Selection Strategy of Effort Control: Allocation of Function to Manual Operator or Automation System

Akihiro Maehigashi (mhigashi@cog.human.nagoya-u.ac.jp)
Kazuhisa Miwa (miwa@is.nagoya-u.ac.jp)
Hitoshi Terai (terai@is.nagoya-u.ac.jp)
Graduate School of Information Science, Nagoya University, Japan

Kazuaki Kojima (koj@aoni.waseda.jp)
Faculty of Human Sciences, Waseda University, Japan

Junya Morita (j-morita@jaist.ac.jp)
School of Knowledge Science, Japan Advanced Institute of Science and Technology, Japan

Abstract

In this study, we experimentally investigated the human selection strategy of effort control, the control of function allocation to either the manual operator or the automation system. We conducted two experiments using two types of tracking tasks. As a result, we found that people tended to perform effort control based on manual-based selection, depending more on manual performance than system performance. Also, we confirmed that the tendency to use an automation system was related to the selection strategy.

Keywords: Human-automation system interaction; Misuse; Disuse; Effort control.

Introduction

The development of technologies has rapidly increased in recent years. People have more opportunities to work with automation systems as important resources for performing tasks (Hutchins, 1995). Lee and Moray (1994) stated that in the situation where people work with automation systems, they do not play only the role of a manual operator, but also play the role of a supervisory controller who monitors the whole system consisting of human and automation system from the meta viewpoint.

A primary role of such a supervisory controller is effort control, the control of function allocation to either the manual operator or the automation system. In previous studies about human use of external resources, it was confirmed that people adaptively control such a function allocation to either internal processing or external processing (processing using external resources), appropriately estimating the costs of a task and using external resources (e.g., Cary & Carlson, 2001; Gray & Fu, 2004; Walsh & Anderson, 2009). On the other hand, in previous studies about human use of automation systems, it has been pointed out that many failures emerged in the effort control, and these failures often caused fatal accidents (Norman, 1990). Parasuraman and Riley (1997) defined these maladaptive effort controls as misuse and disuse. Misuse is overreliance on automation systems, and disuse is underutilization of the systems. Many researchers are rigorously investigating human misuse and disuse of automation systems (e.g., Bahner, Hüper, & Manzey, 2008; Dzindolet, Peterson, Pomranky, Pierce, & Beck, 2003).

Lee and Moray (1994) stated that effort control is not performed depending only on the performance of an automation system, but also on the performance of human manual operation. In a normative manner, it is ideal to allocate functions based on evaluations of both kinds of performances evenly. However, the balance of the consideration might be disproportionate. Our first interest in the current study is to investigate the selection strategy of effort control. In this study, we define system-based selection as effort control depending more on system performance than on manual performance. In contrast, we define manual-based selection as effort control depending more on manual performance than on system performance. We investigate whether people perform effort control based on system- or manual-based selection.

Human ability to evaluate manual performance has been investigated in the study area of metacognition. The term metacognition here means people's ability to monitor their own actions (Metcalfe & Greene, 2007). Metcalfe and Greene (2007) found that people could appropriately judge their manual operation performance (Judgment of performance: JOP). On the other hand, human evaluation of system performance has been investigated in the study area of human-computer interaction. Madhavan and Phillips (2010) found that people tend to evaluate system performance as lower than its actual performance. Moreover, many researchers are investigating situation awareness. These studies showed that there are two types of monitoring: active monitoring (monitoring situations while manually conducting a task) and passive monitoring (monitoring situations while observing an automation system's operation) (e.g., Metzger & Parasuraman, 2001). Endsley and Kiris (1995) and Metzger and Parasuraman (2001) found that people show higher situation awareness during active monitoring than during passive monitoring.

These previous studies lead to an expectation that in cooperative work with an automation system, people are expected to perform effort control depending more on manual performance than on system performance. In other words, we expect that people perform effort control based on manual-based selection. The first research question of the current study is as follows.

Research Question 1: Do people perform effort control based on manual-based selection rather than on system-based selection?

Moreover, Lee and Moray (1994) and Madhavan and Phillips (2010) showed that the human tendency to use automation systems is influenced by individual differences. There are many studies investigating the human tendency to use automation systems from the viewpoints of misuse and disuse. However, only a few studies have been conducted, focusing on the relationship between the tendency to use automation systems and the selection strategy of the effort control. Therefore, our second interest in this study is to investigate the relationship between the tendency to use automation systems and the selection strategy of the effort control. In particular, our second research question is as follows.

Research Question 2: Do people whose styles of using an automation system differ, i.e., misuse-biased users and disuse-biased users, adopt different selection strategies of effort control?

Experimental Task

We used two tracking tasks (line and road tasks) as experimental tasks (Figure 1). In the line task, the participants track a line that scrolls downward past a circle vehicle. When the circle vehicle veers off the line, the performance score is reduced as operational error. On the other hand, in the road task, the participants track a road that scrolls downward past a dot vehicle. When the dot vehicle hits the edge of the road, the performance score is reduced as operational error. The participants were allowed to switch to either auto mode (operation completely performed by the program) or manual mode (operation performed by participants using left and right arrow keys) by pressing a selector on the keyboard. In these tasks, we manipulated the automation capability (Ca) and the manual capability (Cm) with five levels: 30, 40, 50, 60, and 70. Technically, each value indicates the success rate of the operation command. Therefore, the higher the values of Ca or Cm are, the more controllable the circle or the dot vehicle is. In contrast, the lower the values of Ca or Cm are, the less controllable the circle or the dot vehicle is.

Analysis

In this section, we introduce the analysis method used in this study. We propose and conduct an innovative performance-based analysis. First, the average percentage of using the auto mode is recorded at each combination of Ca (5 levels) × Cm (5 levels). Second, we fit the logistic curve to the percentages at the 25 data points. The predicted percentage of using the auto mode is described as follows.

$$Percentage\ of\ using\ auto\ mode = 100 * 1/(1+e^{-(\beta_0+\beta_1 Ca+\beta_2 Cm)})$$

Finally, we use the odds ratios of Ca ($e^{(\beta_1 * 10)}$) and Cm ($e^{(\beta_2 * 10)}$), calculated from the coefficients of Ca (β_1) and Cm (β_2), and investigate the selection strategy of the effort control based on the odds ratios. The odds ratio of Ca indicates the increase of the percentage of using the auto mode with the increase of the value of Ca. On the other hand, the odds ratio of Cm indicates the decrease of the percentage of using the auto mode with the increase of the value of Cm. We investigate whether the percentage of using the auto mode increases or decreases when the values of both Ca and Cm equivalently increase. In particular, we analyze whether the product of the odds ratios of Ca and Cm exceeds 1 or falls below 1.

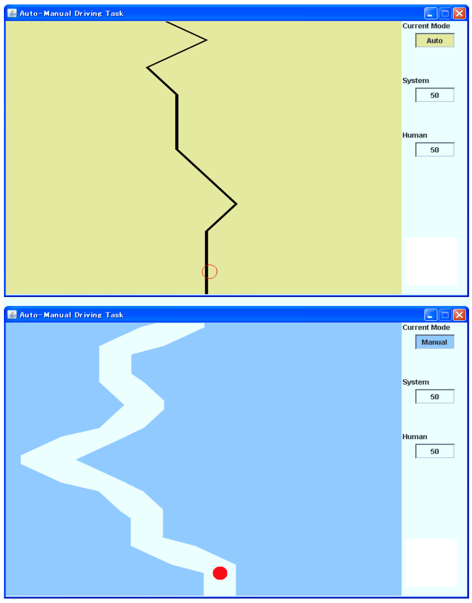


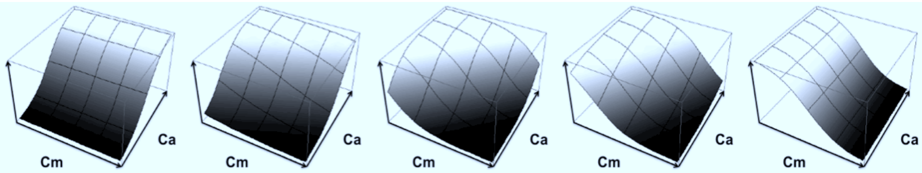
Figure 1: Line (top) and road (bottom) tasks.

Figure 2 shows the relation of the graphical images of the logistic curves and the products of the odds ratios of Ca and Cm. If the product exceeds 1, this means that the increase of the percentage of using the auto mode with the increase of Ca is greater than the decrease of the percentage of using the auto mode with the increase of Cm. This indicates that effort control is performed depending more on system performance than on manual performance, and system-based selection was adopted. On the other hand, if the product falls below 1, this means that the decrease of the percentage of using the auto mode with the increase of Cm is greater than the increase of the percentage of using the auto mode with the increase of Ca. This indicates that effort control is performed depending more on manual performance than on system performance, and manual-based selection was adopted.

Experiment 1

Method

Participants Twenty-four university students participated in the experiment. The participants conducted both line and road tasks, and the order of the tasks was counterbalanced



Product of ORs of Ca and Cm	2	1.5	1	0.75	0.5
OR of Ca	2	2	2	1.5	1
OR of Cm	1	0.75	0.5	0.5	0.5

Figure 2: Relation of graphical images of logistic curves and products of odds ratios (ORs) of Ca and Cm. The x-axis represents the value of Cm, the y-axis represents the value of Ca, and the z-axis represents the percentage of using the auto mode.

among the participants.

Procedure The participants were required to achieve as high a score as possible in each task, adaptively selecting either the auto or manual mode. In each task, we conducted 25 trials consisting of 5 (Ca: 30, 40, 50, 60, 70) $\times$ 5 (Cm: 30, 40, 50, 60, 70). Each trial lasted 40 seconds. When one trial ended and another began, the display showed "the capabilities changed" on the center of the screen. At the same time, the number of completed trials among the 25 trials was shown. Before conducting each task, the participants performed two training trials for 40 seconds each as practice for switching the auto and manual modes. In the first training trial, the value of Ca was set to 70 and that of Cm was set to 30. Also, in the second training trial, the value of Ca was set to 30 and that of Cm was set to 70. Throughout the experiment, the values of Ca and Cm were not displayed on the screen; therefore, the participants were not informed of the values.

Result and Discussion

First, in each line and road task, the average percentage of using the auto mode was recorded at each combination of Ca (5 levels) $\times$ Cm (5 levels). Second, we fitted the logistic curve to the 25 data points. The predicted percentages of using the auto mode are as follows.

Line task

$$Percentage\ of\ using\ auto\ mode = 100 * 1/(1+e^{-(0.505+0.042Ca-0.046Cm)})$$

Road task

$$Percentage\ of\ using\ auto\ mode = 100 * 1/(1+e^{-(1.317+0.022Ca-0.044Cm)})$$

The Hosmer-Lemeshow test was applied to assess goodness of fit of the predicted curves. The test was neither significant in the line ($p = .89$) nor road ($p = .97$) tasks, indicating that the logistic curves described the data well. The top two rows in Table 1 show the odds ratios of Ca and Cm, and the product of the odds ratios of Ca and Cm in each task.

First, we investigated the selection strategy of the effort control in Research Question 1. Table 1 shows that the product of the odds ratios of Ca and Cm fell below 1 in both tasks. Thus, the results confirmed that the effort control was performed based on manual-based selection in both tasks. The participants depended 1.043 ($= 1/0.958$) and 1.254 ($= 1/0.797$) times more on manual performance than on system performance in the line and road tasks respectively.

Misuse- and Disuse-Biased Groups Next, in order to investigate the relationship between the tendency to use automation systems and the selection strategy of effort control in Research Question 2, we divided the participants into two groups: misuse-biased and disuse-biased. In each task, the participants whose average percentage of using the auto mode was higher than the median average were put in the misuse-biased group; and the other half of the participants became the disuse-biased group.

In each of the misuse- and disuse-biased groups engaging in each line and road task, the average percentage of using the auto mode was recorded at each combination of Ca (5 levels) $\times$ Cm (5 levels). Second, we fitted the logistic curve to the 25 data points. The predicted percentages of using the auto mode are as follows.

Table 1: Odds ratios of Ca and Cm, and product of odds ratios of Ca and Cm in Experiment 1.

		OR of Ca	OR of Cm	Product of ORs of Ca and Cm
Line		1.522	0.629	0.958
Road		1.248	0.638	0.797
Line	Misuse	1.600	0.711	1.138
	Disuse	1.578	0.535	0.845
Road	Misuse	1.372	0.623	0.856
	Disuse	1.189	0.616	0.732

Line task

Misuse-biased group

$$Percentage\ of\ using\ auto\ mode = 100 * 1/(1 + e^{-(0.249+0.047Ca-0.034Cm)})$$

Disuse-biased group

$$Percentage\ of\ using\ auto\ mode = 100 * 1/(1 + e^{-(0.522+0.045Ca-0.062Cm)})$$

Road task

Misuse-biased group

$$Percentage\ of\ using\ auto\ mode = 100 * 1/(1 + e^{-(1.696+0.031Ca-0.047Cm)})$$

Disuse-biased group

$$Percentage\ of\ using\ auto\ mode = 100 * 1/(1 + e^{-(1.080+0.017Ca-0.048Cm)})$$

The Hosmer-Lemeshow test was neither significant in the misuse- ($p = .94$) nor disuse- ($p = .78$) biased groups in the line task. Also, the test was neither significant in the misuse- ($p = .95$) nor disuse- ($p = .93$) biased groups in the road task. These results indicated that the logistic curves described the data well. The bottom four rows in Table 1 show the odds ratios of Ca and Cm, and the product of the odds ratios of Ca and Cm in the four groups.

In each task, we compared the products of the odds ratios of Ca and Cm in the misuse- and disuse-biased groups. The product was lower in the disuse-biased group than in the misuse-biased group. This result showed that the participants in the disuse-biased group performed the effort control depending more on manual performance than those in the misuse-biased group did. Thus, the results confirmed that there is a relationship between the tendency to use automation systems and the selection strategy of the effort control.

In summary, the participants in Experiment 1 tended to perform effort control based on manual-based selection rather than on system-based selection. Also, we confirmed that there is a relationship between the tendency to use automation systems and the selection strategy of the effort control. In the following Experiment 2, we aimed at corroborating these findings in different situations.

Experiment 2

In Experiment 2, using the same tasks as in Experiment 1, we set up two different situations. In the first situation, during the task, the value of Ca was displayed on the screen, but that of Cm was not displayed (Ca-displayed situation). In this situation, the participants could know the performance potential in the auto mode by the displayed value of Ca during the task. However, they needed to evaluate the manual performance through observing their manual operations. In the second situation, during the task, the value of Cm was displayed on the screen, but that of Ca was not displayed (Cm-displayed situation). In this situation, the participants could know the performance potential in the manual mode by the displayed value of Cm during the task. However, they needed to evaluate the system performance through observing the system operation.

It is assumed that in the Ca-displayed situation, the participants could know the system performance more easily and would be guided to depend more on the system performance in their effort control. In other words, in such a situation, we expect that the system-based selection would be facilitated in the effort control. On the other hand, it is assumed that in the Cm-displayed situation, the manual-based selection would be facilitated in the effort control.

If the findings of Experiment 1 are robust human behavior, the following is predicted.

About Research Question 1, the Ca-displayed situation would facilitate the system-based selection, and the Cm-displayed situation would facilitate the manual-based selection. Additionally, the latter promotion of the manual-based selection in the Cm-displayed situation would be larger than the former promotion of the system-based selection in the Ca-displayed situation.

About Research Question 2, the participants in the disuse-biased group would depend more on the manual performance than those in the misuse-biased group would in both Ca- and Cm-displayed situations.

Method

Participants Eighty-three university students participated in the experiment. The participants were divided into four groups: 21 for the line task and 22 for the road task in the Ca-displayed situation; and 20 for the line task and 20 for the road task in the Cm-displayed situation.

Procedure Basically the same procedure was followed as in Experiment 1. However, in Experiment 2, throughout the experiment, the value of Ca was displayed and that of Cm was not displayed in the Ca-displayed situation, and the participants were not informed of the value of Cm. On the other hand, the value of Cm was displayed and that of Ca was not displayed in the Cm-displayed situation, and the participants were not informed of the value of Ca.

Result and Discussion

First, in each group, the average percentage of using the auto mode was recorded at each combination of Ca (5 levels) $\times$ Cm (5 levels). Second, we fitted the logistic curve to the 25 data points. The Hosmer-Lemeshow test was neither significant in the line ($p = .83$) nor road ($p = .99$) tasks in the Ca-displayed situation. Also, the test was neither significant in the line ($p = .97$) nor road ($p = .98$) tasks in the Cm-displayed situation. These results indicated that the logistic curves described the data well. The top two rows in Table 2 show the odds ratios of Ca and Cm, and the product of the odds ratios of Ca and Cm in each of the Ca- and Cm-displayed situations.

Table 2: Odds ratios of Ca and Cm, and product of odds ratios of Ca and Cm in Experiment 2.

		Ca-displayed			Cm-displayed		
		OR of Ca	OR of Cm	Product of ORs of Ca and Cm	OR of Ca	OR of Cm	Product of ORs of Ca and Cm
Line		2.106	0.557	1.175	2.143	0.333	0.714
Road		2.229	0.548	1.222	1.418	0.453	0.643
Line	Misuse	2.443	0.568	1.388	2.506	0.314	0.787
	Disuse	1.996	0.521	1.040	1.908	0.334	0.638
Road	Misuse	2.362	0.556	1.314	1.441	0.525	0.757
	Disuse	2.230	0.513	1.146	1.466	0.342	0.502

First, we investigated the selection strategy of the effort control in each situation. Table 2 shows that in the Ca-displayed situation, the product of the odds ratios of Ca and Cm exceeds 1 in both tasks. This result shows that the effort control was performed based on the system-based selection in both tasks in the Ca-displayed situation. On the other hand, in the Cm-displayed situation, the product of the odds ratios of Ca and Cm falls below 1 in both tasks. This result showed that the effort control was performed based on manual-based selection in both tasks in the Cm-displayed situation. Thus, the results confirmed that the Ca-displayed situation facilitated system-based selection, and the Cm-displayed situation facilitated manual-based selection.

Next, we compared the promotions of the system-based selection in the Ca-displayed situation and the manual-based selection in the Cm-displayed situation in each task. In particular, we compared the product of the odds ratios of Ca and Cm in the Ca-displayed situation with the reciprocal number of the product of the odds ratios of Ca and Cm in the Cm-displayed situation.

In the line task, the participants in the Ca-displayed situation depended 1.175 times more on system performance than on manual performance. In contrast, the participants in the Cm-displayed situation depended 1.400 ($= 1/0.714$) times more on manual performance than on system performance. Moreover, in the road task, the participants in the Ca-displayed situation depended 1.222 times more on system performance than on manual performance. In contrast, the participants in the Cm-displayed situation depended 1.553 ($= 1/0.643$) times more on manual performance than on system performance. This result showed that the participants' dependency on manual performance in the Cm-displayed situation was larger than that on system performance in the Ca-displayed situation. Thus, the results confirmed that the promotion of the manual-based selection in the Cm-displayed situation was larger than that of the system-based selection in the Ca-displayed situation, and the manual-based selection in the effort control is robust human behavior.

Misuse- and Disuse-Biased Groups Next, in order to investigate the relationship between the tendency to use automation systems and the selection strategy of the effort control, we grouped the participants into two groups as in Experiment 1. In each misuse- and disuse-biased group engaging in each task in each situation, the average percentage of using the auto mode was recorded at each combination of Ca (5 levels) $\times$ Cm (5 levels). Second, we fitted the logistic curve to the 25 data points.

In the Ca-displayed situation, the Hosmer-Lemeshow test was neither significant in the misuse- ($p = .80$) nor disuse- ($p = .94$) biased groups in the line task. Also, the test was neither significant in the misuse- ($p = .97$) nor disuse- ($p = .99$) biased groups in the road task. Moreover, in the Cm-displayed situation, the test was neither significant in the misuse- ($p = .94$) nor disuse- ($p = .98$) biased groups in the line task. Also, the test was neither significant in the misuse- ($p = .99$) nor disuse- ($p = .86$) biased groups in the road task. These results indicated that the logistic curves described the data well. The bottom four rows in Table 2 show the odds ratios of Ca and Cm, and the product of the odds ratios of Ca and Cm in the eight groups.

In each task in each situation, we compared the products of the odds ratios of Ca and Cm in the misuse- and disuse-biased groups. The product was lower in the disuse-biased group than in the misuse-biased group in both tasks in both situations. This result showed that the participants in the disuse-biased group depended more on manual performance for their effort control than those in the misuse-biased group did. Thus, the results confirmed that there is a robust relationship between the tendency to use automation systems and the selection strategy of effort control.

General Discussion

Selection Strategy of Effort Control

As a result of our experiments, we found that people perform effort control based on manual-based selection rather than on system-based selection. This result is consistent with the findings of the preceding studies about performance evaluation of a system and manual operations and situation awareness. In our experiments, the participants needed to evaluate the performance of the system and manual operations in order to allocate the function to either the manual operator or the automation system. However, they might not be able to consider such evaluations from both viewpoints evenly because of the limitation of human cognitive capacities. This limitation led the participants to perform effort control based on a single viewpoint. As a result, manual-based selection was adopted because active monitoring was more preferred than passive monitoring.

Moreover, in this study, we investigated the relationship between the tendency to use an automation system and the selection strategy of effort control. We also found that the disuse-biased users depended more on manual performance than the misuse-biased users did. This result might be caused by the differences in the abilities of the misuse- and disuse-biased participants for evaluating the system performance.

Madhavan and Phillips (2010) experimentally investigated the relationship between the computer self-efficacy (CSE) and the tendency to use automation systems. CSE reflects persons' self-judgment of their abilities to use a computer. In their experiment, the high-CSE participants calibrated the system performance more appropriately and utilized an automation system more adaptively than the low-CSE participants did. On the other hand, the low-CSE participants could not appropriately estimate the high performance of the system and tended to underutilize it. In our experiments, there is a possibility that the disuse-biased participants had lower CSE than the misuse-biased participants, and were inferior in abilities to evaluate the system performance. From their limitations of the abilities in evaluating the system performance, the disuse-biased participants tended to perform the effort control depending on the manual performance more saliently.

Influence of Tasks

We used two types of tracking tasks. It was more difficult to evaluate both auto and manual performances in the road task than in the line task. In the line task, the circle vehicle could keep moving away from the line. Therefore, both system and manual performances were visibly externalized. On the other hand, in the road task, the dot did not go over the edge of the road and was knocked back into the road. Therefore, both system and manual performances were not externally represented.

In Experiment 1, the participants performed the effort control based on the manual-based selection more saliently in the road task than in the line task. In order to compensate for the difficulty in evaluating the performances in the road task, the participants might evaluate the controllability of the dot and use it as a cue in the effort control. Metcalfe and Greene (2007) experimentally investigated the nature of human judgment of agency (JOA), i.e., self-judgment of controlling their own actions. In their experiment, they manipulated the degree of the participants' operability of mouse movements that controlled the movement of an object on a computer screen. The participants appropriately judged the degree of controllability of the object as their JOA. In our experiment, it was more difficult to evaluate both system and manual performances in the road task than in the line task. In such a situation, the participants could estimate their controllability of manual operation and compensate for the difficulty.

On the other hand, in Experiment 2, there was no clear difference in the selection strategy of the effort control between the line and road tasks. There is a possibility that explicit information of Ca and Cm had a strong impact on the selection strategy and attenuated the difference between the tasks. A detailed investigation of this result should be conducted as future work.

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