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Psychological Experiments on Avoidance Action Characteristics for Estimating Avoidability of Harm to Eyes from Robots

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***Abstract*— In this study, psychological experiments are conducted to investigate harm-avoidance action characteristics in humans in close contact with robotic devices. For the experiments, a situation is created in which the sharp end-effector tip of a robot suddenly approaches the eyes of a facing participant. The avoidance reaction time is defined as the time interval from the beginning of the end-effector motion to when the participant begins movement to avoid harm. The results suggest that the avoidance reaction time does not depend on the type of work being performed but on the initial distance between the human's eyes and the approaching object. Using this information, safe human-robot working distances can be determined.**

I. Introduction

A. Background

We previously proposed and developed a next-generation cell production system in which a human and robot work cooperatively in a practical study [1]. In that system, light curtains were placed between the human worker and the robot for safety reasons. However, there is a strong desire to remove the light curtains at production sites because the reduction in available space tends to lead to a decrease in productivity.

Light curtains can be removed if the coexistent robot is basically designed as being inherently safe, yet there is always the fundamental problem that a powerless robot grasping a sharp-edged object will cause more harm to a human eye compared with another part of the body (e.g., a shoulder). Therefore, there should be a sufficient distance between the human and robot to ensure a safe working environment.

Humans, by nature, perform harm-avoidance behavior when perceiving a threat. Hence, the possibility of avoiding or limiting harm (hereafter referred to as "avoidability"), which is one element of risk [2], should be taken into consideration when the sufficient human-robot distance is assessed. Nonetheless, avoidability currently tends to be either neglected or intuitively estimated because harm-avoidance behavior is an unexplored human factor. Thus, it is difficult to assess the optimal human-robot distance in a coexistence space.

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B. Related Studies

Previous research into the safety of human-robot interactions has focused mainly on the end result of a harmful interaction. Oberer and Schraft [3] investigated injury indices by simulating collisions of a robot with the head, chest, and pelvis of a dummy by using finite element models, and Haddadin *et al.* [4] followed up with head and chest collision experiments. Park *et al.* [5] proposed a model for the collision between a human head and a robot and showed that the optimal elastic modulus and thickness of the robot covering could be determined to prevent skin injuries. However, harm-avoidance behavior, which a human is most likely to engage in, was not taken into consideration in these studies.

Human reactions have been considered in some studies. Ikeura *et al.* [6] measured the galvanic skin reflex of a subject when a robot approached straight toward the subject's face to investigate which robot motions the human regarded as threatening. Yamada *et al.* [7] measured the pupillary diameter of the subject when a robot endtip was accelerated toward the subject's face to identify robot motion conditions that aroused human fear. However, statistical investigations of the characteristics of avoidance actions against approaching robot motion have not been conducted.

We conducted psychological experiments to investigate human harm-avoidance action characteristics during a particular situation in which human's eyes were threatened during a human-robot interaction [8].[1] This paper presents the experimental results that contribute to reasonably estimating avoidability.

II. Method for Estimating the Reaction Time Distribution

We deal with the reaction time (RT) as a parameter that represents the characteristics of avoidance actions. In this study, probability distributions of the RT are estimated from RT data obtained in the experiments. We use the kernel estimator [9] to estimate the RT distribution. This is expressed as

$$\hat{f}(t) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{t - T_i}{h}\right), \qquad (1)$$

where t is the RT, n is the total number of RTs, h is the bandwidth, T_i is the i-th RT, and $K(t)$ is the kernel function.

[1] The present study was approved by a local ethics committee.

Here, the standard normal probability density function is used for $K(t)$:

$$K(t) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right). \tag{2}$$

The bandwidth is calculated by the method proposed by Silverman [10], which is expressed as

$$h = \frac{0.9}{n^{1/5}} \min\left(s, \frac{Q_3 - Q_1}{1.34}\right), \tag{3}$$

where s, Q_1, and Q_3 are the standard deviation and the first and third quartile of the RT data, respectively. Accordingly, $Q_3 - Q_1$ is the interquartile range of the RT data.

III. Psychological Experiment I

We consider a general situation in which a gripper or grasped object of a next-generation robot that is desired to coexist with humans becomes a mechanical hazard. In reference to a practical study [1], we assume a situation in which a sharp end-effector tip of a production site robot suddenly attacks the eyes of a worker sitting opposite.

In the assumed situation, the worker essentially performs harm-avoidance behavior based on visual and auditory information. Nevertheless, workers may not necessarily hear the motors installed in the robots while in the actual working environment. For this reason, we focus on the more hazardous situation in which visual information only is provided to the worker.

A diagram of the psychological experiments is shown in Fig. 1.

A. Experimental Overview

Four types of tasks were set that resembled work performed at production sites. The objective of the experiment was to investigate whether human avoidance-action characteristics are influenced by the type of task.

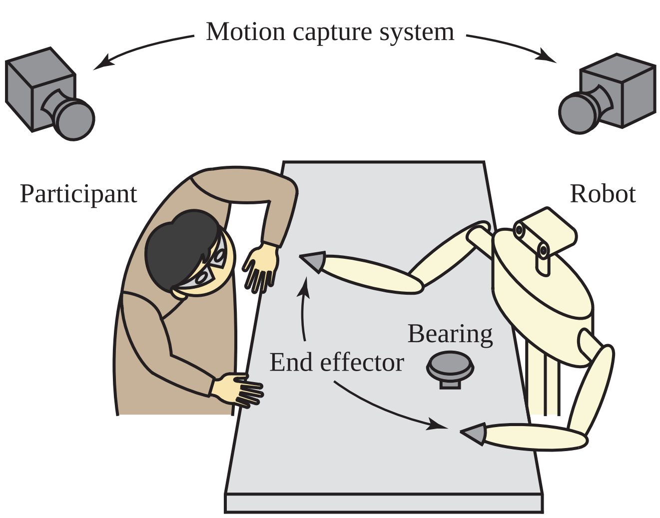

Fig. 1. Illustrative diagram of the psychological experiments

1) Apparatus: An upper-body humanoid robot (HIRO, Kawada Industries, Inc.), designed to operate collaboratively with a human [1], [11], was used in the experiments. A photograph of the robot is shown in Fig. 2. The participant wearing protective glasses and the robot were separated by a working table. To minimize harming the participant, the original end effectors for picking up and placing mechanical parts were replaced with square pyramid-shaped flexible polyurethane foam.

2) Participants: Eleven people, six males and five females between the ages of 19 and 28, participated in the experiment. Every participant was healthy with good eyesight; no one reported suffering from belonephobia.[2]

3) Experimental Setup: Each participant wore a cap on which motion capture markers were attached and sat on a stool in front of the robot. The participants wore noise-canceling earphones (NW-A845, Sony Corporation) to block any external auditory information; they instead listened to sounds recorded in a factory. The participants were exposed to the working area of the robot and performed the following four tasks.

- Task A Inserting two mechanical parts, i.e., rollers and retainers, between the bearing rings using tweezers.
- Task B Removing the rollers between the bearing rings using tweezers.
- Task C Silently reading a document shown on a liquid crystal display (LCD).
- Task D Gazing at parts between the bearing rings.

Tasks A, B, and D were conducted with the bearing rings shown in Fig. 3. Task A was performed in a manner similar

Fig. 2. Upper-body humanoid robot

[2]For safety reasons, initial experiments had to be conducted with young people in good health who seemed to have reasonably good reactions.

(a) Tasks A and D (b) Task B

Fig. 3. Bearing rings used for the tasks

to the way workers perform the task in actual production.

When the participant performed these tasks, the robot initially idled without motion, and one end effector at the tip of the robot arm suddenly approached the eyes of the participant.[3] The movement of the participant and robot were captured by a video camera, with the motion capture system recording the participant's head movement.

B. Experimental Conditions

The probability distribution of the foreperiod for a participant not expecting the timing of stimulus is often modeled using an exponential distribution [12]. In this manner, statistically random foreperiods were used by taking the sum of 10 s and exponential random values with a mean of 20 s, excluding those longer than 90 s in the experiment.

Fig. 4 shows a schematic diagram of the locations and distances for psychological experiment I. The device for the task, the bearing rings or the LCD, was located at the position indicated by the bold cross. The initial distance between the participant's eyes and an end-effector tip was set to be approximately 400 mm. Each participant was asked to confirm that the end-effector tips were in his or her peripheral vision when the tips were located at a viewing angle of approximately $40°$ with the task position in the center of the visual field. In a trial, the end-effector tip arrived in the vicinity of the participant's initial eye position at the end of the robot motion.

On the assumption that the robot fell into a runaway state, the maximum speed of the end-effector tip was set to approximately 960 mm/s. The initial acceleration was set to approximately 4400 mm/s^2. The approaching paths of both end effectors were elliptical and symmetrical, and the approaching motion profile was the same in each trial.

C. Experimental Procedure

Each participant performed 24 trials: six trials for each task. Tasks were assigned in a random order to prevent any order effects. The approaching end effector was also chosen to be random for each trial.

D. Experimental Results

1) Avoidance RT Distributions for All Types of Tasks: In this study, the avoidance RT is defined as the time

[3]Every participant was informed in advance that the end effector would approach his or her eyes.

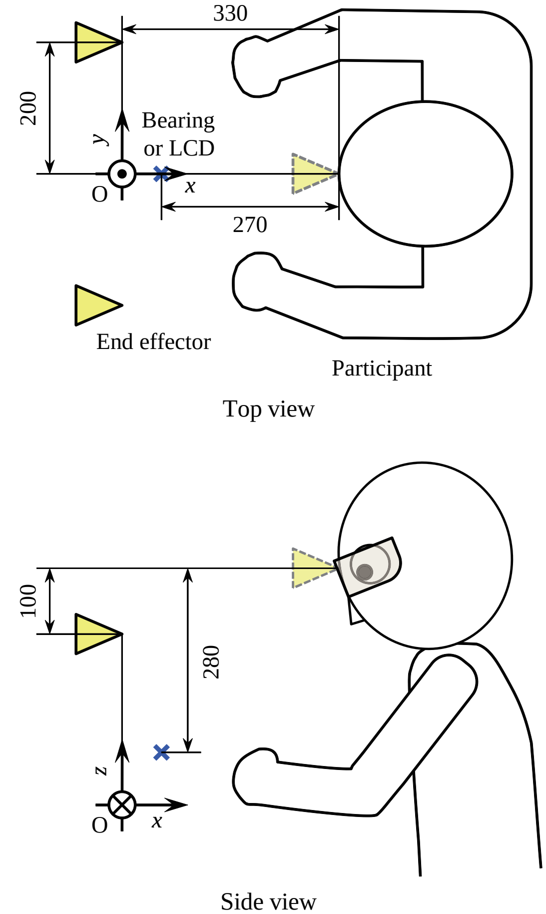

Fig. 4. Schematic diagram of the interactive human-robot locations during psychological experiment I (unit: mm)

interval from the beginning of the end-effector motion to the beginning of the participant's head movement.

Fig. 5 shows the avoidance RT distributions estimated with respect to each task based on the data from all participants. The graph shows that the positions of the leading edges as well as the positions of the distribution peaks do not differ notably from each other.

2) Statistical Analysis: Statistical tests were carried out to investigate whether the task had any effect on the avoidance RT. Because conditions applicable to parametric tests were not met, we used the Steel-Dwass test [13], [14], which is a nonparametric test for investigating whether the difference between two of more than three groups is significant. The null hypothesis was set such that the avoidance RT for each pair of tasks was identical. Table I summarizes the results of the Steel-Dwass tests based on the avoidance RT data from all participants. From this table, the difference between any combination is considered insignificant at a significance level of $\alpha = 0.05$.

Therefore, the avoidance RT does not appear to depend on the type of work.

3) Effect of Participant Posture on the Avoidance RT: We consider the possibility that participant posture at the moment the end effector began to move affected the avoidance RT.

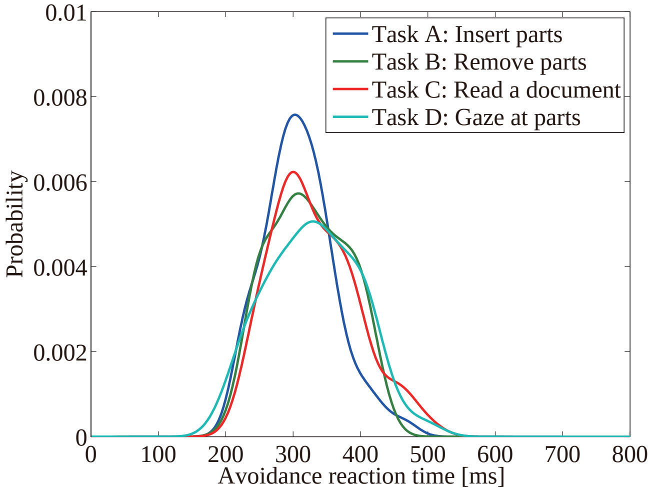

Fig. 5. Probability distributions of the avoidance RT for all types of tasks

TABLE I
STEEL-DWASS TESTS FOR THE AVOIDANCE RT BETWEEN THE TASKS

Tasks	Range of two-sided p-value
A & B	$p > 0.20$
A & C	$0.10 < p < 0.20$
A & D	$p > 0.20$
B & C	$p > 0.20$
B & D	$p > 0.20$
C & D	$p > 0.20$

Hence, we defined the x-coordinate of the participant's eyes at this moment as x_{e1} and carried out further analysis. Here, we regard the position of the eyes to be that of the glabella. The median of the x_{e1} data from all participants was denoted by $\tilde{x}_{e1}$, and all trials were then divided into trials F in which $x_{e1} < \tilde{x}_{e1}$ and trials B in which $x_{e1} > \tilde{x}_{e1}$. Namely, type F trials are those in which the participant sat forward.

For this test we used the Mann-Whitney U test [15], which is a nonparametric significant difference test for two groups. The null hypothesis was set such that the avoidance RT for F and B was identical. The result of the Mann-Whitney U test for the avoidance RT between F and B was a two-sided p-value of 0.0002. From this, the difference between F and B is considered to be significant at a significance level of $\alpha = 0.001$.

This result suggests that the avoidance RT is shorter when the participant sits forward.

IV. PSYCHOLOGICAL EXPERIMENT II

A. Experimental Overview

The results of psychological experiment I suggest that the avoidance action characteristics are contingent on the initial distance between the human's eyes and the robot's end-effector tip. To investigate this dependence, psychological experiment II was conducted with three different initial positions of the end effectors. The experimental setup and conditions are similar to those in psychological experiment I except as described below.

1) Participants: Nine people, five males and four females between the ages of 18 and 28, participated in the experiment.

2) Experimental Setup: Each participant was exposed to the working area of the robot and performed task A as set in psychological experiment I.

B. Experimental Conditions

In the experiment, statistically random foreperiods were used by taking the sum of 10 s and exponential random values with a mean of 15 s, excluding those longer than 60 s.

Fig. 6 shows a schematic diagram of the locations and distances for psychological experiment II. The bearing rings were located at the position indicated by the bold cross. Three initial positions were set for the end effectors: pattern 1 started at the farthest position, while pattern 3 was the nearest. The initial distance between the participant's eyes and an end-effector tip was set to be approximately 470, 370, and 270 mm for patterns 1, 2, and 3, respectively. Each participant was asked to confirm that the end-effector tips were in his or her peripheral vision when the tips were located at a viewing angle of approximately 30° for all patterns with the task position in the center of the visual field. In a trial, the end-effector tip arrived at a point approximately 50 mm forward of the participant's initial eye position at the end of the robot motion.

Table II lists the motion parameters of the robot's end-effector tip for this experiment. The maximum speed and initial acceleration of the end-effector tip were set for each pattern, as shown in the table, based on the runaway assumption.[4]

C. Experimental Procedure

Each participant performed 60 trials, and the end-effector pattern and approaching end effector were both chosen to be random for each trial.

D. Experimental Results

1) Avoidance RT Distributions for All Types of Patterns: Fig. 7 shows the avoidance RT distributions estimated with respect to each end-effector pattern based on the data from all participants. The graph shows that each distribution peak position is different. There is a tendency also for a shorter

TABLE II
MOTION PARAMETERS OF THE ROBOT'S END-EFFECTOR TIP DURING PSYCHOLOGICAL EXPERIMENT II

Pattern	Maximum speed [mm/s]	Initial acceleration [mm/s^2]
1	~1330	~8900
2	~1180	~7500
3	~990	~6800

[4] We set the robot to output the same highest possible speed percentage for each pattern. The maximum speed and initial acceleration inevitably decreased in the order pattern 1, 2, 3 due to differences in the travel distance.

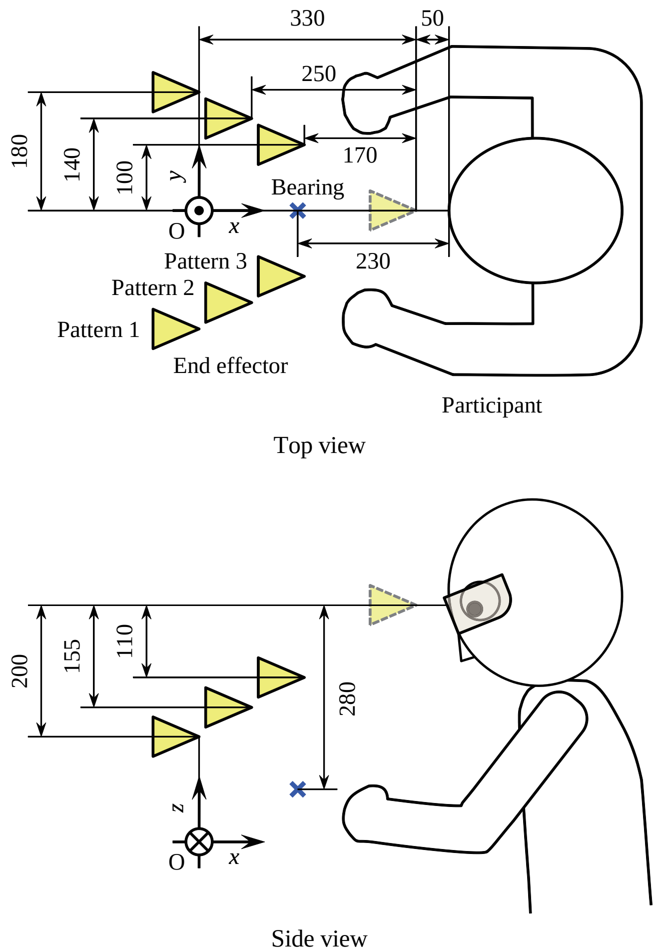

Fig. 6. Schematic diagram of the interactive human-robot locations during psychological experiment II (unit: mm)

initial distance between the human's eyes and the end-effector tip to result in a shorter avoidance RT.

2) Statistical Analysis: Steel-Dwass tests were carried out to investigate whether the end-effector pattern had any effect on the avoidance RT, and the null hypothesis was set such that the avoidance RT for each pair of patterns was identical. Table III summarizes the results of the Steel-Dwass tests based on the avoidance RT data from all participants. From this table, the difference between patterns 1 and 2 is marginally significant. The difference between patterns 1 and 3 is considered significant at a significance level of $\alpha = 0.001$, while that of patterns 2 and 3 is considered significant at a significance level of $\alpha = 0.05$.

TABLE III

Steel-Dwass Tests for the Avoidance RT between the Patterns

Patterns	Range of two-sided p-value
1 & 2	$0.05 < p < 0.10$
1 & 3	$p < 0.0001$
2 & 3	$0.025 < p < 0.05$

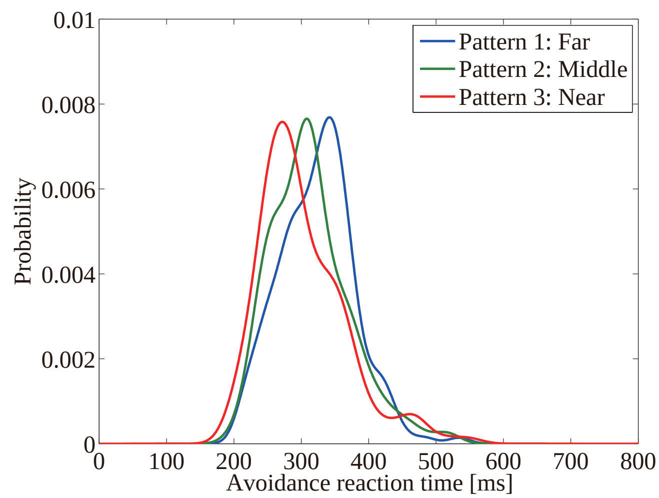

Fig. 7. Probability distributions of the avoidance RT for all types of patterns

These results suggest that a shorter initial distance between the human's eyes and the end-effector tip is associated with a shorter avoidance RT.

V. Discussion

Even though the types of tasks and end-effector patterns were limited, we could determine the avoidance action characteristics under experimental conditions.

The velocity and acceleration of an approaching object are likely to be important factors for the avoidance action characteristics. Differences in the maximum speed and initial acceleration of the robot's end-effector tip would affect the avoidance RT in psychological experiment II. A higher maximum speed and initial acceleration were expected to result in a shorter avoidance RT; however, the experiment showed the opposite. We concluded that the avoidance RT was, instead, mainly influenced by the initial distance between the participant's eyes and the end-effector tip.

It is possible that the participants prepared themselves for the approaching end effector in the present experiments. This is based on the idea that avoidance actions are associated with cognitive processes. In contrast, we consider avoidance actions to be reflexive processes with reference to the results of psychological experiment I, but we cannot rule out any cognitive influences at this point. The avoidance RT distributions, which statistically represent the avoidance action characteristics, can, however, be regarded as statistical distributions based on various psychological states. Hence, these findings can be used to reasonably estimate avoidability. For a simple example, based on the fact that the longest avoidance RT is approximately 550 ms as shown in Figs. 5 and 7, we can assess whether sufficient distance is provided in the coexistence space for preventing a human-robot collision. Thus, the findings can contribute to managing human-robot coexistence spaces by taking avoidability into consideration.

VI. Conclusions and Future Work

We have conducted psychological experiments to investigate human avoidance-action characteristics under a scenario in which a sharp end-effector tip of a robot suddenly approached the eyes of a participant sitting in front of the robot. While the results of psychological experiment I did not suggest that the avoidance RT depended on the type of work, they did suggest that the participant posture affected the avoidance RT. The results of psychological experiment II suggested that the avoidance action characteristics depend on the initial distance between the human's eyes and the approaching object.

We believe that avoidance actions are reflex processes; however, the influence of cognitive processes cannot be ruled out. The relationship between avoidance actions and the velocity and acceleration of an approaching object has not yet been clarified. These are areas for further study.

VII. Acknowledgment

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