation' and 'wide-choice automation' at the same time. The size of the range limits the number of LOAs that can be offered to the operator.

The use of certain design options for adaptable automation may have consequences for information processing cost and mode errors. The cost of information processing is to be considered in system design (Wickens and Hollands 2000). If there are more LOAs available to the operator, this may incur extra information processing costs to the operator because there are more options to choose from. This may correspond to the principles from Hick's law for determining choice reaction time (Hick 1952).

Automation-related mode errors may also play an important role. Mode errors (Sarter and Woods 1995) refer to an erroneous action that operator has taken because the system is now in a different mode than the operator had assumed (though the action would have been highly appropriate in the other mode). Different modes may be equivalent to different LOAs. A mode error may be less likely to occur if the range of LOA is wide than if it is small. This is because if the range is wide, modes are more easily distinguishable. Similarly, a mode error may be less likely to occur if there is limited choice than if there is wide choice. This is because in 'limited choice automation' fewer modes to be considered by the operator, which reduces the risk of mixing up modes or LOA.

Clearly, information processing costs and the possibility of mode errors being committed should not be the only criteria that drive the design of adaptable automation. There are other criteria that are also important to consider (e.g. performance of human–machine system) when deciding on the final system design.

For the design of adaptable automation, theoretical considerations should also be taken into account. We believe that the concept of wide-choice adaptable automation is well supported by several theories of work and job design. First, it relates well to the demand-control model of Karasek and Theorell (1990). It proposes that high levels of control (or decision latitude) provide benefits to the human operator when being faced with demanding working conditions. Such decision latitude is clearly to be found in adaptable automation (and in particular in wide-choice automation) while it is rather limited in static and adaptive automation. Second, it relates well to a concept from the German-language literature on work design, which may be termed 'person-tailored job design' ('differentielle Arbeitsgestaltung'; Ulich 1978). It proposes that workplaces should be made adaptable to individual needs and requirements. Adaptable automation clearly generally matches the underlying idea of person-tailored job design whereas adaptive automation does so to a much lesser extent and static automation does not do so at all.

These considerations suggest that the implications of theories of work design are at odds with the deliberations based on information processing cost and mode errors. While the former suggests advantages for wide-choice adaptable automation over small-choice automation (and indeed adaptive and static automation), the opposite prediction would be made on the basis of the deliberations associated with mode errors and information processing costs. Having these conflicting predictions suggests a clear need for some empirical examination of this question.

### Examining the utility of adaptable automation

Research on flexible automation generally used automation designs characterised by very limited choice (e.g. Riley 1996; Vries, Midden, and Bouwhuis 2003). Such 'very-limited-choice' adaptable automation refers to automation that offers two levels to choose from, which includes a manual control option. In the present framework, binary adaptable automation may be considered a particular example of very limited choice automation (i.e. LOA1 and one other LOA). Due to this focus on binary adaptable automation in research there is little knowledge of how operators manage automation when being able to choose between more than two LOA. In particular, the use of 'wide-choice' automation in research may be promising since it allows us to examine which of the up to 10 LOAs would actually be used by operators.

The examination of the utility of adaptable automation should not be limited to variables of automation management but include other measures as well. The following four groups of variables were identified as relevant: automation management, performance, automation-related errors and subjective evaluation. They all provide important data to evaluate the utility of automation and each groups contains several measures (see Table 2).

Automation management behaviour may provide important information about which elements of adaptable automation are particularly well used. This includes the automation levels chosen by operators (e.g. to see whether they actually make use of the LOA offered by the system) but also refers to the frequency with which operators change automation levels to adjust the system according to changing operational requirements. This category may also include the measurement of complacency (i.e. the extent to which automation verification behaviour is not sufficiently shown by operators, based on a normative model of optimal non-complacent behaviour; Bahner, Hüper, and Manzey 2008). Information

**Table 2.** Critical variables in research on adaptable automation (examples are based on industrial process control as a prominent application area for adaptable automation).

| Superordinate category | Measure | Description and examples |
|---|---|---|
| Automation management behaviour | Use of automation (reliance) | Refers to the levels of automation selected (e.g. manual control or full automation) and to the percentage of time spent on preferred automation level |
| | Frequency of change | Frequency with which levels of automation have been changed |
| | Magnitude of change | Size of change made from one automation level to another (e.g. 1-level or 5-level change) |
| | Complacency | It is expressed as a percentage by relating the number of diagnostic checks completed to the number of checks prescribed to identify the fault. |
| Performance | Primary task performance | For example, time needed to re-stabilise system after departure from stable system state or time needed to identify the cause of a system disturbance |
| | Secondary task performance | For example, regular logging of system data (prospective memory task) or responding to system warnings (simple reaction time task) |
| Automation-related errors | Error of omission | Operators heeds advice from the automation by not making a response (reliance, Meyer 2001) |
| | Error of commission | Operators heed advice from the automation by taking the suggested action (compliance, Meyer 2001) |
| | Mode error | Operators mistake one automation level for another |
| Subjective evaluation | Trust | For example, the Checklist of Trust between People and Automation (CTPA; Jian, Bisantz, and Drury 2000) may be employed |
| | Self-confidence | A measure of operator self-confidence in task completion may be adapted from Lee and Moray (1994) |
| | Workload | For example, the NASA-TLX (Hart and Staveland 1988) may be used to capture perceived taskload |
| | Automation state awareness | Measures of situation awareness (e.g. Endsley 1995) may be adapted to capture awareness of automation state |

sampling and control behaviour can be used as an indicator of non-optimal automation management, providing further indications of an impending risk of performance decrements (resulting from such inadequate automation management). Primary task performance is important to evaluate overall effectiveness of the human–machine system while secondary task performance may provide early indications of excessive workload or impending decrements of primary task performance (Hockey 1997). Automation-related errors are somewhat related to performance but they may merit a separate section because of their high relevance in automation research (e.g. errors of omission and commission). There is a strong tradition of error research in the design of technical systems (e.g. Reason 1990). Qualitative error analysis can be helpful for understanding the flaws in system design and the negative behavioural consequences. It helps identify erroneous thinking on the part of the operator (e.g. believing that the automation was in a different mode), which results in observable behavioural consequences (e.g. taking the wrong action). Finally, subjective measures pertain to important operator attitudes that may substantially influence operator behaviour. There are models that describe such relationships (e.g. Wickens et al. 2004) such as the link between operator attitudes (e.g. trust), system variables (e.g. reliability) and operator behaviour (e.g. complacency).

This taxonomy of measures is also expected to apply to automation design other than adaptable automation (e.g. static and adaptive automation). Although the descriptions and examples were taken from the process control environment, many of them would also apply to other domains (e.g. aviation, air traffic control, driving).

## Present work

This article has examined the utility of wide-choice adaptable automation, based on five published experiments that were carried out as part of a research programme investigating automation design issues. The rationale behind the present analysis was to focus on data that were collected in experimental conditions modelling adaptable automation rather than making a comparative analysis between adaptable automation and other forms of automation (e.g. static or adaptive automation). This represents a focus which is different from the one used in each single study. An overview of the studies is provided in Table 3. This overview shows that there were many issues examined, which centred on the design of static, adaptive and adaptable automation.

The present work examined three main research questions. First, the use of adaptable automation by individual operators was examined to identify any possible preferences for certain automation levels. Second, we aimed to examine the propensity of operators to change LOA, including the magnitude of any such changes. The first analysis of operator preferences based on a small sample suggested great differences between operators (Chavaillaz and Sauer, forthcoming) so that these findings are followed up in the present article using a much larger sample. Third, a correlation analysis of all the relevant variables measured in automation research was conducted, based on the aggregated data from all studies. This kind of analysis allowed us to use a large sample to follow up some interesting findings that emerged from another study based on a small sample (Sauer and Chavaillaz 2017).

This work was able to make use of a simulation of a highly automated work environment in the domain of complex process control in which participants had to identify system faults. When a system fault occurred, they had to diagnose it and stabilise the system (a detailed description may be found below). The simulation was able to model different automation designs ranging from static automation through adaptable automation to different forms of adaptive automation (e.g. performance and event-based). The simulation also modelled six automation levels, based on the model of Sheridan and Verplank (1978). At LOA1, the system provided no support at all (i.e. participants needed to diagnose the fault and stabilise the system using manual control) whereas at LOA2, the system signalled the presence of a fault but did not provide further support. At LOA3, the automatic system carried out the fault diagnosis but participants needed to stabilise the system and repair the fault. At LOA4, the system carried out the fault diagnosis and also proposed

**Table 3.** Overview of experimental work.

| Study | *N* | Main goals of study | References |
|---|---|---|---|
| 1 | 60 (20) | Evaluation of different forms of adaptable automation (forced choice, prompted choice) are evaluated under noise and no-stress conditions | Sauer, Kao, Wastell, and Nickel (2011) |
| 2 | 36 (10) | Evaluation of adaptable and adaptive automation (performance-based and event-based) under noise and no-stress conditions | Sauer, Kao, and Wastell (2012) |
| 3 | 39 (39) | Evaluation of influence of system reliability in adaptable automation | Chavaillaz, Wastell, and Sauer (2016) |
| 4 | 40 (40) | Evaluation of training to prepare operators for different levels of system reliability | Chavaillaz and Sauer (Forthcoming) |
| 5 | 45 (45) | Evaluation of training to prepare operators for different types of automation failure | Sauer, Wastell, and Chavaillaz (2016a) |

Note: Please note that sample size in parenthesis refers to the number of participants that were exposed to an experimental condition using adaptable automation. Only these subsamples were used for data analyses in the present article.

a procedure to stabilise the system. At LOA5, both fault diagnosis and system recovery were automated but needed to be activated by the operator. At LOA6, fault diagnosis and system recovery were automatically carried out without any operator required (though the operator could veto the implementation of the automatic procedure).

In order to address the research questions, the data-sets from all five studies were aggregated. The statistical analyses were carried out on the aggregated data-set. Since the statistical tests differed between dependent variables, we will describe them in Results section. As only part of the data-set was available for experiment 1, some of the analyses were carried out on a sample of $N = 134$.

The literature review revealed little empirical work on adaptable automation upon which to base any hypotheses. This stresses the explorative nature of the present work. Despite this explorative approach, we formulated some predictions based on the following deliberations. First, we assumed that three LOAs (i.e. 1, 5 and 6) will be more frequently used than others because each of them provides a specific benefit for certain situations. LOA1 provides an opportunity for practising manual control skills to avoid automation-induced skill decrements. LOA5 provides very high level of support but still affords complete control to the operator. While LOA6 provides the same level of support, the automatic system will implement its suggested response within 60 s unless vetoed by the operator. This may be useful if the operator feels completely overloaded and does not have sufficient cognitive resources to take such a decision. We assumed that LOA5 is more frequently used than LOA1 and LOA6 since the last two are suitable for very specific circumstances, which are not expected to be of a very frequent occurrence (i.e. need for practising skills and suffering from complete overload). Second, given that we assumed that these three LOAs are preferred, we assumed that LOA changes between these three mainly occur, that is, large changes (e.g. from LOA1 to LOA5 or from LOA6 to LOA1) as well as very small changes (i.e. changing between neighbouring LOA5 and LOA6) are expected to be more frequent than medium-sized changes (e.g. from LOA2 to LOA4). Third, due to the powerful support that automation can provide, we predicted a significant positive relationship between LOA and performance (i.e. performance improves with increasing LOA).

## Simulation environment and methodological approach

### *Development and general description of simulation environment*

The simulation environment AutoCAMS (see Figure 2) has been developed over a considerable number of years, with several research groups having contributed to its development (e.g. Hockey, Wastell, and Sauer 1998; Lorenz et al. 2002; Bahner, Hüper, and Manzey 2008; Chavaillaz, Wastell, and Sauer 2016a). A major advantage of AutoCAMS is that it allows us to model the first six levels proposed by the taxonomy of Sheridan and Verplank (1978). Furthermore, it is possible to model static, adaptable and adaptive automation designs. Due to its many functions, AutoCAMS was already used in a wide range of research areas, such as training (e.g. Kluge, Grauel, and Burkolter 2013), visual attention allocation (Wickens et al. 2015) or distributed team performance (Gonzalez et al. 2015).

Four different tasks are carried out by the operator, which are embedded in a simulated life support system in a spacecraft. The tasks are system control and recovery, fault

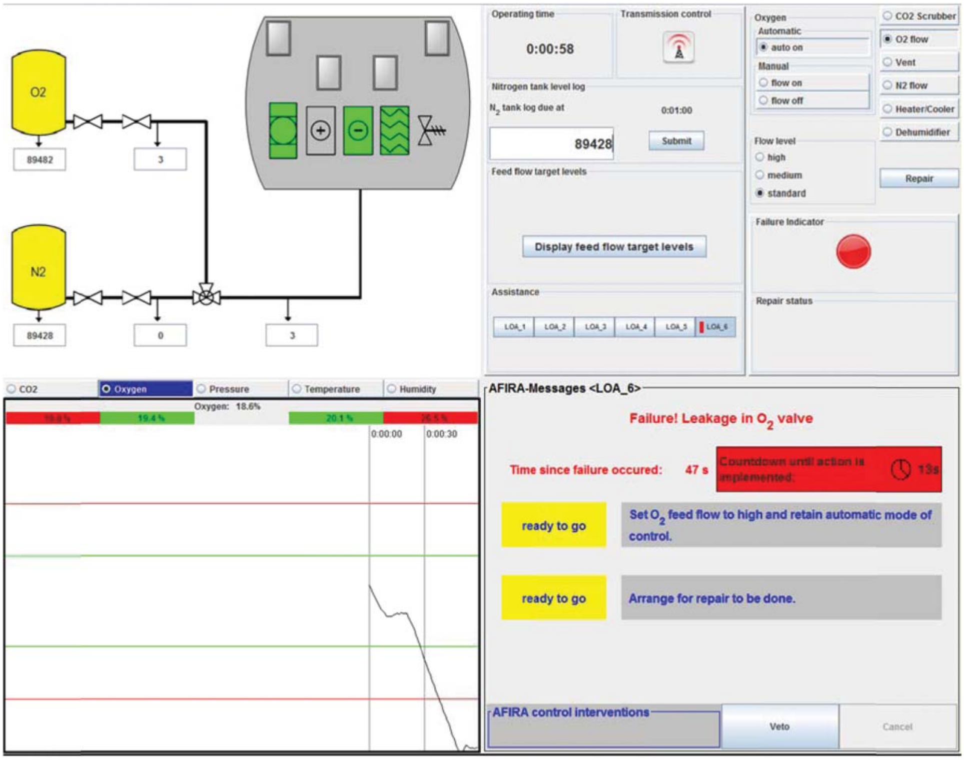


**Figure 2.** Main interface of the simulation environment AutoCAMS (Automated Cabin Air Management System).

diagnosis and repair, signal detection and data logging. The first two are classified as primary tasks, the last two as secondary tasks. System control and recovery is to maintain the key parameters of the life support system in a safe state and to intervene if the stable state is disturbed by a system fault. Fault diagnosis and repair requires from the operator to identify the cause of a system fault and successfully carry out the repair of the fault. The detection of system alarms is essentially a reaction time task and refers to the monitoring of alarms (i.e. if a warning signal appears on screen, the operator needs to click upon it as soon as possible). Data logging is essentially a prospective memory task, which requires the operator to record the nitrogen tank levels at fixed intervals.

## *Description of adaptable support system AFIRA*

The adaptable support system AFIRA (automatic fault identification and recovery agent) has three principal functions: alarm, fault diagnosis and system recovery. AFIRA can signal the operator that there is a fault in the system, which requires some attention (alarm function). Furthermore, AFIRA can provide support to the operator with regard to diagnosing and repairing system faults (diagnostic function). Finally, AFIRA can help the operator stabilise the system following a disturbance caused by a system fault (system recovery function).

The adaptable support system AFIRA currently offers up to six LOAs, which matches the levels 1–6 described in the automation taxonomy of Sheridan and Verplank (1978).

**Table 4.** Description of six automation levels of AFIRA support system (based on the 10-level model of Sheridan and Verplank [1978]) and their relationship to the three main function of AFIRA.

| Level of automation | Description of degree of assistance provided by support system | Alarm function | Diagnostic function | System recovery function |
|---|---|---|---|---|
| 1 | No assistance is provided by the system. | Not available | Not available | Not available |
| 2 | The system alerts the operator if a fault occurs. | Available | Not available | Not available |
| 3 | The system alerts the operator if a fault occurs and makes a fault diagnosis. | Available | Partly available (makes suggestions but cannot implement them) | Not available |
| 4 | The system alerts the operator if a fault occurs, makes a fault diagnosis and suggests a course of action to remedy the fault. | Available | Partly available (makes suggestions but cannot implement them) | Partly available (makes suggestions but cannot implement them) |
| 5 | The system alerts the operator if a fault occurs, makes a fault diagnosis and suggests a course of action to remedy the fault. The system repairs the fault and carries out the remedial action if the operator accepts it. | Available | Fully available (makes suggestions and implements them) | Fully available (makes suggestions and implements them) |
| 6 | The system alerts the operator if a fault occurs, makes a fault diagnosis and suggests a course of action to remedy the fault. The system repairs the fault and carries out the remedial action unless vetoed by the operator within 60 s. | Available | Fully available (makes suggestions and implements them) | Fully available (makes suggestions and implements them) |

The different levels are described in Table 4. The operator was able to switch between all LOAs available. AutoCAMS allows the measurement of virtually all objective variables in automation research that are listed in Table 2.

## *Training*

The description of AutoCAMS has already indicated that it is a simulation environment of considerable complexity. Therefore, extensive operator practice is needed which requires between 2.5 and 3 hours of training in most cases. This includes the acquisition of several types of knowledge for successful system management (four basic tasks; see above). While the exact content of the training session needs to be tailored to the research question addressed, it may include the following basic modules. (a) Basic technical training: it is based on the principles of part-task training and involves theoretical instructions and hands-on practice on each of the four tasks to be completed (e.g. acknowledgement of system alarms). (b) Advanced technical training: it is based on the principles of whole-task training and integrates the four different tasks into a coherent structure. (c) Automation training: the principles of adaptable automation are explained to the trainee, which is followed by some practising of fault scenarios with all six LOA. (d) Fault management training: while basic and advanced technical training is carried out in normal operational conditions (i.e. fault-free), fault management training aims to instruct trainees about how to operate the system in the presence of system faults. (e) Specific non-technical training: for certain research questions, additional non-technical training may be needed (e.g. team management training, communication training). (f) Mission training: as part of the instruction, the trainee may be asked to adopt a certain role in the experiment (e.g. team leader) or may be given behavioural guidance (e.g. to be supportive to the teammate).

## Results

In order to obtain a better understanding of how adaptable automation should be designed, there is a need to collect behavioural data about how the automatic system is managed by the human operator. This refers to the two measures of automation management strategies (see Table 2): automation levels chosen by operators and the frequency with which operators change automation levels. These measures allow us to examine whether operators actually make use of the different LOAs offered by the system. This could enable us to give recommendations of which LOA should actually be offered by the system.

Please note that the simulation environment AutoCAMS did not offer LOA6 in all experiments. While the majority of participants (i.e. 85 out of 154) could choose between six LOAs (i.e. in experiments 4 and 5), experiments 1–3 employed LOA1–5. This implies that the usage frequency of LOA6 may be slightly underestimated in the subsequent analyses, but this will be taken into account in the discussion of the findings.

### *Automation management: LOA usage*

Analysing the time each LOA was used by operators revealed a rather unequal use of the six LOAs on offer (see Table 5). The data showed that intermediate levels (i.e. LOA3–5) were much more frequently used than extreme levels. In particular, LOA6 (allowing the operator some limited time to veto the decision of the automation) showed a very low score, whereas LOA5 (involving powerful automatic support but leaving the decision of whether and when to initiate action implementation to the operator) was used for nearly a third of the time, representing the most frequently used LOA. A similar pattern emerged when identifying the preferred LOA of each operator. The results showed considerable differences in operator preferences (see Table 5). More than a third of operators preferred LOA5 whereas not even 2% showed a preference for LOA6.

Since the previous analysis suggested that most operators had a clear preference for a certain LOA, we wished to find out how pronounced this preference was. The analysis showed that for most operators the preference was very pronounced indeed (see Figure 3). It showed that about 55% of operators spent more than 90% of their time on their preferred LOA. Only a small number of operators did not have a pronounced preference for

**Table 5.** Usage of automation levels by operators ($N = 134$).

| | LOA1 | LOA2 | LOA3 | LOA4 | LOA5 | LOA6 |
|---|---|---|---|---|---|---|
| LOA use by operators (% of time) | 7.8 | 9.4 | 24.9 | 23.2 | 32.5 | 2.2 |
| Preferred LOA of operators (%) | 7.4 | 9.6 | 24.3 | 23.5 | 33.8 | 1.5 |

LOA, level of automation.

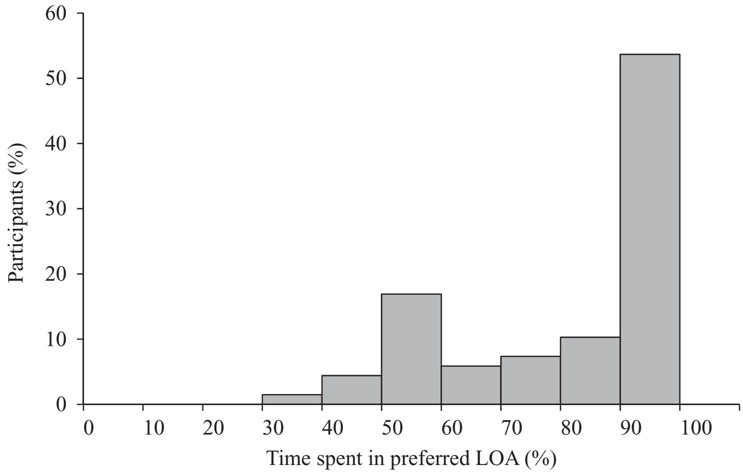


**Figure 3.** Percentage of operators as a function of the percentage of time they spent in their preferred LOA ($N$ = 134)

one of the LOAs, that is, about 95% of operators spent more than 50% of their time on their favourite LOA.

### *Automation management: frequency and magnitude of LOA change*

Since a potential advantage of adaptable automation is that operators can change LOA at any time according to changing operational requirements (e.g. onset of fatigue, need for more task involvement), we analysed the data with regard to whether such adaptations of LOA actually took place. The data in Table 6 show that out of a total number of $N$ = 1543 faults analysed, in more than 70% of cases no change of LOA was initiated by the operator. The analysis also revealed that large changes of LOA were much less common than small adjustments of automation levels (see Table 6). Small adjustments (e.g. changing LOA by one level) were made in 14.5% of cases, whereas larger changes of four or five levels were only made in 2.5% or 1.0% of cases, respectively.

When examining participants individually with regard to their most frequently initiated LOA change, more than two-thirds of them typically made one-level changes (see Table 6). Conversely, operators that made mainly large or even very large changes (i.e. four or five levels) were very small in numbers (i.e. less than 1% in each group). We also categorised the sample into four groups according to the frequency with which they switched between automation levels. About a quarter of operators (23.9%) never switched between automation levels. About 4 out of 10 operators (41.8%) showed occasional switching behaviour (i.e. not exceeding 30% of faults). A smaller proportion of operators

**Table 6.** Magnitude of automation level changes ($N_{faults}$ = 1543, $N_{participants}$ = 134).

| | No change | 1-level change | 2-level change | 3-level change | 4-level change | 5-level change |
|---|---|---|---|---|---|---|
| Faults (%) | 70.8 | 14.5 | 7.4 | 3.8 | 2.5 | 1.0 |
| Participants (%) | 23.9 | 67.2 | 5.2 | 2.2 | 0.7 | 0.7 |

**Table 7.** Correlations between primary and secondary tasks performance, automation management behaviour and subjective evaluation ($N = 154$).

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Automation management behaviour | | | | | | | | | |
| 1. Mean LOA chosen (1–6) | | | | | | | | | |
| 2. LOA change frequency (no/min) | −.15 | | | | | | | | |
| Primary tasks | | | | | | | | | |
| 3. Diagnostic error (%) | −.27*** | .33*** | | | | | | | |
| 4. Diagnostic speed (s) | −.45*** | −.04 | .42*** | | | | | | |
| 5. Unstable system state (%) | .02 | .30*** | −.02 | −.38*** | | | | | |
| Secondary tasks | | | | | | | | | |
| 6. Prospective memory failure (%)[a] | −.18* | .06 | -.16 | .21* | .13 | | | | |
| 7. Probe detection time (s) | −.34*** | −.11 | .21** | .72*** | −.22** | .46*** | | | |
| Subjective evaluation | | | | | | | | | |
| 8. Trust | .25** | −.04 | −.02 | −.30*** | .12 | −.21* | −.25** | | |
| 9. Self-confidence† | −.18* | −.04 | .10 | −.17 | −.06 | .00 | −.11 | .14 | |
| 10. Workload | −.07 | −.09 | −.09 | .24** | −.08 | .22* | .24** | −.16 | −.11 |

*$p < .05$, **$p < .01$; ***$p < .001$.
[a]$N = 134$.

(19.4%) may be described as moderate switchers (i.e. between 30% and 60% of faults) whereas an even smaller group (14.9%) may be considered frequent switchers (i.e. between 60% and 100% of faults).

### *Associations between critical variables in adaptable automation*

Pearson product–moment correlation coefficients were computed for the following variables, which may be classified into different categories. (a) Measures of primary task performance were diagnostic speed (s), diagnostic errors (%) and unstable system state (%). Measures of secondary task performance were prospective memory failures (%) and probe detection time (s). Measures of behavioural preferences were LOA change frequency (no/min) and mean LOA chosen (1–6). Measures of subjective evaluation were trust, self-confidence and workload. The correlation coefficients for some variables listed in Table 2 were not computed because they were measured in too small numbers in the respective studies (e.g. complacency, automation bias). The results of the correlation analysis, based on $N = 154$, are presented in Table 7.

Of primary interest was the relationship between automation management behaviour and the variables measuring performance and subjective state. Automation management behaviour (mean LOA and frequency of LOA changes) was significantly related to most performance measures. Choosing high automation levels was associated with better performance for diagnostic speed, diagnostic errors, prospective memory performance and probe detection performance. Frequency of LOA changes also showed a significant relationship to two measures of primary task performance. More LOA switching was associated with worse performance for diagnostic errors and system recovery (i.e. a more unstable system state). Interestingly, subjective workload did not decrease under high LOA. Finally, it emerged that higher LOAs were associated with increased operator trust and decreased self-confidence of operators in their own abilities.

The other dependent variables were also analysed to examine their associations with each other. Within primary task performance, diagnostic speed was associated with system control performance and diagnostic errors. While probe detection time was related to all measures of primary task performance, prospective memory was only related to diagnostic errors. Some significant relationships between subjective variables and objective measures were also found. Subjective workload ratings were also associated with both secondary tasks, which may be considered as objective measures of workload (i.e. higher workload was associated with more prospective memory failures and longer probe detection times).

## Discussion and implications

The present article aimed to examine the use of wide-choice adaptable automation and the relationship between automation management behaviour and other important variables of automation design such as performance and subjective operator state. The analysis of behavioural data in the use of adaptable automation revealed a number of interesting findings. Operators preferred intermediate to extreme LOAs. During the large majority of system faults, no change of LOA was initiated by operators but when they initiated one, it tended to be small in magnitude. The correlation analysis revealed a positive relationship between LOA used and performance (i.e. higher LOAs are beneficial) and a negative one between frequency of LOA change and performance (i.e. fewer LOA changes are beneficial).

The findings showed that the LOAs enjoyed different preference gradients but not in the way predicted. Operators had a strong preference for intermediate LOAs (i.e. 3, 4 and 5), whereas LOAs at the lower or upper end of the scale (i.e. 1, 2 and 6) were much less used. In particular, LOA6 (characterised by powerful automatic support combined with a veto function) did not meet the needs of the operators. When examining the favourite LOA of each operator, the preference gradients were even more pronounced for the most and least frequently used LOA. While more than a third of participants preferred LOA5, only 1.5% of participants (i.e. two participants from the aggregated sample) had selected LOA6 as their favourite LOA. There may be two reasons for the extremely low level of usage. First, the veto feature in LOA6 may have been disliked by operators because it removes some control. While need for control may generally represent a strong force (Hockey and Maule 1995), there may be circumstances where such a need loses its importance. For example, the advantage of LOA6 may be seen in not having to initiate the implementation of the decision if workload levels are excessive. In the present study, participants may not have experienced such excessive workload levels for the veto feature to pay off. Second, anecdotal evidence from the post-experimental debriefing sessions suggested that a time limit of 60 s for exercising the veto was generally perceived by participants as being too long. Therefore, LOA6 may have been considered an inefficient way of automation management due to the considerable time delay. This indicates a difficult trade-off in automation design since too short a time limit may leave operators with insufficient time to make the necessary checks. The problem may be solved by equipping the current LOA6 design with an additional button that would allow the operator to initiate the repair before the time limited for the veto had expired. This option would correspond to a design that combines LOA5 and LOA6 into one automation level. Alternatively, LOA7 could also be offered to the operator, that is, the AFIRA system implements its own recommendation immediately and informs the operator that it has done so. LOA7 would be efficient in that it acts quickly and it would not tax the cognitive resources of the operator. These deliberations show that taxonomies of automation levels (such as the one from Sheridan and Verplank [1978]) can be very helpful in designing complex automation modes. It may also help consider using combined levels such as merging the features of LOA5 and LOA6.

While high automation levels provided performance benefits for operators, frequent switching of LOA did not do so. The more frequently LOA was switched, the worse their performance on two primary tasks was found to be. However, the direction of causality is not clear. There are some arguments in favour of the assumption that frequent switching will result in poorer performance. First, it increases information processing cost because cognitive resources are committed to keeping track of the current LOA and to considering the advantages and disadvantages of changing into another LOA (e.g. Kaber and Riley 1999; Bailey et al. 2006). Second, frequent switching may increase the likelihood of a mode error because operators may more easily lose track of the automation level in which they were (Andre and Degani 1997). Third, each LOA has its particularities and operators may need some time to optimise their system management behaviour with regard to each LOA. If they frequently change LOA, they have less time available to optimise their system management behaviour. Conversely, it is also conceivable that frequent switching is a consequence of poor performance. Operators who have general difficulties in managing the system well (e.g. due to lower competence levels) may begin to intervene more frequently. Using such frequent control actions makes them look busy and may serve as a means to compensate for lack of effectiveness. This approach may correspond to 'thematic vagabonding' (Dörner 1983). Thematic vagabonding was conceptualised as the tendency of humans to change a plan as soon as a problem is faced (Strohschneider and Güss 1998).

In contrast to expectations, operators made small adjustments rather than large changes when switching LOA. The question of how many levels a change would typically involve is closely related to the preferred LOA of the operator. The prediction that operators would make large changes rather than small ones was based on the assumption that LOA1, LOA5 and LOA6 would be predominantly used by operators. This, in turn, should result in larger changes (e.g. from level 1 to 6 or from level 5 to 1). As the first prediction was not supported by the data, the second prediction lost its theoretical foundation. Operators made small adjustments mainly between LOA3, LOA4 and LOA5. Several factors may have contributed to this automation management behaviour. Operators may have considered these LOAs to be most supportive because the automation makes at least a suggestion of how to deal with a system fault (in terms of fault diagnosis but also system recovery). It was easier for the operator to verify whether this suggestion was correct or not instead of having to select the right fault out of a large set of possible fault states. In addition to this explanation of the findings, we will also speculate whether a further factor may have contributed to the results. It is conceivable that some operators made small adjustments because they had an incorrect mental representation of an automation failure. The accuracy of the mental model of a technical system has an influence on operator behaviour (de Kleer and Brown 1983; Norman 1983). Some operators might have assumed that if the automation failed at one level, it may still work at another level (e.g. LOA5 failed but LOA4 was working). This false mental representation may have led to them making minor adjustments rather than large changes because they preferred using a neighbouring automation level with similar features like the one they had just used.

Misled by this false assumption, operators may have checked several neighbouring LOA, hoping that one of them would be working. These questions could be followed up in future research.

The correlation analysis showed several interesting findings. It emerged that having chosen high LOA during task completion was positively related to primary task performance (i.e. diagnostic errors and system recovery). This may be due to the reduced cognitive load experienced by operators when automation levels are high. This may even apply in the presence of an automation failure (Sauer and Chavaillaz 2017). It seems to require less cognitive resources to verify whether the AFIRA recommendation was correct or not instead of having to select the correct system fault from a large number of possible system faults. For example, this may be equivalent to using a partly reliable in-car navigation system, which provides wrong directions on occasions. It may still be easier and more effective to check the recommendations of the system for correctness (e.g. by checking it against the information offered by road signs) rather than to not use the navigation system at all. The following strategy may have also been adopted with a view to conserving cognitive resources. Operators implemented the AFIRA recommendation without carrying out the necessary checks prior to implementation (which would correspond to complacent behaviour; Bahner, Hüper, and Manzey 2008). Instead, the required checks would only be carried out after the fault repair process had been initiated. The advantage of this approach is that system recovery is initiated by AFIRA immediately and does not have to be taken care of by the operator who can then focus on other tasks such as checking how accurate the automated fault diagnosis was. However, this approach comes at a cost because it is likely to increase the rate of diagnostic errors. Such system management strategies correspond to a risky approach, which has been described previously when task management strategies had to be adapted under periods of high task demands (Hockey 1997). This suggests that we need to take into account the multifunctional nature of many automatic systems to better understand why operators sometimes rely on automation that is partly unreliable. The multifunctional role of an automatic system is also demonstrated in Table 4, showing that a support system may have several functions, which not all may fail at the same time. If some elements fail (e.g. diagnostic function), the operator may still benefit from elements that have not failed (e.g. alarm function, see also Chavaillaz and Sauer [forthcoming]).

The correlation analysis also revealed that the higher LOA was associated with higher trust levels and lower self-confidence. Operators who trusted the system would be more inclined to assign the task to the system. This corresponds to the pattern predicted by the model from Wickens et al. (2004). Operators with less self-confidence in their own abilities may have selected high LOA because they presumed that the system would be better at completing the task. These patterns point to the complex relationship between trust and self-confidence discussed by Lee and Moray (1994). Their work showed that automation was generally used when trust had been larger than self-confidence and automation was generally not used when the reverse pattern had been found. Similar results were found by Vries, Midden, and Bouwhuis (2003) in the context of route planning. The relationship between trust and expertise showed a similar pattern since experienced users were found to be more confident in their abilities to manage the particular system manually they are trained on (Sanchez et al. 2014). In the present work, the two factors trust and self-confidence might have had a similar influence on the way automation is used.

The interplay of the two factors with automation use remains an interesting research question even though little work has addressed this issue since the publication of the Lee and Moray's study.

It may be worthwhile adopting a broader perspective, which does not only look at adaptable automation but also considers these questions in the context of adaptive automation, which represents another form of flexible automation. Previous work has also considered the question of LOA change in adaptive rather than adaptable automation (Sauer, Kao, and Wastell 2012; Sauer, Chavaillaz, and Wastell 2016b). While some issues raised in the present work are highly specific to the design of adaptable automation, at least three of them bear some resemblance to the pertinent questions raised in the design of adaptive automation (e.g. in performance-based adaptive automation where the system determines LOA on the basis of operator performance; Kaber and Endsley 2004). First, adaptive automation is also concerned with the magnitude of LOA change and its consequences for performance. For example, it needs to be determined whether automation should change by more than one level if there was a dramatic decrement in operator performance. Second, designers of adaptive automation need to define the range and number of LOA offered by the system. Each additional LOA requires extra design and programming efforts but it remains unclear whether this additional LOA would lead to performance improvements. Generally, there is little guidance in the research literature about which LOAs from the taxonomy should be offered in adaptable or adaptive automation. Third, designers need to define how sensitive adaptive automation should react to changes in operator performance (which would correspond to 'frequency of change'). For example, it needs to be determined whether automation levels should already change even if the decrement in operator performance was quite small. Clearly, these issues need to be researched in their respective automation mode (i.e. either adaptable or adaptive) but the findings from one automation mode may stimulate research in the other.

The findings have several implications for the design of adaptable automation. First, not all LOAs were used by operators to the same degree. This suggests that the number of levels could be somewhat reduced. If AutoCAMS modelled a real system, one may consider not implementing LOA2 and LOA6 in the real system because of their low appeal to operators. This conclusion is valid even if we take into account that LOA6 may have been slightly underestimated because it was unavailable to some operators due to the set-up in the experiment. However, a redesign may make LOA6 more appealing to operators (e.g. by combining it with elements of LOA5, by shortening the veto time or by replacing it with LOA7). The case is slightly different for LOA1 even though similar usage levels were observed. One may still wish to implement LOA1 with a view to being able to provide opportunities of practice under full manual control (e.g. as part of embedded training), given that the decline of skills appears to be problem in highly automated systems (e.g. Manzey, Reichenbach, and Onnasch 2012). Second, given that frequent switching is associated with poorer performance, the implication of this observation is less straightforward. This is because the direction of causality is not entirely clear, though there seem to be stronger arguments for frequent switching causing poor performance. One may, therefore, argue that those forms of adaptable adaptation should be avoided that encourage users to adapt their LOA. For example, one should not provide prompts to remind and encourage operators that they should change LOA.

The implications from the present work may also guide the design of systems in industry. There are already examples where adaptable automation has been successfully implemented in real systems. For instance, a parking assist system that allows the driver of a car to use video support during the parking manoeuvre or to delegate the completion of the parking manoeuvre to the machine. It is clearly advisable to conduct field tests to identify the LOA preference of operators for a specific system before adaptable automation is taken implemented in an industrial system. The finding of the present article may help guide industrial engineers in this work. For example, in the evaluation they could focus on those LOAs first that were preferred by operators in the present work.

Overall, the data provided some support for the utility of adaptable automation. The primary advantage is that it caters well for the diversity of operators, who differ in their preferences for automation levels. Future research could also include the variable 'magnitude of LOA change', which has not been previously used in automation research. More elaborate post-experimental interviews may be helpful to gain a better understanding of the reasons why operators chose certain LOA and switched (or did not) between them. For this purpose, the thinking-aloud method (e.g. Nielsen 1993) may be used. In this method, operator behaviour is recorded on video and then watched by the operator and the experimenter after task completion so that operators can explain the thinking behind their actions and decisions. Lastly, research using wide-choice automation is also needed in other domains (e.g. aviation, vehicle driving) to determine whether research findings are transferable between domains.

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## References

Andre, A., and A. Degani. 1997. "Do You Know What Mode You're in? An Analysis of Mode Error in Everyday Things." In *Human–Automation Interaction: Research and Practice*, edited by Mouloua Mustapha Jefferson M. Koonce, 19–28. Mahwah, NJ: Lawrence Erlbaum Associates Publishers.

Bahner, J. E., A.-D. Hüper, and D. Manzey. 2008. "Misuse of Automated Decision Aids: Complacency, Automation Bias and the Impact of Training Experience." *International Journal of Human-Computer Studies* 66(9): 688–699. doi:10.1016/j.ijhcs.2008.06.001.

Bailey, N. R., M. W. Scerbo, F. G. Freeman, P. J. Mikulka, and L. A. Scott. 2006. "Comparison of a Brain-Based Adaptive System and a Manual Adaptable System for Invoking Automation." *Human Factors* 48(4): 693–709. doi:10.1518/001872006779166280.

Chavaillaz, A., and J. Sauer. Forthcoming. “Operator Adaptation to Changes in System Reliability Under Adaptable Automation.” *Ergonomics*.
Chavaillaz, A., D. Wastell, and J. Sauer. 2016. “System Reliability, Performance and Trust in Adaptable Automation.” *Applied Ergonomics* 52: 333–342.
de Kleer, J., and J. Brown. 1983. “Assumptions and Ambiguities in Mechanistic Mental Models.” In *Mental Models*, edited by D. Gentner A. L. Stevens, 155–190. Hillsdale, N.J.: Lawrence Erlbaum.
Dörner, D. 1983. “Heuristics and Cognition in Complex Systems.” In *Methods of Heuristics*, edited by R. Groner M. Groner W. F. Bischof, 89–108. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
Endsley, M. R. 1995. “Toward a Theory of Situation Awareness in Dynamic Systems.” *Human Factors* 37(1): 32–64. doi:10.1518/001872095779049543.
Endsley, M. R., and D. B. Kaber. 1999. “Level of Automation Effects on Performance, Situation Awareness and Workload in a Dynamic Control Task.” *Ergonomics* 42(3): 462–92. doi:10.1080/001401399185595.
Endsley, M. R., and E. O. Kiris. 1995. “The Out-of-the-Loop Performance Problem and Level of Control in Automation.” *Human Factors* 37(2): 381–394. doi:10.1518/001872095779064555.
Gonzalez, K., K. L. Mosier, J. Lam, and U. Fischer. 2015. “Characteristics Impacting Teamwork and Performance for Space Operations.” *Proceedings of the Human Factors and Ergonomics Society Annual Meetings* 59(1): 936–940. doi:10.1177/1541931215591272.
Hart, S., and L. Staveland. 1988. “Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research.” In *Human Mental Workload*, edited by Peter A. Hancock Najmedin Meshkati, 139–183. Vol. 52 of *Advances in Psychology*. Amsterdam: North-Holland.
Hick, W. E. 1952. “On the Rate of Gain of Information.” *Quarterly Journal of Experimental Psychology* 4(1): 11–26. doi:10.1080/17470215208416600.
Hockey, G. R. J. 1997. “Compensatory Control in the Regulation of Human Performance Under Stress and High Workload: a Cognitive–Energetical Framework.” *Biological Psychology* 45(1–3): 73–93. doi:10.1016/S0301-0511(96)05223-4.
Hockey, G. R. J., and A. J. Maule. 1995. “Unscheduled Manual Interventions in Automated Process Control.” *Ergonomics* 38(12): 2504–2524. doi:10.1080/00140139508925283.
Hockey, G. R. J., D. G. Wastell, and J. Sauer. 1998. “Effects of Sleep Deprivation and User Interface on Complex Performance: A Multilevel Analysis of Compensatory Control.” *Human Factors* 40 (2): 233–253. doi:10.1518/001872098779480479.
Jian, J.-Y., A. M. Bisantz, and C. G. Drury. 2000. “Foundations for an Empirically Determined Scale of Trust in Automated Systems.” *International Journal of Cognitive Ergonomics* 4(1): 53–71. doi:10.1207/S15327566IJCE0401_04.
Kaber, D. B., and M. R. Endsley. 2004. “The Effects of Level of Automation and Adaptive Automation on Human Performance, Situation Awareness and Workload in a Dynamic Control Task.” *Theoretical Issues Ergonomics Sciences* 5(2): 113–153. doi:10.1080/1463922021000054335.
Kaber, D. B., and J. M. Riley. 1999. “Adaptive Automation of a Dynamic Control Task Based on Secondary Task Workload Measurement.” *International Journal of Cognitive Ergonomics* 3(3): 169–187.
Karasek, R., and T. Theorell. 1990. *Healthy Work: Stress Productivity and the Reconstruction of Working Life*. 1st ed. New York: Basic Books.
Kluge, A., B. Grauel, and D. Burkolter. 2013. “Combining Principles of Cognitive Load Theory and Diagnostic Error Analysis for Designing Job Aids: Effects on Motivation and Diagnostic Performance in a Process Control Task.” *Applied Ergonomics* 44(2): 285–296. doi:10.1016/j.apergo.2012.08.001.
Lee, J. D., and N. Moray. 1994. “Trust, Self-confidence, and Operators' Adaptation to Automation.” *International Journal of Human–Computer Studies* 40(1): 153–184. doi:10.1006/ijhc.1994.1007.
Lorenz, B., F. Di Nocera, S. Rottger, and R. Parasuraman. 2002. “Automated Fault-Management in a Simulated Spaceflight Micro-world.” *Aviation, Space, and Environmental Medicine* 73(9): 886–897.
Manzey, D., J. Reichenbach, and L. Onnasch. 2012. “Human Performance Consequences of Automated Decision Aids: The Impact of Degree of Automation and System Experience.” *Journal of Cognitive Engineering Decision Making* 6(1): 57–87. doi:10.1177/1555343411433844.

Meyer, J. 2001. "Effects of Warning Validity and Proximity on Responses to Warnings." *Human Factors* 43(3): 563–572. doi:10.1518/001872001775870395.

Nielsen, J. 1993. *Usability Engineering*. Boston, MA: Academic Press.

Norman, D. A. 1983. "Some Observations on Mental Models." In Mental Models, D. Gentner A. L. Stevens, 7–14.Hillsdale, N.J.: Lawrence Erlbaum.

Onnasch, L., C. D. Wickens, H. Li, and D. Manzey. 2014. "Human Performance Consequences of Stages and Levels of Automation: An Integrated Meta-analysis." *Human Factors* 56(3): 476–488. doi:10.1177/0018720813501549.

Parasuraman, R., T. Sheridan, and C. Wickens. 2000. "A Model for Types and Levels of Human Interaction with Automation." *IEEE Transactions. System, Management, Cybernetics. A* 30(3): 286–297. doi:10.1109/3468.844354.

Reason, J. T. 1990. *Human Error*. Cambridge: Cambridge Univ. Press.

Riley, V. 1996. "Operator Reliance on Automation: Theory and Data." In *Automation and Human Performance: Theory and Applications*, edited by Raja Parasuraman Mustapha Mouloua, 19–35. Hillsdale, N.J: Lawrence Erlbaum Associates, Inc.

Sanchez, J., W. A. Rogers, A. D. Fisk, and E. Rovira. 2014. "Understanding Reliance on Automation: Effects of Error Type, Error Distribution, Age and Experience." *Theoretical Issues in Ergonomics Science* 15(2): 134–160. doi:10.1080/1463922X.2011.611269.

Sarter, N. B., and D. D. Woods. 1995. "How in the World Did We Ever Get into That Mode? Mode Error and Awareness in Supervisory Control." *Human Factors* 37(1): 5–19. doi:10.1518/001872095779049516.

Sauer, J., and A. Chavaillaz. 2017. "The Use of Adaptable Automation: Effects of Extended Skill Lay-off and Changes in System Reliability." *Applied Ergonomics* 58: 471–481.

Sauer, J., A. Chavaillaz, and D. Wastell. 2016a. "Experience of Automation Failures in Training: Effects on Trust, Automation Bias, Complacency, and Performance." *Ergonomics* 59: 767–780. doi:10.1080/00140139.2015.1094577.

Sauer, J., A. Chavaillaz, and D. Wastell. 2016b. "On the Effectiveness of Performance-Based Adaptive Automation, ." *Theoretical Issues in Ergonomics Science* 1–19. doi:10.1080/1463922X.2016.1207824.

Sauer, J., C.-S. Kao, and D. Wastell. 2012. "A Comparison of Adaptive and Adaptable Automation under Different Levels of Environmental Stress." *Ergonomics* 55(8): 840–853. doi:10.1080/00140139.2012.676673.

Sauer, J., C.-S. Kao, D. Wastell, and P. Nickel. 2011. "Explicit Control of Adaptive Automation Under Different Levels of Environmental Stress." *Ergonomics* 54(8): 755–766. doi:10.1080/00140139.2011.592606.

Scerbo, M. W. 2006. "Dynamic Function Allocation." In *International Encyclopedia of Ergonomics and Human Factors*, edited by Karwowski Waldemar, 2nd ed., 1080–1082. London: CRC/Taylor & Francis.

Scerbo, M. W., F. G. Freeman, and P. J. Mikulka. 2003. "A Brain-Based System for Adaptive Automation." *Theoretical Issues in Ergonomics Science* 4(1–2): 200–219. doi:10.1080/1463922021000020891.

Sheridan, T. B., and W. L. Verplank. 1978. *Human and Computer Control of Undersea Teleoperators*. Technical Report. Cambridge, MA: MIT Man–Machine Systems Laboratory.

Spector, P. E. 1986. "Perceived Control by Employees: A Meta-analysis of Studies Concerning Autonomy and Participation at Work." *Human Relations* 39(11): 1005–1016. doi:10.1177/001872678603901104.

Strohschneider, S., and D. Güss. 1998. "Planning and Problem Solving: Differences Between Brazilian and Berman Students." *Journal of Cross Cultural Psychology* 29(6): 695–716. doi:10.1177/0022022198296002.

Ulich, E. 1978. "Über das Prinzip der differentiellen Arbeitsgestaltung." *Industrielle Organisation* 47 (12): 566–568.

Vagia, M., A. A. Transeth, and S. A. Fjerdingen. 2016. "A Literature Review on the Levels of Automation During the Years. What Are the Different Taxonomies that Have Been Proposed? " *Applied Ergonomics* 53(A): 190–202.

Vries, P. de, C. Midden, and D. Bouwhuis. 2003. "The Effects of Errors on System Trust, Self-confidence, and the Allocation of Control in Route Planning." *International Journal of Human-Computer Studies* 58(6): 719–735. doi:10.1016/S1071-5819(03)00039-9.

Wickens, C. D., and J. G. Hollands. 2000. "Attention, Time-Sharing, and Workload." *Engineering Psychology of Human Performance*, 3 439–479.

Wickens, C. D., J. D. Lee, Y. Liu, and S. Gordon-Becker. 2004. *Introduction to Human Factors Engineering*. 2nd ed. Upper Saddle River, NJ: Pearson Education/Prentice Hall, cop.

Wickens, C. D., H. Li, A. Santamaria, A. Sebok, and N. B. Sarter. 2010. "Stages and Levels of Automation: An Integrated Meta-analysis." *Proceedings of Human Factors and Ergonomics Society Annual Meeting* 54(4): 389–393. doi:10.1177/154193121005400425.

Wickens, C. D., A. Vieanne, B. Clegg, A. Sebok, and J. Janes. 2015. "Visual Attention Allocation Between Robotic Arm and Environmental Process Control Validating the STOM Task Switching Model." *Proceedings of Human Factors and Ergonomics Society Annual Meeting* 59(1): 617–621.