Paper:

Activeness Improves Cognitive Performance in Human-Machine Interaction

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In human-machine interaction, automation brings both advantages and potentially unpredictable disadvantages to human cognitive performance. In this study, we hypothesized that active behavior improves cognitive performance in human-machine interaction, and verified this hypothesis through three experiments. Experiment 1 examined the relationship between activeness and reaction time in a target-search task. Experiments 2 and 3 analyzed the factors that improved cognitive performance. Experimental results demonstrated that activeness positively affects cognitive performance and suggested that predictability associated with activeness plays a key role in improving cognitive performance.

Keywords: activeness, sense of agency, prediction, reaction time

1. Introduction

Automation has progressed with rapid expansion in computer technologies. Parasuraman and Riley have defined automation as execution by a machine agent, usually a computer, of a function that was previously carried out by a human being [1]. Machine agents have even begun to undertake various tasks for humans and have brought significant benefits with them.

Simple automation is useful for stand-alone machines. In human-machine interaction, however, automation has drastically changed the cognitive demands and responsibilities of human operators [2, 3]. Simple automation thus may bring both advantages and potentially unpredictable disadvantages [1, 4].

Situation awareness consists of the following three aspects [5]:

(i) perception of elements in the environment within a certain time and space,

(ii) comprehension of the meaning of elements,

(iii) projection of the status of elements in the near future.

In human-automation interaction, situation awareness is critical to good human decision-making and performance [6]. According to past studies [5, 7, 8], human awareness of environmental change falls to a low level when these changes are controlled by another agent. That is, the feeling that "I" control the machine is very important in human-machine interaction.

In the fields of psychology and neuropsychiatry, much research has been conducted on the sense of agency, i.e., the sense that "I" am the one who is causing or generating an action [9, 10].

Some studies have suggested that the inferior parietal cortex plays a crucial role in judging whether an action is caused or generated by oneself or by others [11–13]. Several areas of the brain contribute to voluntary action. Signals related to voluntary action that converge on the primary motor cortex are transmitted to the spinal cord and muscles. There are two principal inputs to the primary motor cortex [14]. One is from the presupplementary motor area [15] and the other is from the premotor area [16]. The former is for the voluntary actions without external stimuli and the latter is for those responding to external visual signals. In parallel with signal transmission to the primary motor cortex, copies of signals are considered to have been sent to the inferior parietal cortex [17]. In this area, these copies are used to predict the sensory consequences of movement.

Blakemore et al. have proposed a *comparator model* for explaining the sense of agency [18]. Two types of internal models are generally proposed for motor control in the human brain – a forward model and an inverse model. These models simulate motor system response. The inverse model determines the motor commands required to achieve a desired state. When a person's arm reaches a certain position, for example, the position is input to the inverse model and the model calculates the required arm motor command. The forward model uses an efferent copy of the motor command to predict the sensory consequences of movement. The comparator model is based on the forward model [19–21].

The above motor command is transmitted to the muscles through the parietal cortex, and an efference copy of the command is simultaneously sent to the forward model. The forward model consists of two parts, a forward dynamic model and a forward output model. The forward dynamic model predicts the consequences of motor commands and a comparison is made to the desired state. The forward output model predicts sensory consequences, which are then compared to the actual sensory feedback of movement. Sensory discrepancy is calculated based on this comparison. A judgment on whether movement is self-generated is made based on discrepancy. In other words, a large difference between predicted and the actual sensory consequences attributes movement to others, while a small difference attributes movement to one's self.

Based on the comparator model, it is important for the sense of agency to generate an efference copy, i.e., to perform voluntary actions plays an important role in the sense of agency.

In this study, we hypothesized that voluntary action, or activeness, improves human cognitive performance. The objective of this paper is to verify this hypothesis through three sets of experiments. According to the comparator model, motor commands generate efference copies to predict sensory feedback, which leads to the sense of agency. That is, activeness influences both the prediction of sensory feedback and the sense of agency. In this paper, we examine how these factors associated with activeness influence human cognitive performance through experiments.

This paper is organized as follows: Section 2 describes experiments for examining the influence of active target searching behavior on reaction time. In Section 3, the relationship between the sense of agency and reaction time is discussed through experiments. Section 4 describes experiments for examining the influence of predictability on reaction time. In Section 5, we discuss the hypothesis mentioned above on the basis of experimental results. We conclude the paper and mention projected work in Section 6.

2. Experiment 1

The objective of this set of experiments is to examine the effect of activeness on cognitive performance.

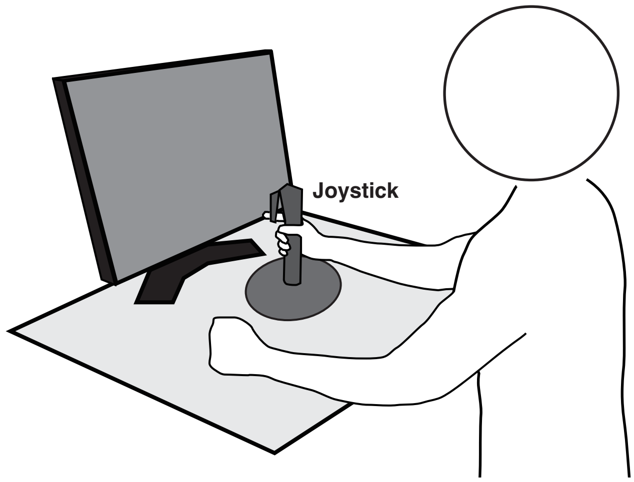

Fig. 1. Experimental apparatus.

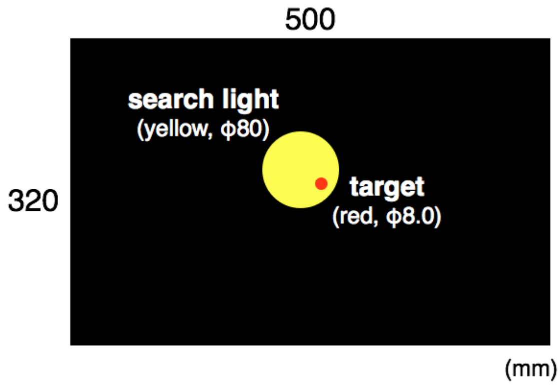

Fig. 2. Appearance of the computer screen. Searchlight is a yellow circle with 40 mm radius, and target is a red circle with 4 mm radius. Participants search for the target in a search area (320 mm × 500 mm) using a searchlight.

2.1. Method

2.1.1. Participants

This set of experiments was carried out under ethical approval, and participants gave informed consent before experiments were started. A total of 21 healthy volunteers (aged 20–28 years, mean = 22.5; 12 men, 9 women) participated in experiments.

2.1.2. Procedure

Experiments were conducted in a dark silent room. Visual stimuli were created and experiments conducted using Visual C++ and OpenGL on a Windows PC.

Participants were required to sit in front of a computer screen and hold a joystick (Saitek Cyborg evo Force; Mad Catz, Inc.) in the right hand (**Fig. 1**). The joystick was equipped with a trigger to input user commands.

In experiments, participants searched for a target – a red circle with a 4 mm radius – in the area illuminated by a searchlight – a yellow circle with 40 mm radius (**Fig. 2**). Participants were required to pull the joystick's trigger as soon as they detected the target. The speed of the search-

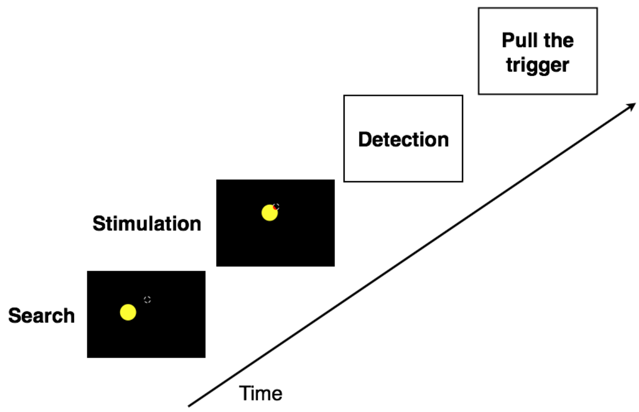

Fig. 3. Procedure of an experimental trial. Time interval was measured between stimulation and response moments (pull the trigger).

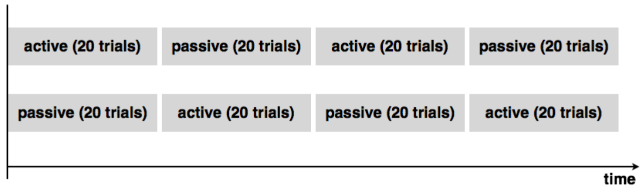

Fig. 4. Procedure of Experiment 1.

light was 60 mm/s. **Fig. 3** shows the procedure of an experimental trial.

To examine the influence of activeness on human cognitive performance, the following two conditions were compared:

- **Active condition:** A participant used the joystick to control the searchlight.
- **Passive condition:** The searchlight was moved automatically, i.e., diagonally in linear uniform motion and bounced off the search area boundary. Angles of incidence and reflection are equal.

Before experiments, participants practiced enough to control the searchlight using the joystick.

In experiments, reaction time was measured. Reaction time is defined as the time interval between the visual stimulus (target) presentation and the moment the trigger is pulled.

Experiments consisted of 4 blocks – 2 active conditions + 2 passive conditions – with 20 trials conducted in each block. The sequence of blocks – active, passive, active, passive or passive, active, passive, active – was counterbalanced among participants (**Fig. 4**).

2.2. Results

Figure 5 shows a box plot of reaction time in experiments. Each box shows the 50th percentile as well as 25th and 75th. Mean reaction time under the active condition was 435.50 ms ($SD = 35.73$) and that under the passive condition was 464.99 ms ($SD = 41.43$).

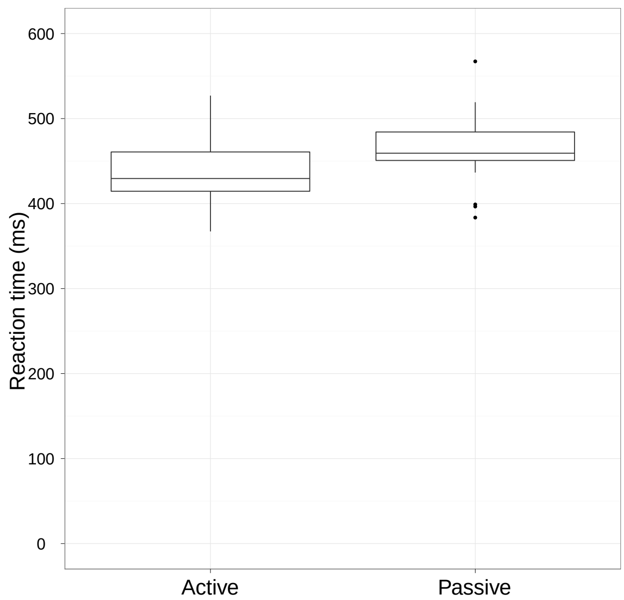

Fig. 5. Box plot of reaction time under active and passive conditions.

Mean reaction time was tested using a bootstrap paired t-test [22] in which the sample size was 2000. There was a significant difference between active and passive conditions ($p < 0.01$).

Based on the above results, we concluded that the active searching behaviors shorten the reaction time. That is, activeness can improve human cognitive performances.

3. Experiment 2

The objective of this set of experiments is to examine the relationship between a sense of agency and cognitive performance.

3.1. Method

3.1.1. Participants

This set of experiments was carried out under ethical approval, and participants gave informed consent before experiments were started. A total of 21 healthy volunteers – the same ones who were in Experiment 1 – participated.

3.1.2. Procedure

The experimental apparatus and the procedure of a trial were the same as in Experiment 1.

Here, it was necessary to change the degree of the sense of agency. Essentially however, the sense of agency cannot be controlled directly by an experimenter. According to past studies [23, 24], a temporal delay between control and feedback may decrease the sense of agency. We therefore set temporal delays between joystick input and searchlight motion. Five temporal delay conditions – 0, 100, 300, 500, or 700 ms – were used to change the degree

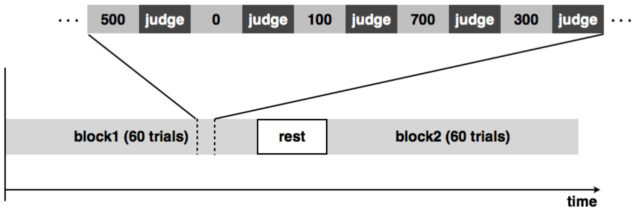

Fig. 6. Procedure of Experiment 2.

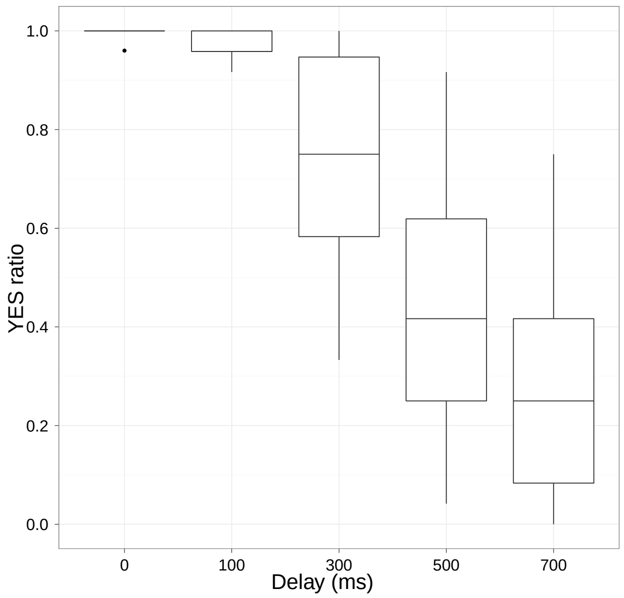

Fig. 7. Relationship between feedback delay length and degree of sense of agency.

of the sense of agency. Participants were not informed about these delays.

Figure 6 shows the experimental procedure. The experiment consisted of 2 blocks. In each block, 60 trials (5 conditions $\times$ 12 times) were conducted in random sequence. Participants took breaks between blocks. Just after each trial, participants were asked to judge whether they felt that they moved the searchlight by themselves or not.

3.2. Results

Figure 7 shows the relationship between sensory feedback delay length and the degree of the sense of agency. The horizontal axis shows the length of temporal delays between joystick input and searchlight motion. The vertical axis is the ratio of trials in which participants judged the motion of the searchlight as self-generated ("YES"). Each box shows the 50th percentile as well as 25th and 75th. The average "YES ratio" of each feedback delay length (0, 100, 300, 500, or 700 ms) was 0.994 ($SD = 1.46 \times 10^{-2}$), 0.968 ($SD = 3.38 \times 10^{-2}$), 0.749 ($SD = 0.207$), 0.450 ($SD = 0.251$), and 0.286 ($SD = 0.216$), respectively.

As a whole, the ratio tended to decrease as delay increased. Results were analyzed using a bootstrap paired

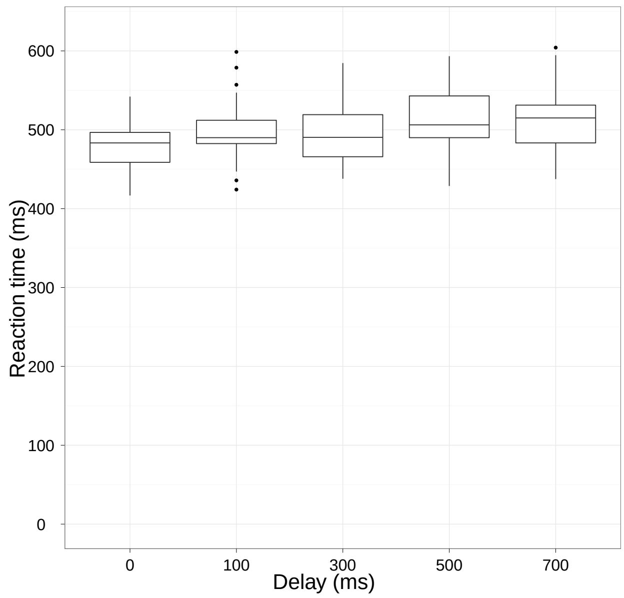

Fig. 8. Relationship between feedback delay length and reaction time.

t-test with Holm's correction [25]. Results showed significant differences between each pair of two conditions ($p < 0.01$). Results support the comparator model [18].

Based on results, the sense of agency could be controlled indirectly by sensory feedback delays in these experiments.

Figure 8 shows a box plot of reaction time to sensory feedback delay. Each box shows the 50th percentile as well as 25th and 75th. The average reaction time for each feedback delay length (0, 100, 300, 500, and 700 ms) was 481.57 ($SD = 33.04$), 498.51 ($SD = 42.63$), 500.28 ($SD = 39.19$), 511.53 ($SD = 42.47$), and 512.92 ($SD = 44.38$), respectively.

The reaction time tends to increase as delay increases. A bootstrap paired t-test with Holm's correction was conducted for each combination of conditions. According to the test, there were significant differences between the no-delay condition (delay = 0 ms) and other conditions (delay = 100, 300, 500, and 700 ms), and between 100 ms and 500 ms ($p < 0.05$). Differences for other combinations were not significant, however ($p > 0.05$).

In order to analyze the relationship between the sense of agency and cognitive performance, reaction time was normalized. In the normalization process, the mean reaction time of each participant under the no-delay condition was set to 1.0, and the mean reaction time at other conditions was divided by that under the no-delay condition. Normalization enabled us to put together results of participants.

The relationship between the degree of the sense of agency and normalized reaction time is shown in **Fig. 9**. Normalized reaction time tended to decrease as the degree of the sense of agency increased. There is a negative correlation ($r = -0.46$) between the degree of the sense of agency and reaction time.

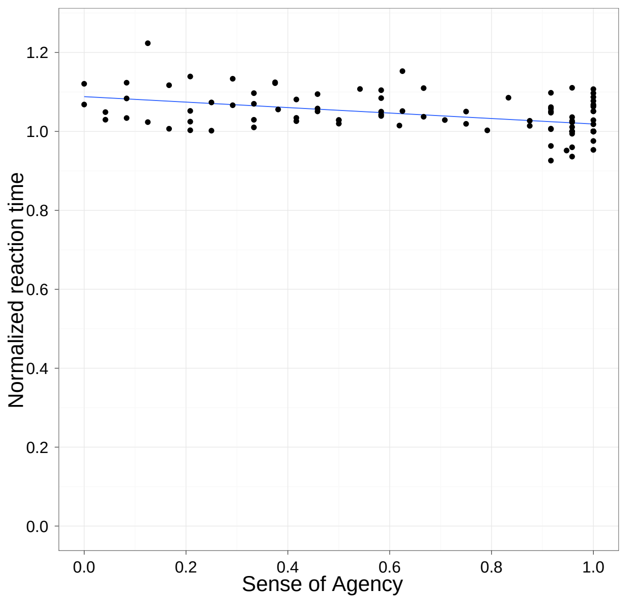

Fig. 9. Relationship between degree of sense of agency and normalized reaction time.

Fig. 10. Procedure of Experiment 3.

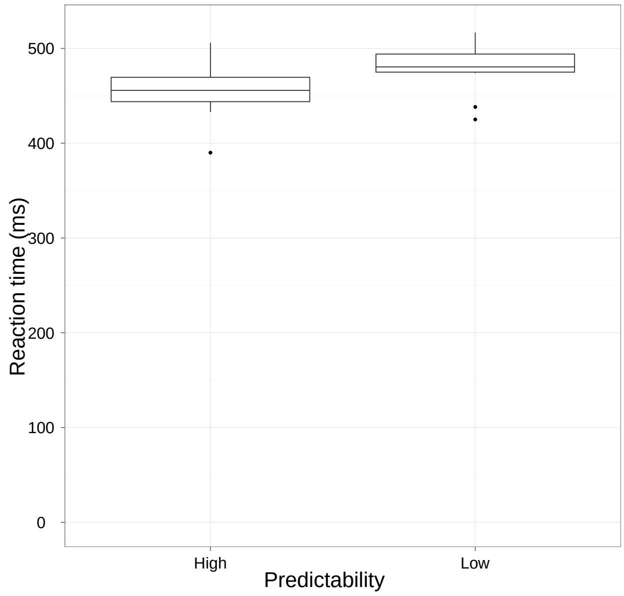

Fig. 11. Box plot of reaction time under high/low predictability conditions.

4. Experiment 3

The objective of this set of experiments is to verify the effect of predictability on cognitive performance.

4.1. Method

4.1.1. Participants

Experiments were carried out under ethical approval, and participants gave informed consent before experiments were started. A total of 10 healthy volunteers (aged 21–28 years, mean = 23.0; 7 men, 3 women) participated in experiments.

4.1.2. Procedure

The experimental apparatus and the procedure of an experimental trial were the same as in Experiments 1 and 2.

To examine the influence of predictability on reaction time, the searchlight was moved automatically and the following two conditions were compared:

- **High predictability condition:** The searchlight was moved diagonally in a linear uniform motion and bounced off the boundary of the search area. The angles of incidence and reflection are equal, the same as under the passive condition in Experiment 1.
- **Low predictability condition:** The searchlight's direction was changed at random timing and direction. When it reached the boundary of the search area, it disappeared and emerged at a random location.

Before experiments, participants practiced to control the searchlight using the joystick. In experiments, reaction time was measured.

The experiment consists of 4 blocks (2 high predictability + 2 low predictability) – with 20 trials conducted in each block. The order of blocks – high, low, high, low or low, high, low, high – was counterbalanced among participants (**Fig. 10**).

4.2. Results

Figure 11 shows a box plot of reaction time in experiments. Each box shows the 50th percentile as well as 25th and 75th. Average reaction time under the high predictability condition was 454.91 ms ($SD = 29.42$) and that under the low predictability condition was 477.64 ms ($SD = 26.20$). Average reaction time was tested using a bootstrap paired t-test. There was a significant difference between high and low predictability conditions ($p < 0.05$).

5. Discussion

In Experiment 1, the active search condition was compared to the passive search condition. Participants were required to handle two tasks, searchlight control and target detection, under the active condition, while they were required to handle only one task, target detection, under the passive condition. Considering this from the viewpoint of workload, the passive condition burdened participants less than the active condition. This likely enabled participants to focus on the detection task and improve reaction time. Experimental results were, however, opposite those expected. This fact suggests that the substitution of machines for human beings may not always deliver good results in human-machine interaction.

Why was the reaction time under the active condition shorter than that under the passive condition? As mentioned, motor commands of voluntary movement generate efference copies, and the human brain predicts consequences of its own body movement. Human beings feel the sense of agency based on a comparison between sensory anticipation and actual sensory feedback. In this study, we considered that the sense of agency may have played an important role in the increase of cognitive performance, and conducted an experiment to examine the relationship between the sense of agency and reaction time (Experiment 2). The results of this experiment showed that reaction time decreased as the degree of the sense of agency increased. In experiments, the sense of agency was indirectly controlled by changing sensory feedback delay length. Considering the comparator model [18], however, indirect control not only changed the degree of a sense of agency but also enlarged the discrepancy in the comparison between predicted and actual sensory consequences. That is, controlling feedback delays caused a change in predictability.

In response to this, the relationship between the degree of predictability and cognitive performance was examined independently of the sense of agency in Experiment 3. Results showed that higher predictability shortened reaction time.

The results of Experiments 2 and 3 suggest that predictability greatly influences the fact that reaction time under the active condition is shorter than that under the passive condition. Although human beings can predict sensory consequences under passive conditions, based on the fact that the passive condition in Experiment 1 is the same as the high predictability condition in Experiment 3, prediction using efference copies of motor commands may be more accurate than prediction of externally generated movement.

In general, situation awareness has been stressed in the design of human-machine systems. According to Endsley's definition [5], the highest level of situation awareness is "an understanding of what will happen with the system in the near future." Existing excellent automated systems provide users with easily understandable information on system behavior to increase the level of situation awareness. Experiment 3 results support this effort and we concluded that the pursuit of predictability is very important. Experiment 1 results, in contrast, suggest that even if automated systems show easily predictable behavior, user task performance will be lower than when users actively operate systems.

In other words, the main contribution of this study is clarifying the limitation on existing automated systems in improving task performance and demonstrating the need to consider user activeness in the design of human-machine systems.

6. Conclusions

In this study, we have hypothesized that activeness improves cognitive performance in human-machine interaction, and have verified this hypothesis through experiments. Experimental results supported the hypothesis and have suggested that predictability is a crucial element in the improvement of cognitive performance. Results have also suggested that prediction during active search behavior achieves higher accuracy than that during a passive search.

In the future, the development of an automated system based on this study will be required. Automation negatively affected the performance of simple target search task, so we should design a mechanism in which the user plays an active role and human-machine interaction is improved.

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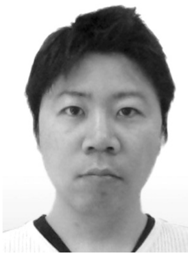

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- The Institute of Electrical and Electronics Engineers (IEEE)
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)
- The Society of Instrumentation and Control Engineers (SICE)