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Study on Avoidance Action Parameters against a Sharp End-Effector Tip Approaching Human's Eyes

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Abstract— **In this study, a psychological experiment is conducted to investigate harm-avoidance action characteristics in humans in close contact with robotic devices. For the experiment, a situation is created in which the sharp end-effector tip of a robot suddenly approaches the eyes of a facing participant. We define three parameters that represent harm-avoidance action characteristics: the avoidance reaction time, maximum avoidance acceleration, and maximum avoidance speed. The results suggest that the avoidance reaction time depends on the initial distance between the human's eyes and the approaching object. The results show that there are individual differences in all parameters studied. The results also show that the avoidance reaction time is negatively correlated with the other two parameters, which have a strong positive correlation with each other. We conclude that the avoidance reaction time and maximum avoidance speed are considerable parameters on avoidance actions.**

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. The characteristics of avoidance actions have to be investigated to assess the optimal human-robot distance in a coexistence space.

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], [9].[1] We here discuss parameters that represent harm-avoidance action characteristics, based on the experimental results.

II. Psychological Experiment

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

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

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 experiment is shown in Fig. 1.

A. Experimental Overview

Three different initial positions of the robot's end effectors were set. The objective of the experiment was to investigate whether human avoidance-action characteristics are influenced by the initial distance between the human's eyes and the end-effector tip.

1) Apparatus: An upper-body humanoid robot (HIRO, Kawada Industries, Inc.), designed to operate collaboratively with a human [1], [10], was used. 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: Nine people, five males and four females between the ages of 18 and 28, participated. 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 task: they inserted two mechanical parts, i.e., rollers and retainers, between the bearing rings using tweezers. The task was conducted with the bearing rings shown in Fig. 3 and performed in a manner similar to the way workers perform the task in actual production. The participants were instructed to keep their work productivity as high as possible.

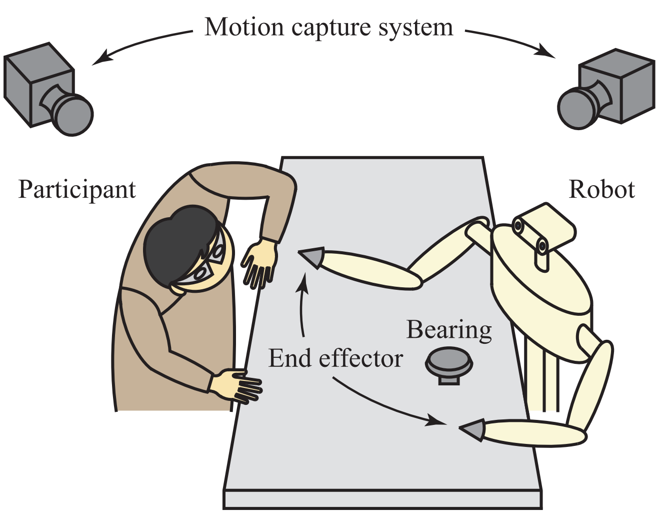

Fig. 1. Illustrative diagram of the psychological experiment

Fig. 2. Upper-body humanoid robot

Fig. 3. Bearing rings used for the task

When the participant performed the task with concentration, 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 (Motion Analysis Corporation) 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 [11]. In this manner, 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. 4 shows a schematic diagram of the locations and distances for this experiment. The bearing rings were located at the position indicated by the bold cross. Three initial

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

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

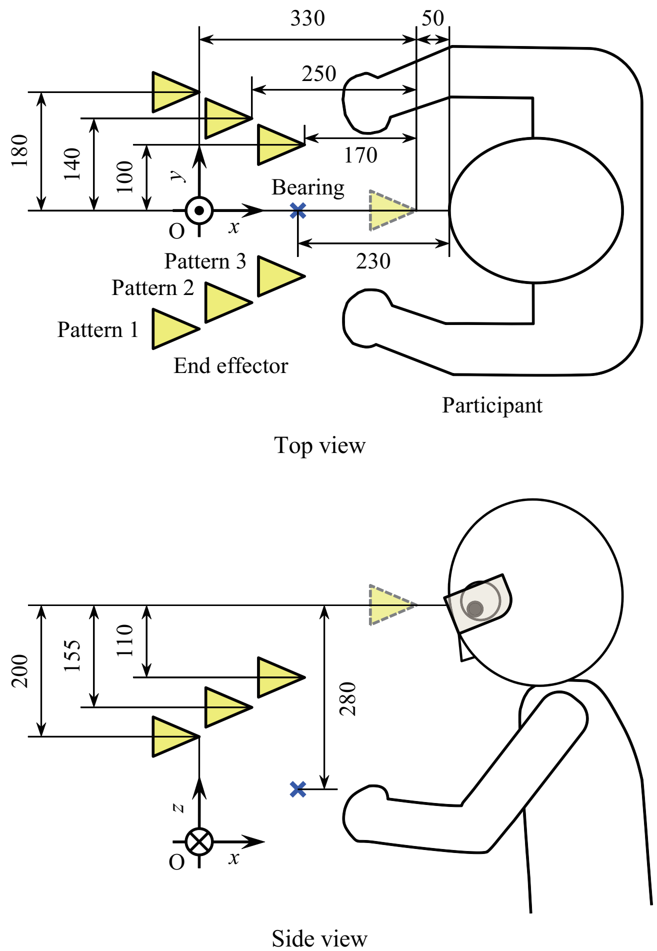

Fig. 4. Schematic diagram of the interactive human-robot locations during the psychological experiment (unit: mm)

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 I 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] The approaching paths of both end effectors were elliptical and symmetrical, and the approaching motion profile was the same for each pattern.

[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.

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

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

C. Experimental Procedure

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

D. Experimental Results

1) Statistical Analysis on the Avoidance Reaction Time: In this study, the avoidance reaction time (RT) is defined as the time interval from the beginning of the end-effector motion to the beginning of the participant's head movement.

Statistical tests were carried out to investigate whether the end-effector pattern had any effect on the avoidance RT. Because conditions applicable to parametric tests were not met, we used the Steel-Dwass test [12], [13], 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 patterns was identical. Table II 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 $\alpha = 0.05$.

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.

2) Investigation of Individual Differences in the Avoidance RT: Steel-Dwass tests were carried out to investigate whether the avoidance RT differed between participants, and the null hypothesis was set such that the avoidance RT for each pair of participants was identical. Tables III, IV, and V summarize the results of the Steel-Dwass tests between the participants based on the avoidance RT data in patterns 1, 2, and 3, respectively. Terms A–I denote the participants, and $*$, $**$, and $***$ denote whether the difference is considered significant at a significance level of $\alpha = 0.05$, $\alpha = 0.01$,

TABLE II
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	$0.025 < p < 0.05$

TABLE III

STEEL-DWASS TESTS FOR THE AVOIDANCE RT BETWEEN THE PARTICIPANTS IN PATTERN 1

	B	C	D	E	F	G	H	I
A	**	***	***	*	*	***	n.s.	**
B		+	n.s.	n.s.	***	***	n.s.	n.s.
C			**	**	***	*	*	**
D				n.s.	***	***	n.s.	n.s.
E					***	***	n.s.	n.s.
F						***	***	***
G							***	***
H								n.s.

TABLE IV

STEEL-DWASS TESTS FOR THE AVOIDANCE RT BETWEEN THE PARTICIPANTS IN PATTERN 2

	B	C	D	E	F	G	H	I
A	+	***	**	+	n.s.	***	n.s.	**
B		**	n.s.	n.s.	***	***	n.s.	n.s.
C			**	***	***	n.s.	***	*
D				n.s.	***	***	n.s.	n.s.
E					***	***	n.s.	n.s.
F						***	***	***
G							***	***
H								*

and $\alpha = 0.001$, respectively. Symbol + denotes that the difference is marginally significant, and n.s. denotes that the difference is not considered significant.

These tables show that the avoidance RT differs between participants.

3) Statistical Analysis on the Maximum Avoidance Acceleration: In this study, the maximum avoidance acceleration is defined as the maximum acceleration of movement at the participant's glabellar position.

Steel-Dwass tests were carried out to investigate whether the end-effector pattern had any effect on the maximum avoidance acceleration, and the null hypothesis was set such that the maximum avoidance acceleration for each pair of patterns was identical. Table VI summarizes the results of the Steel-Dwass tests based on the maximum avoidance acceleration 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 maximum avoidance acceleration does not appear to depend on the initial distance between the human's eyes and the end-effector tip.

TABLE V

STEEL-DWASS TESTS FOR THE AVOIDANCE RT BETWEEN THE PARTICIPANTS IN PATTERN 3

	B	C	D	E	F	G	H	I
A	***	***	***	*	+	***	*	***
B		n.s.	n.s.	n.s.	***	***	n.s.	n.s.
C			n.s.	**	***	*	*	n.s.
D				+	***	***	n.s.	n.s.
E					***	***	n.s.	*
F						***	***	***
G							***	***
H								n.s.

TABLE VI

STEEL-DWASS TESTS FOR THE MAXIMUM AVOIDANCE ACCELERATION BETWEEN THE PATTERNS

Patterns	Range of two-sided p-value
1 & 2	$p > 0.20$
1 & 3	$p > 0.20$
2 & 3	$p > 0.20$

4) Investigation of Individual Differences in the Maximum Avoidance Acceleration: Steel-Dwass tests were carried out to investigate whether the maximum avoidance acceleration was different between participants, and the null hypothesis was set such that the maximum avoidance acceleration for each pair of participants was identical. Table VII summarizes the results of the Steel-Dwass tests between the participants based on the maximum avoidance acceleration data.

This table shows that the maximum avoidance acceleration differs between participants.

5) Statistical Analysis on the Maximum Avoidance Speed: In this study, the maximum avoidance speed is defined as the maximum speed of movement at the participant's glabellar position.

Steel-Dwass tests were carried out to investigate whether the end-effector pattern had any effect on the maximum avoidance speed, and the null hypothesis was set such that the maximum avoidance speed for each pair of patterns was identical. Table VIII summarizes the results of the Steel-Dwass tests based on the maximum avoidance speed 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 maximum avoidance speed does not appear

TABLE VII

STEEL-DWASS TESTS FOR THE MAXIMUM AVOIDANCE ACCELERATION BETWEEN THE PARTICIPANTS

	B	C	D	E	F	G	H	I
A	***	***	***	***	*	***	n.s.	***
B		***	***	n.s.	***	***	***	***
C			***	***	***	***	***	***
D				***	***	n.s.	***	n.s.
E					***	***	***	***
F						***	n.s.	***
G							***	n.s.
H								***

TABLE VIII

STEEL-DWASS TESTS FOR THE MAXIMUM AVOIDANCE SPEED BETWEEN THE PATTERNS

Patterns	Range of two-sided p-value
1 & 2	$p > 0.20$
1 & 3	$0.10 < p < 0.20$
2 & 3	$p > 0.20$

to depend on the initial distance between the human's eyes and the end-effector tip.

6) Investigation of Individual Differences in the Maximum Avoidance Speed: Steel-Dwass tests were carried out to investigate whether the maximum avoidance speed was different between participants, and the null hypothesis was set such that the maximum avoidance speed for each pair of participants was identical. Table IX summarizes the results of the Steel-Dwass tests between the participants based on the maximum avoidance speed data.

This table shows that the maximum avoidance speed differs between participants.

7) Relationships between the Avoidance Action Parameters: We focus on the relationships between the avoidance action parameters: the avoidance RT, maximum avoidance acceleration, and maximum avoidance speed.

Fig. 5 shows the relationship between the avoidance RT and maximum avoidance acceleration based on the data from all participants. The graph shows that there is a negative correlation between the two, with a coefficient of approximately -0.59.

Fig. 6 shows the relationship between the avoidance RT and maximum avoidance speed based on the data from all participants. The graph shows that there is a negative correlation between the two, with a coefficient of approximately -0.60.

Fig. 7 shows the relationship between the maximum avoidance acceleration and maximum avoidance speed based on the data from all participants. The graph shows that there is a strong positive correlation between the two, with a coefficient of approximately 0.94. This positive correlation was confirmed for all participants.

III. Discussion

Even though the types of 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 the psychological experiment. 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.

TABLE IX
Steel-Dwass Tests for the Maximum Avoidance Speed between the Participants

	B	C	D	E	F	G	H	I
A	***	***	***	**	*	***	n.s.	***
B		***	***	***	***	***	***	***
C			***	***	***	***	***	***
D				***	***	n.s.	***	***
E					***	***	***	***
F						***	n.s.	***
G							***	*
H								***

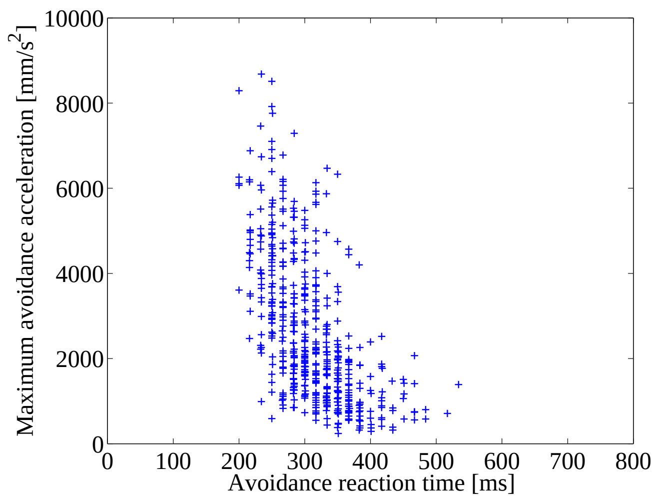

Fig. 5. Relationship between the avoidance RT and maximum avoidance acceleration

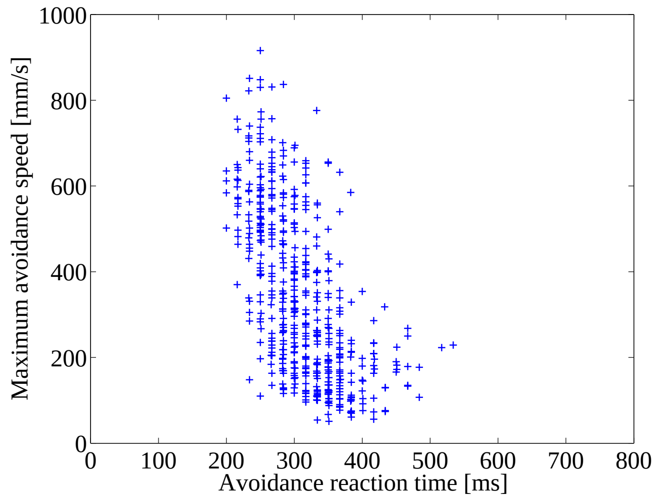

Fig. 6. Relationship between the avoidance RT and maximum avoidance speed

It is possible that the participants prepared themselves for the approaching end effector in the experiment. This is based on the idea that avoidance actions are associated with cognitive processes. In contrast, we consider avoidance actions to be reflexive processes, but we cannot rule out any cognitive influences at this point.

The maximum avoidance acceleration and maximum avoidance speed have a strong positive correlation, and the data of the latter can be manipulated more easily than those of the former. On the basis of these facts, we conclude that the avoidance RT and maximum avoidance speed are considerable parameters on avoidance actions. From the viewpoint of estimating avoidability, we should focus on people with a lower ability to avoid harm. Therefore, we suggest that it is important to investigate people whose data

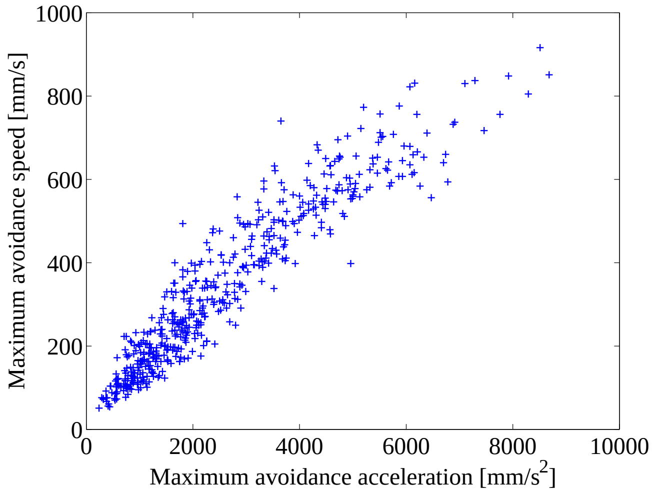

Fig. 7. Relationship between the maximum avoidance acceleration and maximum avoidance speed

has a tendency of being distributed in the lower-right area of the graph shown in Fig. 6. In reference to the relationship between the avoidance RT and maximum avoidance speed for each participant shown in Fig. 8, participant G should be investigated.

IV. Conclusions and Future Work

We have conducted a psychological experiment 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. The experimental results suggested that neither the maximum avoidance acceleration nor maximum avoidance speed depended on the initial distance between the human's eyes and the approaching object, but the avoidance RT does. The results showed that there are individual differences in the avoidance RT, maximum avoidance acceleration, and maximum avoidance speed. The results also showed that the avoidance RT is negatively correlated with the maximum avoidance acceleration and maximum avoidance speed, while that the latter two have a strong positive correlation.

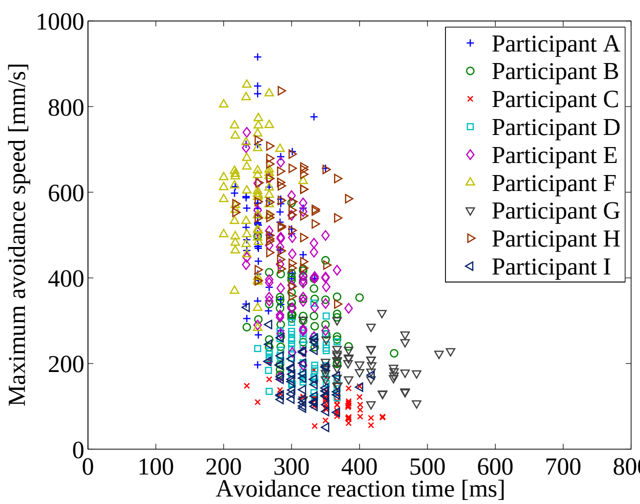

Fig. 8. Relationship between the avoidance RT and maximum avoidance speed for each participant

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, and further investigations into avoidance action characteristics should be pursued with a focus on people who have a lower ability to avoid harm.

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