Mitigating Negative Impacts of Monitoring high levels of Automation: the MINIMA Project

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***Abstract*—In this paper, we present the preliminary study conducted in the framework of the research project *Mitigating Negative Impacts of Monitoring high levels of Automation* (MINIMA). The main objectives of MINIMA are i) to develop vigilance and attention neuro-physiological indexes, and ii) to implement them in a system that can adapt its behavior and guide the operator's attention in order to mitigate negative impacts of the foreseen increasing automation on *Air Traffic Controller* (ATCo) performance in future *Air Traffic Control* (ATC) scenarios. The first step of research activities consists of better comprehension of *Out-Of-The-Loop* (OOTL) phenomena and of current methods to measure and compensate such effects. The innovation proposed by MINIMA stands in the exploitation of recent progress in non-intrusive physiological measures devices, such as eye-tracking or *ElectroEncephaloGraphy* (EEG), combined to gather a unique measure of the level of attention and vigilance of an ATCo. In order to set up a framework for the concept development phase a preliminary study has been conducted on a target attention and basic guidance concept. Our results have shown the validity of the attention guidance concept from a subjective point of view, and have demonstrated to be an adequate starting point for further evaluation through neuro-physiological measurements.**

Keywords—Air Traffic Controller; Terminal Manoeuvring Area; Automation; Vigilance; Attention; Adaptive Task and Support Activation; Attention Guidance; Electroencephalography

I. INTRODUCTION

In the last years, the *Air Traffic Control* domain is experiencing a trend towards high levels of automation, such as decision support systems or electronic flight strips. With advanced flight management systems enabling almost autonomous flights, the aircraft on-board automation goes on in the same manner. The relation of higher automation leading to better performance is used as a basic assumption for the following implications. The changes in the ATC environment also cause a shift of *Air Traffic Controllers*' (ATCo) tasks from active managing of aircrafts to monitoring [1]. In the future, ATCos' actions will only be necessary if an aircraft deviates from its scheduled plan. However, ATCos being less actively involved in the ATC task may be affected by the *Out-Of-The-Loop* phenomena including performance degradation during their work. Such a *new ATCo* may show a "diminished ability both to detect system errors, and subsequently to perform manual tasks in facing automation failures, compared with operators who normally perform the same tasks manually" [2].

The MINIMA research project will help to understand and mitigate OOTL phenomena of controllers in highly automated environments, especially in the *Terminal Maneuvering Areas* (TMA) [3]. *Work package* (WP) 1 will investigate the state-of-the-art concerning operational concepts of "monitoring tasks" in other domains, approaches to evaluate monitoring performance, and *Brain Computer Interfaces* (BCI) to measure vigilance/attention level. Furthermore, a concept for monitoring a highly automated TMA with *Adaptive Automation* (AA) based on vigilance and attention neuro-physiological measures will be developed considering the aforementioned state-of-the-art.

Neuro-physiological indexes to measure the current vigilance and attentional level of the controller will be implemented in WP 2. The vigilance and attention indexes will be integrated into the simulation environment required to test and asses such concepts. The simulation environment comprises a future air traffic scenario with a high degree of automation. Based on that, the distribution of tasks between the human agent and the automated system will be carefully selected and implemented according to the concept of WP 1. This should result in an increased task engagement of the controller and mitigate negative consequences of monitoring tasks (like *loss of situation awareness*). For this purpose, the WP will tune and use EEG (*ElectroEncephaloGraphy*) and other physiological measures, such as EOG (*ElectroOculoGraphy*) or HR (*Heart Rate*), to characterize the vigilance and attentional state of the user involved in "ad hoc" designed tasks to be performed in the simulated environment.

Afterwards, WP 3 will conduct a study to evaluate the MINIMA concept and to develop guidelines for further improvements. Results and suggestions will be disseminated (WP 4) to selected target audiences. To outline the scientific context, paragraph II presents the work related to monitoring tasks, evaluation of controller's performance, and approaches to overcome drawbacks. Paragraph III includes preliminary elements of our concept comprising measuring controllers' actual vigilance and attention, dynamic target attention, and attention guidance in case of OOTL avoidance through monitoring in highly automated environments. The results of the prototypal implemented dynamic target attention and guidance system evaluation are outlined and discussed in paragraph IV. Finally, paragraph V draws initial conclusions and identifies future work in the course of MINIMA project.

II. Related Concepts

Automation could be defined as the process of entirely or partially allocating the activities constituting a task usually performed by a human, a machine or a system. Empirical data on the relationship of people and technology have shown that traditional automation has several negative effects and safety consequences associated to stemming from the human OOTL performance problem [4]. The OOTL performance problem represents a key challenge for both systems designers and human factor society, and it remains difficult to grasp and treat it after decades of research [5],[6]. In the following section, we aim to review the current knowledge regarding this concept, with a specific focus on the origins of the performance decrements observed during these phenomena, its potential biomarkers, and the current solutions proposed to mitigate it.

A. Out-Of-Th- Loop phenomenon

Nowadays, it is clear that automation does not merely supplant human activity, but transforms the nature of human work. In particular, automation technology has created an increasing distance between human operator and loop of control, making the operator disconnected from the automation system. Such a removal leads to a reduced ability to intervene on the system control loops and assume manual control when needed. Importantly, the lack of operator involvement in supervisory modes and passive information processing contribute to critical human cognitive errors. As a major consequence, the OOTL phenomenon can cause a longer latency to determine what has failed (information processing), to decide if an intervention is necessary (decision making), and to perform corrective behavior [7]. Cognitive engineering literature has discussed widely about the origins of these takeover difficulties. Amongst other, the loss of operator Situation Awareness (SA) appears as a first concern to which many safety incidents have been attributed to. Nowadays, it is clear that a loss of situation awareness underlies a great deal of the OOTL performance problem. The literature has shown that OOTL phenomenon is characterized by both failure to detect [8][9], and failure to understand the problem and to find out the appropriate solutions [10][11][12]. Such types of SA problems have been hypothesized to occur through two major mechanisms: (1) changes in vigilance and complacency associated with monitoring, and (2) changes in the quality or form of feedback provided to the human operator [13][14][15][16]. In the MINIMA project, we will mainly focus on the vigilance decrement and complacency associated with monitoring. The later will be addressed with a target attention and initial attention guidance system.

An important behavioral aspect of the OOTL performance problem is reflected in an insufficient monitoring and checking of the automated functions, i.e., the automated system is checked less often than necessary (see for example [7]). Several authors have underlined that monitoring is a role for which humans are poorly suited [17][18] and problems in monitoring automated systems are evident in pilots' incidents reports (see for example [19]). Different evidences could explain such decrease in vigilance. Firstly, several studies showed that vigilance over hours cannot be achieved [20]. Indeed, basic research on vigilance indicates that the time on task will significantly decrease the discriminability of unpredictable and infrequent signals from a noisy background [21][22][23]. Moreover, there is some consensus for the existence of a decrease of human operator vigilance in case of interaction with highly automated system [24][25][26]. Together with this difficulty to maintain high level of vigilance in time, decrease in vigilance could result from an overreliance on automation, the so-called *complacency phenomenon* [27]. The National Aeronautics and Space Administration Aviation Safety Reporting System defines complacency as "self-satisfaction that may result in no-vigilance based on an unjustified assumption of satisfactory system state" [28]. Complacency can lead operators to rely unquestioningly on automation [29][30][31] and result in several form of human error, including decision biases, monitoring system failure [32].

B. Current solution to mitigate the OOTL problem

Several solutions for solving the OOTL problem have been proposed. These solutions can either target the system or the human operators in order to make them less prone to OOTL problems.

Human operator "adaptation": A first solution for OOTL problems targeting human operators is acting on their training. Human operator can be explicitly trained for situations in which OOTL problems can occur. For example, in a laboratory experiment using a process control simulation, Bahner and colleagues [33] showed that a preventive training in which participants were exposed to rare automation failures could significantly reduce complacency. Careful selection of the operators is presented as another solution targeting the human relates. Today, ATCos are carefully selected based on the key ability required by the working environments. Regarding the increase in automation, the ability to monitor automated systems and to switching immediately from monitoring to decision making will become an important competence in the selection of future ATCos [34]. If promising, such solution needs time to become effective and empirical evidence needs to be collected regarding its effectiveness.

System adaptation: Since OOTL problems are caused by changing the system and introducing higher levels of automation, it seems likely that it can also be solved by changing the systems. For example, *MABA-MABA*-like methods (Men Are Better At-Machines Are Better At) rest on the idea that you should exploit the strengths of both humans and machines differently. The basic premise is: give the machines the tasks that they are good at, and the humans the things that they are good at (see for example [8]). However, Dekker and Woods [15] argued that such methods are misleading as automation often has unexpected effects [5]. These include the OOTL problems discussed above. It is now clear that introducing automation does not simply transfer the execution of functions to the machine, but instead create completely new functions and transform human practice. They conclude that automation needs to support cooperation with human operators – in standard and unexpected situations. Also, Rieth and collaborators [35] argued for better design of *Human-Machine-Systems*. They showed that the visual salience of standard indicators “generally do not draw attention to the information needed to identify emerging problems” and suggested other formats by which better mapping the task-relevance of information to the visual salience of how it is displayed. A holist approach is to develop automation in such a way that it can be seen as a *partner*. Human operator and automation should form a team that works cooperatively together, in a highly adaptive way to achieve its objectives. They have to adapt to each other and to the context in order to guarantee fluent and cooperative task achievement. For example, Klein and colleagues [16] defined ten challenges to improve human machine cooperation (model the others’ intentions, be delectable, make their status and intentions obvious and be able to interpret the status and intention of others, be able to engage in goal negotiations and enable a collaborative approach, be able to participate in managing attention, and help controlling the costs of coordinated activity).

A technical solution for some of these challenges is the concept of adaptive systems. The concept of Adaptive Automation (AA) concentrates on the dynamic allocation of function between operators and systems. Particularly, the level of automation of such system is not fixed, but it is adapted during the activity according with the current needs of the operator [36]. Consequently, adaptive automation enables the level or modes of automation to be tied more closely to operator needs at any given moment [37] without requiring the human operator to explicitly state his/her needs or trigger the adaptations. Several evidences have proved the AA can improve operator’s performance and moderate workload in complex environment [38][39]. Besides the dynamic allocation of functions, other aspects of a system can be adapted during operations like, for example, the modality which is used to provide information, the amount of information that is presented to the operator or the lay-out of the information.

The MINIMA project aims to design such cooperative/adaptive system. However, the most critical challenge to implement AA concerns how changes among modes or levels of automation will be accomplished [36][37]. In other words, what should determine and trigger allocation of functions between the operator and the automation system. Vigilance and attentional decrement is a first concern in the degradation of the monitoring process involved in supervisory task. The MINIMA project proposes to focus on both such degradations to monitor the state of the human operator and drive the adaptive automation. In the following part, we assess the possibility to monitor attention and vigilance state of the human operator using neuro-physiological signals collected during the execution of the considered task.

C. Attention and Vigilance Measurement

Attention and vigilance monitoring has been proposed as a useful index to prevent some accident in attention-demanding and monotonous tasks [40][41]. Several approaches have been proposed [43][44], from the analysis of system parameter (see for example [45]) to the evaluation of the operator’s neuro-physiological signals [46][47]. We will here focus on the neuro-physiological measures. The use of neuro-physiological signal in adaptive automation implementation requires that such measures are capable to assess alertness and sustained attention. Several biopsychometrics have been shown to be sensitive to changes in vigilance suggesting them as potential candidates for AA such as *electroencephalography* (EEG), *near-infrared spectroscopy* (NIRS), *transcranial doppler sonography* (TCD), *oculometrics*, *electrocardiogram* (ECG) or *galvanic skin response* (GSR).

Electroencephalography (EEG): EEG has the potential to measure fast electrical signals from the surface of the scalp and is considered as one of the most reliable indicators of vigilance/attention [41]. A number of EEG markers have been specifically correlated with vigilance based on two different methods: *Power Spectral Density* (PSD) analysis and *evoked potentials (EP)* technique. The changes in the EEG density spectrum have been related to the vigilance state and a number of methods have been proposed to make accurate judgments of vigilance levels [48][49]. Overall, slow frequency activity (alpha and theta bands) increased with decrease in vigilance whereas increasing vigilance induces an increase in beta activity. In addition to examining global levels of arousal, it is possible to use EEG signal to characterize discrete cognitive processes, namely the *event related potential* (ERP) technique. Several ERP components have been showed to be modulated by attention, such that their amplitude increases to stimuli which are attended compared to stimuli which are not. For example, attention modulates components that have already been elicited by visual stimuli (P100 and N100), auditory stimuli (N100), infrequent stimuli (P300) or semantic stimuli (N400) (for a review [50]). Interestingly, several studies have demonstrated the suitability of EEG for real-world monitoring of mental states and for *brain computer interface* (BCI) applications [45][52][53][54], and EEG data has already been used to evaluate controller's mental workload or even training progress [55][56]. Automation in an en-route scenario was then adapted every 30 seconds taking into account the resulting workload classification index [57].

Near-infrared spectroscopy (NIRS): NIRS has been successfully used to investigate vigilance [58][59][60]. Particularly, previous research has shown that tissue oxygenation increases with the information processing demands of the task being performed [61][62]. NIRS has also been used in ecologically valid environments to investigate vigilance [63].

Transcranial Doppler sonography (TCD): TCD also offers the possibility of measuring changes in metabolic activity relating to change in vigilance [64]. Particularly, the vigilance decrement is paralleled by a temporal decline in blood flow velocity. As described in recent reviews [65][66], these studies provide support for a resource model of vigilance.

Oculometric changes: Various eye activity measures have been associated with change in vigilance and attentional processes. First, pupillometry (i.e., change in pupil size) is presented as an objective measure of attentional allocation [67]. Indeed, several studies show relationship between pupillary tonic response and the state of arousal or vigilance of the participants [68][69][70]. Particularly, as arousal increases, large increases in pupillary baseline are concomitantly observed. Second, blink duration and frequency also appear as related to vigilance state. Research has shown that changes in blink are the earliest reliable signs of drowsiness, preceding slow eye movement and EEG alpha frequency and amplitude changes [71]. For example, The PERcentage of eye CLOSure (PERCLOS) is related to hypovigilance [72]. Moreover, the spontaneous eye-blink rate (EBR) is also a well-validated indicator of visual attention; it is reduced during periods when attention is oriented toward significant external stimuli, and this reduction is proportional to the required attention [73][74].

Heart-Rate Variability (HRV): Heart rate variability (HRV) is used as a robust metrics for vigilance measurement [75][76][77][78]. HRV was significantly reduced during sustained attention.

Galvanic Skin Response (GSR): GSR is also frequently used as an indirect measure of attention, cognitive effort, or emotional arousal [79]. An increase in tonic e*lectrodermal activity* (EDA) indicates readiness for action and an increase of phasic EDA indicates that one's attention is directed toward a stimulus [80][81]. GSR is therefore expected to decrease during monotonous tasks [77] and could be used as an index of vigilance decrement [82][83].

III. THE MINIMA IDEA

In highly automated environments, operators like ATCos will experience phases of very low workload. Negative impacts of monitoring may rise from resulting OOTL phenomena. Therefore, we keep the human in the loop being aware of the traffic situation. To achieve such result, we first determine ATCo's current vigilance and attention level. Neuro-physiological measures will be aggregated into a single vigilance and attention level index. Such an index will be the input for adapting the simulation environment. If the value is below a certain threshold, the ATCo will be asked to accomplish more tasks. Some of those tasks might be artificial, while others result from a reasonable task distribution (functions allocation). Furthermore, assistance functionalities can be switched on. If the value is far above a certain threshold, adaptations can be switched off, as it is assumed that a high vigilance and attention level will avoid OOTL phenomena implicitly. Nowadays, visual or acoustic indicators for the controller are displayed on the radar screen without taking into account the whole ATC situation. This may lead to confusion resulting in focusing the attention on the wrong event or cascade effects of multiple warnings. Attention should be guided to the most important and time critical event. This can be based on the supervision of attention distribution. If the system recognizes that a controller is about to detect the event, a warning and attention guidance can be suppressed.

One strategy to mitigate negative impacts of monitoring high levels of automation is to help the controller in keeping his attention at the relevant display areas. Therefore, our concept includes the relation of the whole chain consisting of actual attention, dynamic target attention, and attention guidance of the controller regarding the radar display (see figure 1).

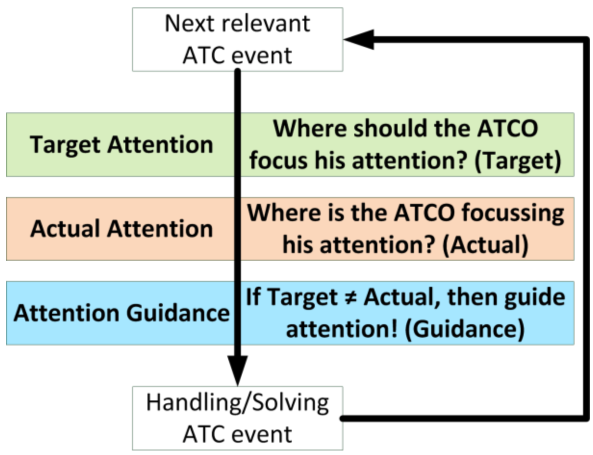

Figure 1. Basic air traffic controller attention cycle [84]

Firstly, it needs to evaluate which ATC event on the radar display is the most relevant for the controllers. Secondly, it has to detect which radar areas the controller actually focuses his attention on, e.g. via eye-tracking. Finally, the controllers' attention needs to be guided to the relevant radar display area if his attention is somewhere else.

As a first step of the development of a controller attention system, tasks and events are defined and weighted (together with ATC experts) by considering the importance and urgency of the ATC situation (see figure 2). The average score leads to the prioritization of events. The events are also categorized into red alerts, amber cautions, and white information similar to the Airbus' ECAM (*Electronic Centralized Aircraft Monitor*) system [85].

Air Traffic Control Event	Status Level	Import.	Urgency	Score	Priority
Minimum Separation Violation (Appr. angle 180°)	Alert	10,0	10,0	10,0	1
Below minimum safe height	Alert	10,0	10,0	10,0	2
Below radar vectoring altitude	Alert	10,0	10,0	10,0	3
Minimum Separation Violation (Appr. angle 90°)	Alert	10,0	10,0	10,0	4
Vertical deviation from glide slope (ILS)	Alert	10,0	9,5	9,8	5
Danger of restricted area entry (<2 minutes)	Alert	9,5	9,5	9,5	6
Minimum Separation Violation (Appr. angle 0°)	Alert	10,0	9,0	9,5	7
Emergency (transponder code 7700)	Alert	9,0	9,0	9,0	8
Flight route (cleared flight level) left (vertical)	Caution	9,0	8,0	8,5	9
Flight route (cleared route) left (lateral)	Caution	9,0	7,5	8,3	10
Lateral deviation from glide slope (ILS)	Caution	9,0	7,0	8,0	11
Upcoming conflict (3 minutes)	Caution	8,0	7,0	7,5	12
Initiate descent/climb	Information	6,5	5,0	5,8	13
Initiate heading change	Information	6,5	4,5	5,5	14
Reaching top of descent	Information	5,0	5,5	5,3	15
Unidentified flight object in airspace	Information	5,0	5,0	5,0	16
Descent deviating from trajectory	Information	5,0	4,0	4,5	17
Handover to next sector	Information	5,0	3,5	4,3	18
Active protection flight	Information	5,0	3,0	4,0	19
Climb deviating from trajectory	Information	5,5	2,5	4,0	20
Initiate speed change (approach)	Information	3,0	3,0	3,0	21
Medical flights	Information	3,0	2,5	2,8	22
Initiate turn to base	Information	3,0	2,0	2,5	23

Figure 2. ATC events classified with inportance and urgency [84]

Determining relevant ATC events can be done by an assistance system such as an arrival manager (AMAN). The AMAN *4-Dimensional Cooperative Arrival Manager* (4D-CARMA) for example can calculate four-dimensional trajectories for each aircraft. In a future highly automated scenario trajectories like these will be flown quite autonomously by the majority of aircraft. By analyzing radar data and controller inputs, potential deviations and thus conflicts can be computed. Those deviations can result in potential ATC events as shown in Figure 2. The "area" of the most relevant ATC events then is considered as the area of controller's target attention. Normally, this area is an aircraft, but it can also be a trajectory or a future conflict point. Actual attention can be determined via the eye-tracking technology. In fact, it is assumed that the ATCo's actual attention is in the same area as his gaze on the radar display. So, after a fixation of a certain dwell time on the radar screen the position and a small area around will be recognized as *actual attention area*. In addition, there is a time in seconds prior to the event during which ATCO's current attention is analyzed. This time is 0 for alerts and cautions as those events need to be displayed immediately. The timespan can be 60 or 120 seconds for information as the need for an immediate action is not given. The controller might have focused an event area earlier, but will act later. The attention analysis time avoids disturbance of the controller by too many displayed information. An event text is displayed if the controller paid no attention to the system generated suggestion. This time value is again 0 seconds for alerts and cautions. The first time an information is displayed can include a buffer of 15, 30, or 60 seconds. If the controller paid attention to an event, but did not solve or handle it after the first time the event text was displayed, the display text presentation will be repeated. The repetition time is 60 seconds for cautions and information. However, an active alert will only disappear if it is solved (see figure 3).

Together with this evaluation of attention focus, we aim to measure the actual level of vigilance by neuro-physiological signals, to identify vigilance decrement. EEG signals (particularly evolution in power spectrum density), change in pupil size and heart rate variability will be used to identify out-of-the-loop episodes.

The attention guidance can then be used to avoid performance problems as typical OOTL phenomenon. Attention guidance could be done via lighter ATC event area color related to the target attention. In addition, the background could be lowlighted darker. Such *attention guidance* concept is aimed at highlighting specific air traffic situations and will be the starting point for development of physiological measures for the vigilance and attention controller. In MINIMA, the authors also planned to define possible new task distribution strategies in order to implement an adaptive automation concept. In other words, the level of automation will be reduced when a decrement of vigilance or attention is detected by activating tasks that commit the ATCo to interact with the system and recall he/she back in the loop.

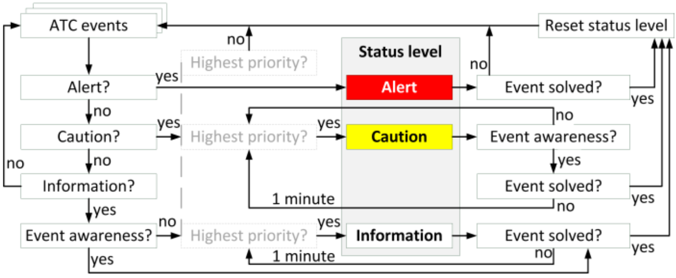

Figure 3. ATC event attention flow to determine working order and display presentation [84]

IV. PRELIMINARY STUDY

In order to set up a framework for the concept development phase a preliminary study has been conducted on a target attention and initial attention guidance concept. Such concept is based on the visualization of elements that should guide the attention of the user which is looking at a radar display to the most critical ATC event.

A. *Experimetnal Group*

A preliminary study to evaluate the controllers‘ target attention concept was conducted by enrolling 6 ATC experts (2 female; 4 male; one of them was an ATCO; average age of 31 years).

B. *Protocol Design*

Participants had to perform a passive ATC task including monitoring of an approach scenario. The ATC scenario lasted 12 minutes and comprised 11 aircrafts approaching Köln-Bonn airport (EDDK) and was displayed on DLR simulator [86]. Participants had to monitor the air traffic flow without giving any commands, and they were able to see each ATC event status level (alert, caution, information) at least once. Afterwards, they had to rate prioritization logic, symbology, situation awareness, dynamic target area of attention, attention guidance on the radar display, and other items presented on a ten item questionnaire. The survey included a *Likert scale* for each of the ten statements ranging from 0 (completely disagree) to 4 (completely agree) [87].

C. *Results and Conclusions*

The results of this preliminary study are shown in figure 4. All items were rated rather positive with many values of 3 and above on the scale. This demonstrated the basic feasibility of the implemented concept. The sum of all ten ratings (between 0 and 40 was possible) was normed to a scale between 0 and 100 similar to the System Usability Scale (SUS) [88]. However, the questionnaire statements were not equal but similar to the original SUS items. Nevertheless, it should be assumed that a score over 75 already indicates good usability. The arithmetic average of all 6 participants was 77.9 (SD=9.9) and lied over the mentioned threshold. Furthermore, symbology was rated as intuitive and attention guiding (Ø=3.3, SD=0.5). Most participants also found reasonable distinction between different status levels (Ø=3.3, SD=1.2). Information texts in aircraft radar labels were understandable (Ø=3.8, SD=0.4) and increased participants‘ situation awareness (Ø=3.7, SD=0.8). These texts also eased identification of highest priority event (Ø=3.2, SD=1.7).

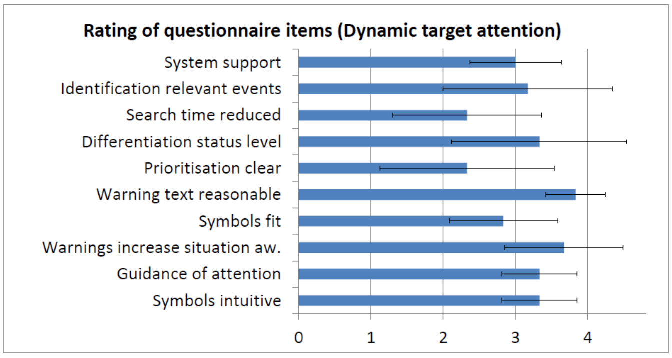

Figure 4. Ratings on questionnaire items regarding dynamic target attention (0: negative; 2: neutral; 4: positive) [84]

V. SUMMARY AND OUTLOOK

This study is an important first step for the MINIMA project. To develop a system that can adapt to the current needs of the operator and guide the operator’s attention, it is crucial that the system has an understanding of the particular situation. Specifically, it must understand where and when attention is necessary in order to guide it in a meaningful way. This paper presented a concept on how the system can identify where attention is necessary and how attention can be guided. The first results of the preliminary study indicate that the developed concept is usable. The next step will be to combine the presented concept with a real time attention measurement using an eye-tracking system to evaluate its benefits on the performance of operator working in environments with a high level of automation.

The presented concept covers one aspect of MINIMA: the controllers’ attention with target and actual attention as well as its guidance. However, MINIMA will also address vigilance. Thus MINIMA will work on solutions for identifying the vigilance of Air Traffic Controllers using EEG and other physiological measures, such as EOG or heartrate, develop a concept for an adaptive task environment and finally combine all these components into one system. This system will be able to react on the vigilance and attention state of the operator. Specifically, this system will change the function allocation and will be able to guide the operator’s attention.

We assume that such a system will be able to mitigate the negative impacts of higher level of automation and reduce the occurrence of the OOTL problem. It will allow increasing automation while keeping the operator involved. We expect that MINIMA will help to increase the performance of future ATC system without creating safety issues.

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