Sense of Agency in Human-Machine Interaction

Debora Zanatto[1(✉)], Mark Chattington[1,2], and Jan Noyes[1]

[1] Faculty of Engineering, University of Bristol, Bristol BS8 1UB, UK
{debora.zanatto,mark.chattington,j.noyes}@bristol.ac.uk
[2] Thales Research, Technology and Innovation, Reading RG2 6GF, UK

Abstract. Although being in control is an important aspect of human-machine interaction, little is known about the combined effect of automation and mental workload on the sense of agency. In this study, participants were asked to reproduce the time interval between a keypress and an acoustic tone presented with different time delays (1250 to 2250 ms). Automation had three levels from the human being in complete control, an intermediate condition, to the machine being fully automatic. Mental workload was manipulated with a secondary memory task with two levels. Results showed a gradual loss of sense of agency with increasing automation intervention. Mental workload was found to affect only the intermediate automation condition. Further, we found an Intentional Binding effect for delays longer than 1750 ms in this intermediate condition. These findings demonstrate the existence of a residual sense of agency, which has important implications for the future design of hybrid, semi-autonomous systems.

Keywords: Sense of agency · Automation human-machine interaction · Mental workload · Time delay

1 Introduction

Over the past decade, the number of circumstances in which humans delegate actions to technology has massively increased. One of the consequences of this loss of action is the reduction of the individual sense of control, called 'Sense of Agency'. Haggard and Chambon [1] defined sense of agency as "the experience of controlling one's own actions, and, through them, events in the outside world". In other words, we experience sense of agency when we perform an action whose consequences are known [1–3]. The main effect of experiencing sense of agency is the well-known Intentional Binding Effect [4, 5] which refers to the compression of the time interval between a voluntary action and its effects. When the individual experiences sense of agency, actions and effects are bound together so that the individual's perception of the time between the two events is shorter than reality.

The role of sense of agency in human-machine interaction has been investigated by Berberian [6] who showed a decrease in agency with an increase in automation during an aircraft supervision task carried out in a flight simulator. Studies have also indicated that driving support decreases the driver's sense of agency [7, 8]. Work on sense of agency has so far focused on manipulating the degrees of human and machine contribution to a

H. Ayaz et al. (Eds.): AHFE 2021, LNNS 259, pp. 353–360, 2021.
https://doi.org/10.1007/978-3-030-80285-1_41

task [6, 9–11]. To our knowledge, no specific study has yet investigated the combined role of automation and mental workload on the sense of agency. Mental workload is a key aspect in human-machine interactions. Although introducing automation has been thought to relieve and simplify the human's task, it can produce fluctuations in the load on the human cognitive system [12, 13]. Those situations vary from the user carrying out other tasks in parallel, to lowering their attention level due to boredom, resulting in a disruption of their performance [14, 15]. One of the main consequences is a phenomenon called Out-Of-The-Loop (OOTL) performance [16] where the human is unable to take over control in the event of automation failure.

There is evidence of mental workload affecting the individual's sense of agency. For example, Hon et al. [17] reported reduced agency under high mental workload. This evidence was further investigated by Howard et al. [18] who looked for the intentional binding effect under two levels of mental workload. They demonstrated that mental workload does affect sense of agency when the task is carried out solely by the individual. In contrast, when the task is performed by a computer, the individual's sense of agency is not affected by any changes in mental workload.

The present study aimed to investigate sense of agency, as an indicator of user control, under different degrees of autonomy and mental workload. A similar experimental approach to Howard et al. [18] was used, but with a third intermediate condition. In our study, participants estimated the time interval between a) their action and a subsequent sound, b) their action when warned by the computer and the subsequent sound, and c) the computer action and the subsequent sound. We hypothesized that sense of agency would gradually reduce as computer intervention increased. Further, it was expected that the mental effort involved in task performance would reduce sense of agency, but only when the participants were physically triggering the action. When the computer triggered the action, we expected to see no effect of workload.

2 Method

2.1 Participants

One hundred and eighty individuals (83 female, 93 male, 4 non-binary), mean age = 20.53 years, SD = 2.00 years, participated in the study. They were recruited through the University students' mailing list. The University Research Ethics Committee approved the study.

2.2 Design

The experiment was counterbalanced in a three factor (automation: human decision, system warning and system decision) between-subject design and a two factor (workload: low or high) within-subject design. Automation was manipulated via the interval reproduction task, where a) participants would trigger a sound event by pressing a key at any time (human decision condition); b) participants would be alerted by the computer to press a key at any time to trigger a sound event (system warning condition); c) the computer would trigger the sound event (system decision condition). Workload

was manipulated at the encoding stage. In the low workload condition, participants were presented with two letters to remember. In the High workload condition, participants were shown eight letters to remember. The order of presentation for the time delays (1250 ms to 2250 ms) was randomized and counterbalanced amongst blocks.

2.3 Materials and Procedure

The experiment was conducted online using Pavlovia open science repository (https://pavlovia.org) and visual stimuli were coded using Psychopy [19]. The experiment composed an encoding stage, the interval reproduction task, and a recall stage. Specifically, participants were asked to memorize letters at the beginning of each trial (encoding stage), to retain the letters while completing the interval reproduction task and finally they faced a recall where a probe letter was presented that they had to report as to whether the letter was previously present at the encoding stage [20]. In the interval reproduction task, participants were asked to reproduce the time interval between a keypress and following tone by pressing the spacebar twice, the first time to begin the estimation and the second to end it.

2.4 Data Analyses

A manipulation check of mental workload was carried out on the accuracy response that participants gave in the recall stage. This has been calculated as the number of times participants gave a correct response divided by the number of trials they completed. A logistic mixed-effects model was fitted to the data. This showed a significant main effect of workload ($\chi^2_{(1)} = 209.00, p < .001$); accuracy response was greater in the low mental workload (mean = 0.95, SD = 0.21) than the high mental workload condition (mean = 0.77, SD = 0.42). This was deemed satisfactory.

3 Results

Sense of agency was assessed by testing the effect of automation and workload on the Estimation Error. This has been calculated as the interval reproduced by the participants minus the actual time delay. A linear mixed effects model was fitted to the data with estimation error as the dependent variable, automation (human decision, system decision, system warning) and mental workload (high/low) as independent variables and participants ID as the random factor. Post hoc comparisons were assessed using t-tests and Bonferroni's correction was applied when needed.

A significant main effect of automation was found ($F(2,178) = 6.19, p = .002$). Estimation error was smaller in the human decision condition than the others (−28.67 ms, SD = 387.67, $p_s < .001$). Moreover, the system warning condition (mean = 30.92 ms, SD = 413.22) had a lower estimation error than the system decision condition (mean = 83.79 ms, SD = 366.83, $p = .004$).

The main effect for mental workload was not significant ($p > .050$). However, a significant two-way interaction between automation and mental workload was found, ($F(2,3161) = 3.84, p = .021$). Post hoc comparisons showed that estimation error was

smaller in the low mental workload condition (mean = 1.80 ms, SD = 361.09) than the high mental workload condition (mean = 60.55 ms, SD = 458.68) for the system warning condition only ($p = .011$). This is shown in Fig. 1.

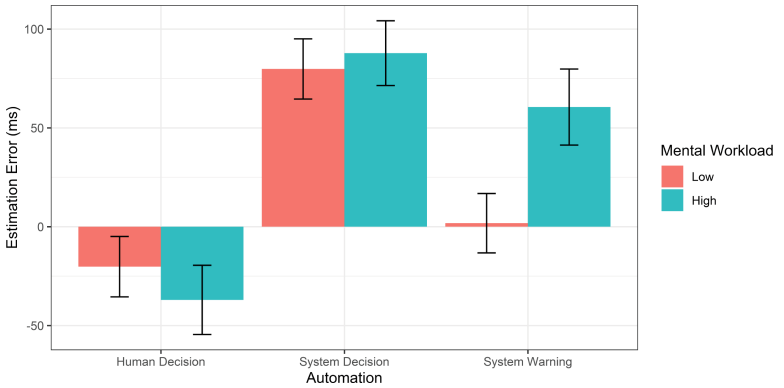

Fig. 1. Participants' estimation error for each automation and mental workload condition. Bars indicate the standard error of the mean.

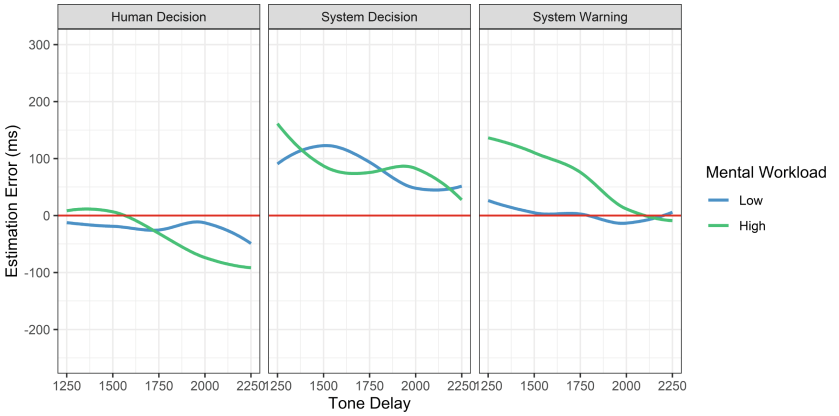

Fig. 2. Estimation error for each automation, mental workload and time delay condition.

The role of time delay in influencing estimation error was also investigated. For each automation condition, a mixed-effects model was fitted to the data, with estimation error as the dependent variable, workload (high and low) and tone delays as independent variables, and participant ID as a random factor. The results are shown in Fig. 2. For the system warning condition, the model showed a significant main effect of mental workload ($F(1,1086) = 7.65, p = .005$), which confirmed previous analysis with smaller error for the low mental workload condition. The tone delay was also found to significantly influence participants' estimation error ($F(4,1086) = 2.59, p = .035$). Post hoc comparisons showed a significantly smaller estimation error for tone delays longer than

2000 ms ($p_s > .050$). An Intentional Binding effect was found for low mental workload in the system warning condition for time delays longer than 1750 ms.

4 Discussion

This study investigated how the combination of automation and mental workload can affect the human sense of agency. The main hypotheses were that both automation and mental workload would degrade human sense of agency. Experimental results on the interval estimation task showed that automation affects the sense of agency and participants' estimation error increased with the reduction of their intervention. Therefore, automation seems to play a key role in the user's control perception, for which even a minimal 'intrusion' to their decisional process reduces their sense of agency. This is in line with previous literature [6–8].

Participants' estimation error did not change with the increase in mental workload. However, a significant two-way interaction between automation and mental workload was found. In the system decision condition, no effect for the mental workload was found. This mirrored the results of Howard et al. [18]. As no human action was involved in the task and no control was by the individual, mental workload did not play any role. No effect for mental workload was found in the human decision condition. This result differs from previous research [17, 18] that showed a greater sense of agency for low mental workloads in the condition of human decision. However, in previous experiments, shorter time delays have been used which may have led to this new finding here. As previous research indicated, a decrease of time estimation with the increase of time delays [21, 22] makes it plausible to assume that the lack of effect for the mental workload in the human decision condition was due to the so-called 'pacemaker effect' [23]. In other words, the individual has an 'internal clock' that is used when a causal link between the individual's action and the effect is established. This clock runs at a lower rate, so that the longer elapsed time between the action and the effect, the greater the bias between the perception of the time interval and the actual elapsed time. As this distance increases for longer time delays, it is possible it would reduce the difference between the two mental workloads.

Finally, mental workload was shown to influence the sense of agency in the system warning condition. Estimation error in this condition was higher than in the human decision condition and also higher still with a high mental workload. An explanation for this effect is that it could be linked to the depletion of cognitive resources. In the system warning condition, the participants were performing the keypress and it is plausible that the secondary memory task competed for resources with the primary task, further reducing the participants' sense of agency. These results confirm that automation and mental workload are related to each other and need to be investigated as complementary aspects of the same phenomenon. This also confirmed our hypothesis on the presence of residual sense of agency in a hybrid human-machine system, thus showing it would be possible to develop a shared human-machine control experience.

The time delay did not have any effects on the system decision and the human decision conditions. However, sense of agency increased in the system warning condition with the lengthening of the time delay. Moreover, intentional binding has been found for

time delays longer than 2000 ms. Estimation error was always relatively small, and even negative for delays longer than 1750 ms in the low workload condition. For the high workload condition, a constant decrease of estimation error can be observed. This confirms the presence of some residual agency, possibly because participants were still in charge or triggering the sound. This, in turn, could depend on the temporal contiguity of the warning and the sound. A sound triggered 1250 ms after the key press could be temporally closer to the warning than a sound triggered after 2250 ms and, therefore, perceived as a consequence of the computer warning rather than the participants' action itself. The opposite would be for a longer delay, where the sound could be temporally closer to the individuals' intentional action.

Anticipating the machine intervention early enough to make the individual's compliance fall into the intentionality area would be an important step forward. This could have important and beneficial consequences, as sense of agency has been shown to be linked to greater attention, improved motivation, and attribution of responsibility [24–27].

5 Conclusion

The paper strengthens the evidence that sense of agency can be used as a tool to measure human involvement in a human-machine interaction task. Results have shown that automation and mental workload are interconnected in playing a key role in influencing the sense of agency whilst at the same time demonstrating the existence of a residual sense of agency in a hybrid environment. This finding opens up the possibility of integrating operator and machine actions while maintaining the individual's perceived control.

These results indicate that sense of agency needs to be considered in the design of hybrid systems. Specifically, a precise time window for the user intervention should be optimised; in this work we found that the system should provide information or instructions around 2 s before the user intervention. This would allow the user to maintain control over the task, thus improving the quality of the performance.

Further, mental workload needs to be carefully considered in a hybrid system when instructions need to be completed sooner than the optimal, in the case investigated 2 s, time window. In conditions in which the user intervention needs to be immediate, mental workload should be light to allow the user to be in control.

Finally, in a fully automated system, the user would not be in control of the system, and the inclusion of sense of agency in the design would not deliver any improvement. However, each system is different and managing what level of user interaction is required in the system should be a topic for future research.

Acknowledgments. This material was funded and delivered in partnership between the Thales Group and the University of Bristol, and with the support of the UK Engineering and Physical Sciences Research Council Grant Award EP/R004757/1 entitled 'Thales-Bristol Partnership in Hybrid Autonomous Systems Engineering (T-B PHASE)'.

References

1. Haggard, P., Chambon, V.: Sense of agency. Curr. Biol. **22**, R390–R392 (2012)
2. Jeannerod, M.: The mechanism of self-recognition in humans. Behav. Brain Res. **142**, 1–15 (2003)
3. Chambon, V., Sidarus, N., Haggard, P.: From action intentions to action effects: how does the sense of agency come about? Front. Hum. Neurosci. **8**, 320 (2014)
4. Haggard, P., Clark, S., Kalogeras, J.: Voluntary action and conscious awareness. Nat. Neurosci. **5**, 382–385 (2002)
5. Moore, J.W., Obhi, S.S.: Intentional binding and the sense of agency: a review. Conscious. Cogn. **21**, 546–561 (2012)
6. Berberian, B., Sarrazin, J.C., Le Blaye, P., Haggard, P.: Automation technology and sense of control: a window on human agency. PLoS ONE **7**, e34075 (2012)
7. Mulder, M., Abbink, D.A., Boer, E.R.: Sharing control with haptics: seamless driver support from manual to automatic control. Hum. Factors **54**, 786–798 (2012)
8. Yun, S., et al.: Investigating the relationship between assisted driver's SoA and EEG. In: Masia, L., Micera, S., Akay, M., Pons, J.L. (eds.) ICNR 2018. BB, vol. 21, pp. 1039–1043. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-01845-0_208
9. McEneaney, J.E.: Agency effects in human-computer interaction. Int. J. Hum. Comput. Int. **29**, 798–813 (2013)
10. Obhi, S.S., Hall, P.: Sense of agency in joint action: influence of human and computer co-actors. Exp. Brain Res. **211**, 663–670 (2011)
11. Wohlschläger, A., Haggard, P., Gesierich, B., Prinz, W.: The perceived onset time of self and other-generated actions. Psychol. Sci. **14**, 586–591 (2003)
12. Banks, V.A., Stanton, N.A.: Keep the driver in control: automating automobiles of the future. Appl. Ergon. **53**, 389–395 (2016)
13. Reinartz, S., Gruppe, T.: Information requirements to support operator-automatic co-operation. In: Human Factors in Nuclear Safety Conference, pp. 22–23. IBC, London (1993)
14. Fan, J., Smith, A.P.: The impact of workload and fatigue on performance. In: Longo, L., Leva, M.C. (eds.) H-WORKLOAD 2017. CCIS, vol. 726, pp. 90–105. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-61061-0_6
15. Young, M.S., Brookhuis, K.A., Wickens, C.D., Hancock, P.A.: State of science: mental workload in ergonomics. Ergonomics **58**, 1–17 (2015)
16. Endsley, M.R., Kiris, E.O.: The out-of-the-loop performance problem and level of control in automation. Hum. Factors **37**, 381–394 (1995)
17. Hon, N., Poh, J., Soon, C.S.: Preoccupied minds feel less control: sense of agency is modulated by cognitive load. Conscious. Cogn. **22**, 556–561 (2013)
18. Howard, E.E., Edwards, S.G., Bayliss, A.P.: Physical and mental effort disrupts the implicit sense of agency. Cognition **157**, 114–125 (2016)
19. Peirce, J., et al.: PsychoPy2: experiments in behavior made easy. Behav. Res. Methods **51**, 195–203 (2019)
20. Sternberg, S.: High-speed scanning in human memory. Science **153**, 652–654 (1966)
21. Van den Bussche, E., Alves, M., Murray, Y.P.J., Hughes, G.: The effect of cognitive effort on the sense of agency. PLoS ONE **15**, 1–20 (2020)
22. Humphreys, G.R., Buehner, M.J.: Magnitude estimation reveals temporal binding at super-second intervals. J. Exp. Psychol. Hum. Percept. Perform. **35**, 1542 (2009)
23. Wenke, D., Haggard, P.: How voluntary actions modulate time perception. Exp. Brain Res. **196**, 311–318 (2009)

24. Wen, W., Haggard, P.: Control changes the way we look at the world. J. Cogn. Neurosci. **30**, 603–619 (2018)
25. Bednark, J.G., Franz, E.A.: Agency attribution: event-related potentials and outcome monitoring. Exp. Br. Res. **232**, 1117–1126 (2014)
26. Eitam, B., Kennedy, P.M., Higgins, E.T.: Motivation from control. Exp. Br. Res. **229**, 475–484 (2013)
27. Shneiderman, B., Plaisant, C.: Designing the User Interface: Strategies for Effective Human-Computer Interaction. Pearson Education, India (2010)