How Automation Effect Mental Workload of Novice Operators in Space Rendezvous and Docking

Xiaoping Du[1], Yijing Zhang[1,2(✉)], Bin Wu[1,3(✉)], Meng Wang[1], Jiayi Cai[1], and Weifen Huang[1,2]

[1] China Astronaut Research and Training Center, Beijing 100094, People's Republic of China
ldlzyj@163.com, wubinacc@sina.com
[2] National Key Laboratory of Human Factors Engineering, Beijing 100094, People's Republic of China
[3] State Key Laboratory of Space Medicine Fundamentals and Application, Beijing 100094, People's Republic of China

Abstract. The present study investigated the effect of automation on the mental workload of novice operators in manual rendezvous and docking (RVD). One within-subject experiment was designed and fifteen participants participated in the experiment. All participants were required to finish six RVD tasks of two automation levels: manual RVD and the automation-aided manual RVD. Workload of the participant during RVD tasks were assessed with subjective and physiological indicators. Subjective workload was measured by NASA Task Load Index (NASA-TLX). Physiological workload indicators included mean heart rate, the root mean square of successive differences (RMSSD), the low frequency (LFNU, 0.04 to 0.15 Hz) and high frequency (HFNU, 0.15 to 0.4 Hz) power spectrum component of heart rate variability (HRV, both in normalization form), the LF/HF ratio, and the total power (TP). The results showed that subjective workload rating were significantly lower in the automation-aided RVD as compared to that of manual RVD task. However cardiovascular measures showed different pattern. Mean heart rates, RMSSD and TP of participants did not change significantly with the change of automation level, LFNU was significantly higher, and HFNU was significantly lower in automation-aided RVD task as compared to that in manual RVD task. The results showed that despite a perceived workload reduction in automation-aided RVD, the objective measures of HRV reflected a workload increment. A possible reason is that novice operators were not familiar with automated system, thus it was difficult for them to understand and anticipate the intention and action of automation. The results inferred that application of automation to such complex and dynamic tasks for novice operators should be cautious; novice participants need more training to build deeper understanding of automation system.

Keywords: Automation · Workload · Heart rate variability · Rendezvous and docking

D. Harris (Ed.): EPCE 2015, LNAI 9174, pp. 317–326, 2015.
DOI: 10.1007/978-3-319-20373-7_30

1 Introduction

Rendezvous and docking (RVD) is a key technology in missions such as assembly of large units in orbit, re-supply of orbital platforms and stations, exchange of crew, and lunar/planetary mission [1]. In performing a manual RVD task, the operators (astronauts) need to control an active vehicle (the chaser, e.g. the space shuttle) into the vicinity of, and eventually into contact with, a passive vehicle (the target, e.g. the space station). Manual RVD is a difficult task, and may impose high workload on astronauts. Therefore, the Guidance, Navigation, and Control system was development to perform autonomous RVD, allowing to improve safety by reducing the risk of operational errors and to reduce physiological effort and workload of astronauts by providing support for such perceptual-cognitive demanding task. However, even the RVD operational task can be fully automated, RVD task requires a backup manual control capability so that astronaut can take over when automated system or critical subcomponent of the spacecraft fails. Thus, RVD are often performed by a way that astronaut performs translational maneuvers, attitude maneuvers are performed by GNC and astronauts are still required to be present inside spacecraft and to interact with autonomous systems [2] in the final approach stage.

In modern complex systems, such as transportation, power plants, and spacecraft, more and more automation has been applied as the assistant of operators [3]. The advent of such technologies has stimulated much research on human-automation interaction. Though technical benefits of autonomous RVD have been suggested [4, 5]. However, few studies have been done on how the automation influences the workload of human, which is major concern of system designer.

Mental workload can be defined as the fraction of an operator's limited capacity used to perform a task [6]. Although it may be difficult to argue for a direct causal link between workload and increased accident risk, a substantial body of research supports a relationship between mental workload and performance [7], which may in turn be related to increased risk. Moray [8] also addressed that to optimize the mental workload allocation could reduce human errors, improve system safety, and increase users' satisfaction. Depending on the type and level of automation and depending on its actual use, automated aids should free the operators from certain activities. This unloading is expected to free information-processing resources, which may directly reduce the workload of operators, or which can be used for other (concurrent) tasks. There is evidence in plenty to show that well-designed information automation can achieve suitable human operator mental workload [9].

However, automation actually fundamentally changes the nature of the cognitive demands and responsibilities of human operators, and the effects of automation on workload in empirical studies of vehicle operation and nuclear power plant appear to produce differing effects in different studies [10], which may depend on the type of automation implemented (e.g. [11, 12]). The role of operators has shifted from manual to supervisory control – that is, from performing "doing" tasks, such as activating manual switches and following an operation procedure, to performing intellectual or cognitive tasks, such as diagnosis, planning, and problem solving [13], and increases the demand for monitoring. For man-machine systems, the lack of proper feedback to the operator can lead to human errors when the situation exceeds the capabilities of the automatic equipment [14]. When working with automated systems, operators may experience loss of situation awareness ([8, 15, 16]), imbalanced workload [17], vigilance decrement [18], complacency [19]. Billings [20] proposed that high human–system performance could only be achieved by excellent human-automation allocation.

Thus, the present study investigated the effect of automation on the mental workload of novice operators in manual rendezvous and docking, which may have practical implication for the use of automation in novice astronaut training in RVD task.

2 Methods

2.1 Participants

Fifteen participants (mean age = 23.2, SD = 0.86, range from 22 to 25) participated in the experiment. They were all science and engineering graduate students from China Astronaut Research and Training Center, with Bachelor Degree, right-handed. No participants were familiar with manual rendezvous and docking procedures, and it was assumed that they were all on the same level of procedure knowledge before the experiment. As heart rate (HR) and HRV measures were used in this study, only participants reporting to be without cardiac disorders and without diabetes mellitus, which can cause chronically decreased HRV [21], took part in the experiment. Participants filled out informed consent before the experiment and were paid for participation after the experiment. The experiment was approved by the ethics committee of China Astronaut Research and Training Center.

2.2 Task

Experiments were conducted using a desktop manual rendezvous and docking simulator located in the China Astronaut Research and Training Center. The RVD process consists of orbital maneuvers and controlled trajectories, which successively bring the active vehicle (chaser) into the vicinity of the passive vehicle (target), and eventually connected together. The task started from the final approve period while two spacecraft were 120 meters apart. Participants were required to observe the target spacecraft image and parameters in the display, estimate the relative position and attitude of the two spacecraft, and make decision about which handle to operate and how to operate it throughout RVD.

During the manual RVD task, operators were required to handle position control lever as well as attitude control lever and performing six degrees of freedom motion of the spacecraft. During the automation-aided RVD scenarios, Operators were free to control both position lever and attitude lever, with automation performing rotational maneuvers of the spacecraft. To complete RVD successfully, the relative position and attitude of two spacecraft had to meet the strict conditions of position deviation, attitude deviation, and relative velocity etc., the moment they were docking. The goal of operators was to complete RVD successfully, precisely and fuel-saving.

Participants were informed that even if the task of monitoring and adjusting was highly automated they were still responsible for supervising the system and reacting to unpredicted emergencies. For example, if there were any attitude deviation that needed to be manipulated, it was the operator's responsibility to assume control of the attitude lever.

2.3 Measures

The subjective rating scales are widely used in almost every aspect of ergonomics research and practice for the assessment of workload, fatigue, usability, annoyance and comfort. Workload effects were assessed with subjective and cardiovascular indicators. Subjective workload was measured by the NASA Task Load Index (NASA-TLX, [22]), which consists of mental demand, physical demand, temporal demand, performance, effort, and frustration six different dimensions. The participants rated each item on a scale from 0 to 10, and the relative importance of each workload dimension, on a paper-based version of the index. Mean heart rate, the root mean square of successive differences (RMSSD, the square root of the mean of the squares of the successive differences between adjacent NNs, representative of parasympathetic activity), the low frequency (0.04 to 0.15 Hz, reflects a mixture of both the sympathetic and parasympathetic nerve systems) and high frequency (0.15 to 0.4 Hz, represents the activity of the parasympathetic nerve system) power spectrum component of HRV (both in normalization form), the LF/HF ratio, and the total power (TP) served as physiological workload indicators [23].

Electrocardiogram (ECG) was recorded for all participants using three channel recorders, which were worn around the chest of each participant when performing the RVD tasks.

2.4 Experimental Design and Procedure

A within-group design was used in the experiment, with automation level as one independent variable, mental workload indices as dependent variable.

The experiment required approximately 2 h of participation. Participants firstly received an explanation of the test procedure and were then provided with necessary instructions upon arrival at the laboratory. They were required to sign a letter of consent containing such information. Afterwards, the RVD operation theory and control methods were demonstrated to participants by a RVD trainer. Participants were permitted to practice the tasks three times in the pre-experiment. Before the formal experiment, the heart rates were measured as to indicate the resting status. When the experiment began, the heart rates of participants were recorded until the end of experiment. All participants were required to finish six trials including two modes of tasks: manual RVD and the automation-aided manual RVD. Ten participants were randomly complete each trial. While each trial completed, there were 10 min break provided to participants.

2.5 Statistical Analysis

The Shapiro-Wilk test and Levene's test were used to test whether the given data presented with a normal distribution. The paired-T test was used to assess the effect of automation. All analyses were carried out in SPSS software Release 20 and all statistical tests with a $P < 0.05$ were considered significant.

3 Result

3.1 Subjective Workload

Results related to the comparison of subjective workload during rendezvous and docking with and without automation support are shown in Fig. 1. As becomes evident from the first column, the data reveal a difference in overall workload between RVD with and without automation support, $t(14) = 3.434$, $p = 0.004$. Moreover, a more detailed inspection of the data revealed beneficial effects among different workload dimensions, which were mental demand, $t(14) = 4.378$, $p = 0.001$, time pressure, $t(14) = 3.521$, $p = 0.003$, performance, $t(14) = 3.596$, $p = 0.003$, effort $t(14) = 3.525$, $p = 0.003$, as well as frustration, $t(14) = 2.688$, $p = 0.018$. Yet, the data reveal no difference in physical demand between RVD with and without automation support.

3.2 Physiological Measures

The effects for the physiological measures are shown in Table 1. Despite the reduced level of subjective workload and several dimensions, heart rate, the data of physiological measures revealed no difference in mean heart rates, RMSSD, and TP. Moreover, HF, LF and LF/HF index of HRV pointed to a lower physiological effort level (as the results reflected enhanced sympathetic nervous activity) while performing RVD with automation support compared to the manual condition. LF showed a stronger increase during the simulated RVD in automation-aided RVD compared to manual conditions, $t(14) = -3.335$, $p = 0.002$ (Fig. 2). LF/HF index also showed a stronger increase during the simulated RVD in automation-aided RVD compared to manual conditions, $t(14) = -2.759$, $p = 0.008$ (Fig. 3). The results of HRV suggested that participants paid even higher attention to their task in the automation-aided RVD.

4 Discussion

Automation is expected to improve performance, and decrease operators' mental workload. However, many automation-induced system failures indicate a need to investigate the influences of automation. In this study, results of the NASA-TLX show that participants' workload ratings in the manual condition were rather moderate, most likely because of operation theory instruction and practice in pre-experiment. As expected, relieving participants of parts of implement tasks by automation led to a significant decrease of subjective workload. Moreover, mental demand, time pressure,

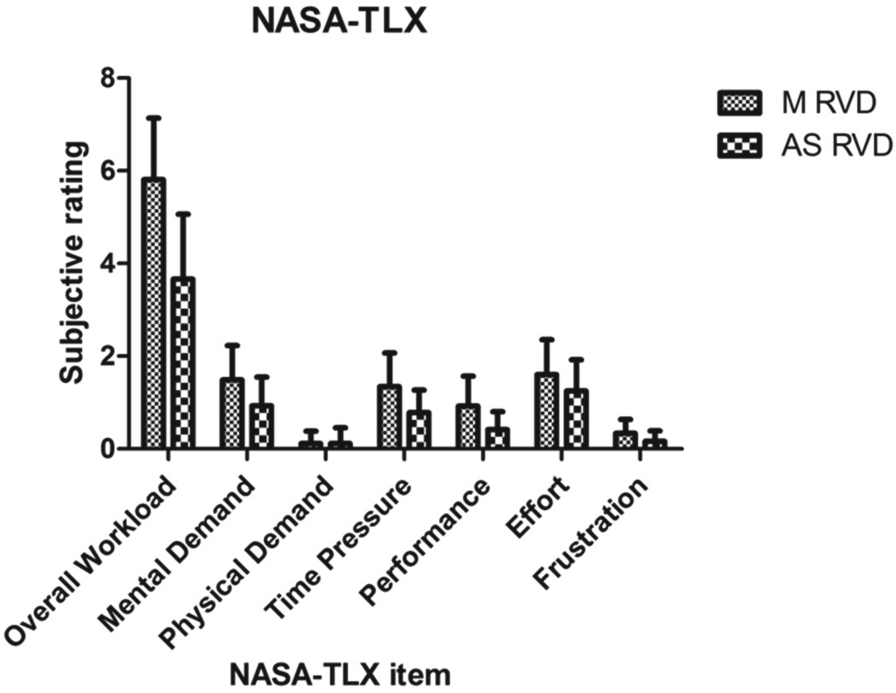

Fig. 1. Comparison of the subjective workload in manual and automation-aided condition. M RVD was short for manual rendezvous and docking; AS RVD was short for automation-aided rendezvous and docking.

Table 1. comparison of the physiological measures in manual and automation-aided condition. (means ± standard deviation, n = 15).

HRV	M RVD	AS RVD	t	P
HR(count/min)	76.29 ± 10.09	75.44 ± 8.58	0.675	0.503
RMSSD(ms)	36.82 ± 17.94	38.71 ± 20.15	-0.817	0.418
LFNU(%)	69.01 ± 10.00	76.14 ± 11.64	-3.335	0.002
HFNU(%)	30.99 ± 10.00	23.86 ± 11.64	3.335	0.002
LF/HF	2.97 ± 2.05	4.25 ± 2.45	-2.759	0.008
TOTAL(ms^2)	2162.1 ± 2271.4	2491.8 ± 2791..5	-1.089	0.282

Note: M RVD was short for manual rendezvous and docking; AS RVD was short for automation-aided rendezvous and docking.

performance, effort, and frustration in manual RVD task are higher than that in automation-aided tasks. According to Yeh and Wickens [24], the amount of tasks that should be performed at once strongly influence subjective workload, and the subjective workload from time-sharing two or more tasks is almost always greater than that from a

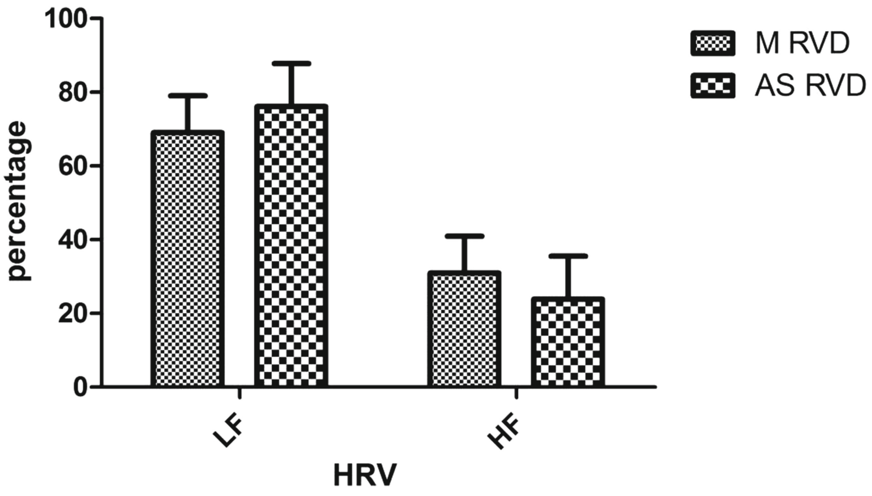

Fig. 2. The effect of automation on LF and HF of participants during rendezvous and docking. M RVD was short for manual rendezvous and docking; AS RVD was short for automation-aided rendezvous and docking.

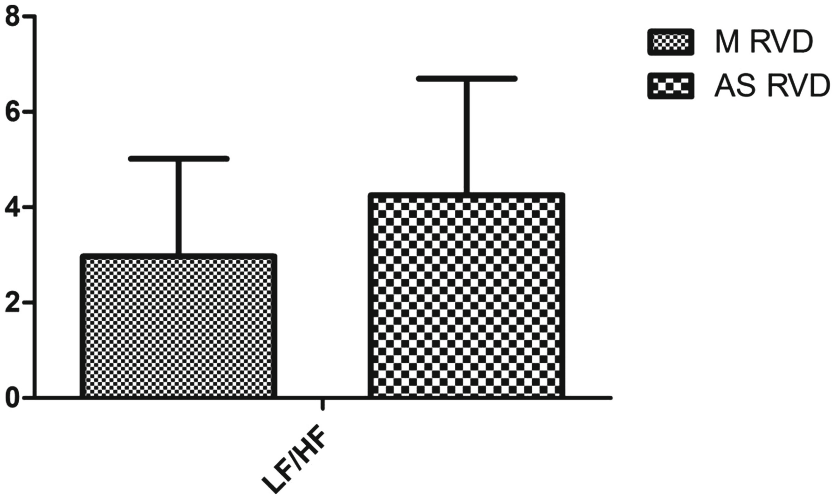

Fig. 3. The effect of automation on LF/HF of participants during rendezvous and docking. M RVD was short for manual rendezvous and docking; AS RVD was short for automation-aided rendezvous and docking.

single task. Thus, the experimental results could be explained with this theory, since automation directly relief participants of attitude operation, and the competence of automation seems to be superior to the novice participants reflected by the sensibility, accuracy, and stability.

Despite this perceived workload reduction, and the fact that the support systems under study did unload participants attitude operation, the more objective measures did not reflect a workload reduction. Mean heart rates, RMSSD and TP of participants did not change significantly in the two modes of tasks, and LFNU was significantly higher, HFNU was significantly lower in automation-aided RVD task as compared to manual RVD task. It was concluded that well designed automation may lead to a reduction in workload; however, it is often the case that while a reduction in physical workload is achieved, there is a potential increase in mental workload for the operator [25]. The previous study had also found that operators' mental workload may have risen due to the additional need to think ahead and anticipate the actions of the automation [26]. Thus, an explanation for the increase of physiology measures is that novice operators were not familiar with automated system, which making operators difficult to understand and anticipate the intention and action of automation. The previous research had also suggested that the complexity of the automation system limited the operators' ability to understand and work cooperatively with it [24], and the act of monitoring an automated system may increase workload [17], perhaps due to the effort of remaining vigilant. Thus, we tentatively put forward that complexity of automation calls for a high monitoring workload.

Moreover, If HRV is taken as an indicator of emotional strain due to perceived risk or perceived time pressure (as suggested by [27, 28]), HRV data show that participants became more tense (reflected by a rise of LF/HF index) in automation-aided RVD task as compared to manual RVD task. However, perceived risk and time pressure were independent of the automation support available and may lead to a reallocation of attentional resources to the primary task.

5 Conclusion

This study aimed to investigate the effect of automation on the mental workload of novice operators in manual rendezvous and docking. The evaluating results show that the decrease of mental workload caused by automation only supported by subjective rating, which may be influenced by the amount of tasks and the performance of task. The objective measures of HRV reflected a workload increment, which may be caused by unfamiliarity of automation. Previous study showed that when operators more accurately understand automation behavior they adopt a more effective attention allocation strategy [29]. Similarly, when informed of the capabilities of the automation operators rely more appropriately ([30, 31]). Thus, the result suggested that novice participants need much deeper understanding of the action of automation system to work better with it.

Although statistical differences were found in the results of the experiment, we acknowledge that the study was particularly limited by the small sample size. However, the results, particularly when combined with previous qualitative studies [24], do have practical significance for the use of automation in complex control environments.

It should be noted that this study has examined on novice operators, and experts are not included. Bainbridge [32] views expert performance as open-loop, anticipatory behavior. It was speculated here that both novice and expert essentially satisfied the criteria for automaticity when supplied with automation [33]. Thus, it is assumed that the extent of familiarity of task may influence the effects of automation. Therefore, further investigation would focus on the effects of automation on operators with different skill levels.

Acknowledgement. This study was supported by the National Natural Science Foundation of China (No. 61273322, 71371174, and 81372126).

References

1. Zhang, Y., Xu, Y., Li, Z., Li, J., Wu, S.: Influence of monitoring method and control complexity on operator performance in manually controlled spacecraft rendezvous and docking. Tsinghua Sci. Technol. **13**, 619–624 (2008)
2. Parasuraman, R., Wickens, C.D.: Humans: still vital after all these years of automation. Hum. Factors: J. Hum. Factors Ergonomics Soc. **50**, 511–520 (2008)
3. Sheridan, T.B.: Humans and Automation: System Design and Research Issues. Wiley, New york (2002)
4. Chen, T., Xu, S.-J.: A fuzzy controller for terminal approach of autonomous rendezvous and docking with non-cooperative target. J. Astronaut. **27**, 416–421 (2006)
5. Weichun, F.: Estimation method of relative position and attitude for spacecraft rendezvous and docking. Chin. Space Sci. Technol. **3**, 1–6 (2004)
6. Gopher, D., Donchin, E.: Workload: An examination of the concept (1986)
7. Kantowitz, B.H., Simsek, O.: Secondary-task measures of driver workload. In: Hancock, P.A., Desmond, P.A. (eds.) Stress, Workload and Fatigue, pp. 395–408. Lawrence Erlbaum Associates, Mahwah (2001)
8. Moray, N.: Mental workload since 1979. Int. Rev. Ergonomics **2**, 123–150 (1988)
9. Parasuraman, R., Sheridan, T.B., Wickens, C.D.: A model for types and levels of human interaction with automation. IEEE Trans. Syst. Man and Cybern. Part A Syst. Hum. **30**, 286–297 (2000)
10. Stanton, N.A., Young, M.S.: Driver behaviour with adaptive cruise control. Ergonomics **48**, 1294–1313 (2005)
11. Sheridan, T.B.: Task analysis, task allocation and supervisory control, Handbook of human-computer interaction, pp. 87–105 (1997)
12. Lee, J.D.: Human factors and ergonomics in automation design. Handbook of Human Factors and Ergonomics (3rd edn), pp. 1570–1596 (2006)
13. Hollnagel, E.: Human-oriented automation strategies. In: Proceedings of the World Congress on Safety of Modern Technical Systems, pp. 443–452 (2001)
14. Norman, D.A.: The 'problem' with automation: inappropriate feedback and interaction, not 'over-automation'. Philos. Trans. R. Soc. B Biol. Sci. **327**, 585–593 (1990)
15. Kaber, D.B., Omal, E., Endsley, M.: Level of automation effects on telerobot performance and human operator situation awareness and subjective workload. In: Scerbo, M.W., Mouloua, M. (eds.) Automation Technology and Human Performance: Current Research and Trends, pp. 165–170. Lawrence Erlbaum, Mahwah (1999)
16. Walker, G.H., Stanton, N.A., Young, M.S.: Feedback and driver situation awareness (SA): A comparison of SA measures and contexts. Transp. Res. Part F: Traffic Psychol. Behav. **11**, 282–299 (2008)

17. Funk, K., Lyall, B., Wilson, J., Vint, R., Niemczyk, M., Suroteguh, C., et al.: Flight deck automation issues. Int. J. Aviat. Psychol. **9**, 109–123 (1999)
18. Finomore, V., Matthews, G., Shaw, T., Warm, J.: Predicting vigilance: A fresh look at an old problem. Ergonomics **52**, 791–808 (2009)
19. Kaber, D.B., Endsley, M.R.: The effects of level of automation and adaptive automation on human performance, situation awareness and workload in a dynamic control task. Theor. Issues Ergonomics Sci. **5**, 113–153 (2004)
20. Billings, C.E.: Aviation Automation: The Search for a Human-Centered Approach. Lawrence Erlbaum Associates, Mahwah (1997)
21. Kudat, H., Akkaya, V., Sozen, A., Salman, S., Demirel, S., Ozcan, M., et al.: Heart rate variability in diabetes patients. J. Int. Med. Res. **34**, 291–296 (2006)
22. Hart, S.G.: NASA-task load index (NASA-TLX); 20 years later. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, pp. 904–908, (2006)
23. Mulder, L.: Measurement and analysis methods of heart rate and respiration for use in applied environments. Biol. Psychol. **34**, 205–236 (1992)
24. Yeh, Y.-Y., Wickens, C.D.: Dissociation of performance and subjective measures of workload. Hum. Factors: J. Hum. Factors Ergonomics Soc. **30**, 111–120 (1988)
25. Megaw, T.: The definition and measurement of mental workload. In: Corlett, E.N., Wilson, J.R. (eds.) Evaluation of Human Work, pp. 525–551. CRC Press, Boca Raton (2005)
26. Balfe, N., Wilson, J.R., Sharples, S., Clarke, T.: Development of design principles for automated systems in transport control. Ergonomics **55**, 37–54 (2012)
27. Nickel, P., Nachreiner, F.: Sensitivity and diagnosticity of the 0.1-Hz component of heart rate variability as an indicator of mental workload. Hum. Factors: J. Hum. Factors Ergonomics Soc. **45**, 575–590 (2003)
28. Sharma, S.: Linear temporal characteristics of heart interbeat interval as an index of the pilot's perceived risk. Ergonomics **49**, 874–884 (2006)
29. Wickens, C.D., Gempler, K., Morphew, M.E.: Workload and reliability of predictor displays in aircraft traffic avoidance. Transportation Human Factors **2**, 99–126 (2000)
30. Bisantz, A.M., Seong, Y.: Assessment of operator trust in and utilization of automated decision-aids under different framing conditions. Int. J. Ind. Ergon. **28**, 85–97 (2001)
31. Dzindolet, M.T., Peterson, S.A., Pomranky, R.A., Pierce, L.G., Beck, H.P.: The role of trust in automation reliance. Int. J. Hum Comput Stud. **58**, 697–718 (2003)
32. Bainbridge, L.: Forgotten alternatives in skill and work-load. Ergonomics **21**, 169–185 (1978)
33. Anderson, J.R.: Cognitive Psychology and Its Implications. Macmillan, New York (2005)