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FULL PAPER

Evaluation of Robots that Signals a Pedestrian Using Face Orientation Based on Analysis of Velocity Vector Fluctuation in Moving Trajectories

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In this paper, we focus on mobile robots' behavior that people around them feel comfortable. The subjective comfort of pedestrians is usually evaluated by a questionnaire, but the high cost of assessment makes it difficult to evaluate in various situations. Towards robot control based on objective measurements of pedestrians, this paper proposes an index to evaluate the ease of walking based on objective measurements of a pedestrian's trajectory. To verify the index, we introduce a mobile robot that 1) signals it has noticed a pedestrian in front of it by moving its head upward, then 2) signals the direction of future movement by turning its head. Then the robot's behavior was evaluated by subjective impressions and objective evaluation index. We examined the relationship between subjective impressions and the objective evaluation index.

Keywords: Human-Robot Interaction; evaluation method; face orientation; preliminary announcement; walking comfort

1. Introduction

In this study, we focus on mobile robots that share an everyday living environment. For example, robots for guiding in museums [1][2] and carrying documents in hospitals [3] have been proposed and considered as important applications of mobile robots. For mobile robots that support us in our daily environment, it is required not only that they do not collide with humans but also that they behave socially appropriate manner so that people around them feel comfortable.

The mainstream of studies in this research field is to construct robots that model and predict human behavior, avoid collisions, and appropriately control the social distance to humans. However, no matter how accurately robots predict and how properly they plan to move, its effectiveness is still limited if the robot's intelligence is not shared with the surrounding people.

Toward mobile robots that move without causing surrounding people anxiety, robots have been developed that present their movement plans with displays, laser beams, and projectors. However, these methods are very different from the eye and face-facing cues that a person gives to a face-to-face pedestrian. Based on this idea, we verify a method in which a robot presents future behavior to pedestrians using face orientation.

To evaluate pedestrians' ease of walking, we propose an index based on objective measurements. Though subjective comfort of pedestrians is usually evaluated by a questionnaire, the high cost of assessment makes it difficult to evaluate comfort in various situations. Towards the design of robot behavior based on measurements of surrounding pedestrians, we propose an evaluation index based on pedestrian trajectories and investigate the relationship with subjective impressions.

The contributions of this paper are as follows.

- We propose a method to quantify the walking comfort of pedestrians by evaluating their movement trajectories passing by the robot. We investigate the relationship between the proposed index and subjective pedestrians' ease of passing.
- We evaluate a mobile robot that signals that it has noticed a pedestrian in front of it by moving its head upward. It is socially appropriate behavior to signal the notice to the surrounding pedestrians before passing each other.
- We implement a robot that signals to a passing person using his face orientation. Then we evaluate the impression given to pedestrians passing the robot in comparison with blinkers used in automobiles.

This paper extended the results of [4] and added a comparative experiment with the method using blinkers, and added the analysis which compared the evaluation of the walking comfort using both subjective impression and the proposed objective index.

2. Related Work

2.1 *Human Behavior Model Considering Social Distance*

Robot control methods that consider the human use of space (proxemics [5]) and socially appropriate distance [6][7] have attracted attention. Based on methods that take social distance into account, studies have been proposed for investigation of human impressions [8][9], robot navigation [10], and modeling of pedestrians' behavior [11]. In addition, an extension of the social model that takes into account face orientation [12] and the investigation of human impression by controlling avoidance behavior according to human behavior [13] was also conducted.

These studies propose methods for robots to make socially appropriate behavior based on modeling and prediction of human movement. However, if robots have socially appropriate movement plans, but do not present the plans to the people around them, we may not consider mobile robots as comfortable coexisting partners. In this study, we evaluate whether the pedestrian's walking comfort changes by presenting the movement plan.

2.2 *Future Behavior Presentation to the People around the Robot*

Researches have been conducted to present the future behavior of mobile robots to their surroundings with various presentation devices. Matsumaru [14][15] conducted a study to display the future behavior of a robot using a laser pointer [14] and a projector [15]. Coovert et al. [16] investigated the confidence of pedestrians who saw the projected information.

However, these information presentation methods are completely different from the methods that we usually use. When we walk and pass by other people, we present various cues to them using gaze and face orientation and also read cues from them to walk smoothly. Ueda and Kitazaki [17] experimented with avoiding pedestrians in a virtual space and showed face orientation greatly affects the prediction. Nummenmaa et al. [18] showed that gaze orientation has a large influence. In order for mobile robots to coexist with us in our daily living environment, the most natural and acceptable behavior of the robots is to send cues in the same way as ours.

Several studies have been carried out to present information to surrounding pedestrians by using their faces and eyes. Hayashi et al. [19] investigated the effect of a mobile guard robot directing their gaze to pedestrians. However, the robot did not present its future behavior. Lu et al. [20] reported that when the direction of movement was presented using face orientation, the oncoming pedestrian's movement speed was reduced. However, their experiments did not confirm whether the pedestrians actually felt noticed, nor did investigate the improvement of pedestrian comfort. May et al. [21] compared the effects of face orientation and blinkers and concluded that blinkers were significantly highly evaluated in terms of clarity and feeling of comfort. In contrast, the robot used in our study shows not only the moving direction but also the motion noticing a pedestrian using the head movement. Khambhaita et al. [22] evaluated the effects of face orientation. The subjects watched the video during passing and evaluated that the robot noticed the pedestrian and that the robot's behavior became predictable. However, the evaluation remains from the third-person view.

In contrast, we evaluate walking comfort and by subjects who actually passed by the robot. We also conduct a comparative experiment between the method using face orientation and a blinker. Besides, as a difference from [21][22], we evaluate not only subjective evaluation but also evaluate the walking comfort based on the analysis of movement trajectories of pedestrians.

2.3 *Evaluation of Walking Comfort based on Analysis of Movement Trajectories*

Studies have been conducted to evaluate the walking comfort by analyzing the trajectories of pedestrians around robots. Shiomi et al. [23] compared the shapes of the average trajectories in response to the robot's avoidance timing to evaluate the pedestrian's comfort. Kidokoro et al. [24] modeled the subjective comfort of pedestrians who passed each other at the intersection using a regression model with the position, velocity, and density as explanatory variables. Watanabe et al. [25] evaluated the walking comfort of pedestrians who passed by a wheelchair robot using the variance of the moving direction in the trajectory.

Evaluation methods of pedestrian comfort have been proposed for the purpose of robot navigation, considering the social distance. Sisbot et al. [10] proposed robot navigation considering cost function considering the human face and body orientation and applied it to robot navigation. Chi et al. [26] proposed a discomfort function that takes into account personal factors such as pedestrian movement speed and height and environmental factors such as pedestrian density. Kollmitz et al. [27] predicted pedestrian behavior and the change of the cost function. Morales et al. [28] focused on the comfort felt by passengers in autonomous wheelchairs.

Referring to these previous studies evaluating the comfort of pedestrians around the robot, we measure the movement of pedestrians passing by the robot and evaluate the walking comfort based on the index that computes fluctuation of the moving velocity vectors. We investigate the relationship between the proposed index and the subjective comfort of pedestrians.

3. Announcement Information Presentation Using Face Orientation

To realize robots that is easy to understand and comfortable for the pedestrians in the daily environment, we verify a method that sends a signal to the pedestrians using face orientation. Figure 1 shows the proposed behavior of robots in passing by. Firstly, the robot (1) turns the face upward to show that it has noticed the pedestrian (2). Next, the robot turns the face in the movement direction (3) to avoid the pedestrian in the future (4).

3.1 *Presentation of Noticing Pedestrians*

When the mobile robot detects a pedestrian to avoid in the traveling direction, prior to the presenting the movement direction and the actual avoidance motion, the robot turns the face orientation to the face of the pedestrian (Figure 2).

3.2 *Presentation of Movement Direction in Advance*

Before the robot actually changes the moving direction, the face orientation of the robot presents the movement direction to the person. When the robot detects a pedestrian to go in the traveling direction, the robot turns the face to the movement direction before actual avoiding behavior (Figure 3). After passing by, the robot returns face orientation to the front again.

4. Analysis of Pedestrian's Trajectories

4.1 *An Index of Walking Comfort Based on Fluctuation of Moving Velocity Vectors*

In Social Force Model [11], pedestrian movement is modeled by going straight toward the destination and changing the direction and speed when there are obstacles and other pedestrians. Based on this assumption, we can assume that the larger the time fluctuation of the moving velocity vectors, the more frequent the adjustment of pedestrian's walking, and the more different from smooth walking to the destination. Therefore, the time fluctuation of the moving velocity vectors would be an index of walking comfort. We compute the index every fixed windows of the trajectory, normalize for each passing trajectory.

The velocity vector fluctuation index is computed as follows. Let $\boldsymbol{x}_i = [x_i, y_i]^{\mathrm{T}}$ be the position of a pedestrian at time t_i, and let $\boldsymbol{x}_i$,$1 \leq i \leq L$, be a trajectory of the pedestrian. The velocity $\boldsymbol{v}_i$ of the pedestrian at t_i is computed based on the difference between two adjacent positions as

$$\boldsymbol{v}_i = (\boldsymbol{x}_i - \boldsymbol{x}_{i-1})/(t_i - t_{i-1}) \tag{1}$$

To compute index in an window of the trajectory, we define a sequence of n velocity vectors as V_i and its average $\bar{V}_l$:

$$V_i = \begin{bmatrix} \boldsymbol{v}_i & \boldsymbol{v}_{i+1} & \cdots & \boldsymbol{v}_{i+n-1} \end{bmatrix}^{\mathrm{T}} \tag{2}$$

$$\bar{V}_l = \begin{bmatrix} \bar{\boldsymbol{v}}_l & \bar{\boldsymbol{v}}_l & \cdots & \bar{\boldsymbol{v}}_l \end{bmatrix}^{\mathrm{T}} \tag{3}$$

where $\bar{\boldsymbol{v}}_l$ is the average velocity vector in V_i.

$$\bar{\boldsymbol{v}}_l = \sum_{k=i}^{i+n-1} \boldsymbol{v}_k / n \tag{4}$$

Then variance-covariance matrix S_i of the velocity vectors in V_i is obtained as

$$S_i = (V_i - \bar{V}_l)(V_i - \bar{V}_l)^{\mathrm{T}} \tag{5}$$

Finally, the index d_i is obtained from the product of eigenvalues of S_i.

$$d_i = \pi {\lambda_i}^{(1)} {\lambda_i}^{(2)} \tag{6}$$

where ${\lambda_i}^{(1)}$ and ${\lambda_i}^{(2)}$ are non-negative eigenvalues of variance-covariance matrix S_i. Then the velocity vector fluctuation index $\hat{d_i}$ is defined as

$$\hat{d_i} = \frac{d_i}{\max\limits_{1 \le i \le L} d_i} \tag{7}$$

When we fit the velocity vectors to multivariate Gaussian distribution, Equation (6) represents the area inside the ellipse represented by Mahalanobis distance $D = 1$ from the center of the distribution. Equation (7) represents the normalized size of the ellipse.

4.2 *Estimation of Avoidance Start Time from Trajectories*

When a mobile robot and a pedestrian pass each other, the pedestrian avoids the robot from side to side in response to the robot's movement and signals. It is considered that a pedestrian's walking comfort appears in the movement trajectory at around the time that pedestrian starts avoiding movement. Based on this idea, we propose to analyze fluctuation of velocity vectors within the window of a few seconds around the time.

First, we obtain the *avoidance start time* as follows. Let θ_t be the direction of the velocity vector at time t (Figure 4). Let t_{AVOID} be the time when the direction of the velocity vector deviates most to the left (or right) from the initial direction in the trajectory:

$$t_{AVOID} = \arg\max_t |\theta_t| \tag{8}$$

At this time t_{AVOID}, the pedestrian is certainly moving from center to side to avoid the robot. Then we compute the time at which the pedestrian is moving straight ahead immediately before the time t_{AVOID}. Let t^* be the maximum t satisfying $t < t_{AVOID}$ and $|\theta_t| < \alpha$:

$$t^* = \max_{t \le t_{AVOID}} \{t \,|\, |\theta_t| < \alpha\} \tag{9}$$

t^* represents the time at which the movement leading to the avoidance action at time t_{AVOID} was started. α is set to a small value that satisfies $|\theta_t| < \alpha$ when moving straight.
Using the avoidance start time t^*, the velocity fluctuation index is computed from the velocity

vector in $t^* - \frac{L}{2} \leq t \leq t^* + \frac{L}{2}$. In the following analysis, we used the values of $\alpha = 5$ [degree] and $L = 3$ [second]. We shifted this time window by 0.05 seconds to obtain a time series of indices.

5. Experimental Setup

In this section, we explain the experimental environment. Figure 5 shows an overview of the developed system. The details of each component are described in the following section.

5.1 *Human Tracking System*

We installed three LiDARs (Hokuyo automatic UTM-30LX) to measure the position of a pedestrian surrounding the experiment environment. To stably measure the position of the pedestrian's center of gravity, we put the sensors at 95 cm, which is about the height of a person's waist and is higher than the height of the robot. We assumed that there was only one pedestrian in the measurement area.

The measurement consists of two steps: pedestrian detection and tracking. In the detection step, it extracts the pedestrian candidates by the background subtraction and clustering. Then it detects an entity that fits a person's size and computes the center of gravity. In the tracking step, it applies a particle filter to estimate the trajectory of the pedestrian. The tracking system computed the smoothed position at a rate of twenty times per second.

5.2 *Robot*

Figure 6 shows the mobile robot used in the experiment. A pan-tilt actuator (TRACKLabs BiclopsPT) is mounted on a mobile robot (T-frog Project Robot Frame i-Cart mini), and a robot head is placed on the pan-tilt actuator. The robot has the function of turning the face in vertical and lateral directions. A LiDAR (UTM-30LX) is mounted at a position 46 cm from the ground and localizes its position by matching the observation with the grid map of the environment acquired in advance based on a particle filter [29]. The robot moves autonomously on the selected route.

Concerning the moving speed of the robot, in previous studies, the speed is set to a slightly slower than our average walking speed (about 1.1 m/s). In Pacchierotti et al., the speed of the robot is set to 0.6 m/s [9]. According to conventional research, the maximum speed of the robot was set to 0.7 m/s.

Robot has three route candidates (normal, left, right) as shown in Figure 7. The robot started to move from the initial position and moves along the normal route (center of the corridor) shown in Figure 7, and then changed the route to the right or left smoothly. The robot presented the avoidance direction 0.5 seconds before actual avoidance, and the action which noticed the pedestrian was further carried out 1.5 seconds before the avoidance. These parameters are set based on the result that the pedestrian turns his or her gaze on the pedestrian who is passing each other about 4 m before [30]. The motion of the robot was determined based on the measured pedestrian position information. The results of the analysis of the moving velocity vectors in Section 4 do not affect the behavior of the robot online.

6. Experiment 1

Using the information presentation method described in Section 3, we conducted an experiment to evaluate the impression of pedestrians who passed by the robot. Twelve subjects (five males and seven females, whose average ages were 21.42) participated in our experiment[1].

6.1 *Hypotheses and Predictions*

When we pass each other in daily life space, we do not feel comfortable when the pedestrians around us do not notice us. Therefore, we believe if a mobile robot turns its face to signal us that he noticed us, we can walk comfortably in coexistence with the robot. Based on these considerations, we made the following hypotheses:

Hypothesis 1: When a robot passes a pedestrian in front of it, if the robot turns its face upward, the pedestrian feels more clearly that the robot has noticed him/her, compared with the robot without turning face.

In addition, when we pass each other, we turn our faces in the direction we move to avoid the other pedestrians and signal our plan to them. Therefore, we believe that if robots use the face orientation to present their behavior, we can move comfortably. Based on these considerations, we made the following hypotheses:

Hypothesis 2: When a robot passes a pedestrian, in addition to the behavior in Hypothesis 1, a robot that turns its face toward the direction of movement to avoid the pedestrian is highly evaluated compared with a robot that does not present direction of the movement.

6.2 *Conditions*

In Experiment 1, an evaluation experiment was carried out under the three conditions shown in Table 1, which combines two presentation behavior. Each subject experienced each condition once (Session 1) and then experienced each condition one time again (Session 2).

6.3 *Measurements*

We measured four subjective items related to the impression of the pedestrian by questionnaires to investigate the information presentation using the face orientation of the mobile robot (Table 2). The items were evaluated on a 5-point Likert scale, where 1 is the most negative, and 5 is the most positive. After experiencing the passing of each condition, the subjects answered the following questions.

6.4 *Procedure*

After subjects were welcomed, they experienced a passing with the robot that went straight without information presentation using the face orientation. In the experiment, subjects were not told in advance about the robot's travel path or the robot's use of face orientation to present information. They were instructed to pass by the robot and move naturally to the destination. Each subject experienced six passing by in total, twice for each of the experimental conditions shown in Table 1. The order of the experimental conditions was counter-balanced. The relative distance at the start point of the robot and the subject was 11 meters, and they started moving at the same time. At first, the robot and the subject moved through the center of the corridor. We computed the average coordinate of the subject to determine the future movement direction of the robot on the opposite side to avoid a collision. When the distance between the pedestrian and the robot became less than 5 meters, the robot avoided by traveling a route 0.5 meters away on the side determined in advance. After passing by, the robot returned to the original route when the distance to the pedestrian reached over five meters. Every time one passing by was

[1] All procedures used in this research were approved by the Ethical Committee of Hiroshima City University.

completed, the subject filled an evaluation questionnaire on the impression of the behavior of the robot.

6.5 *Results*

Figure 8 shows the results of the subjective evaluation of Session 1, and Figure 9 shows the results of Session 2. The horizontal axis represents the three experimental conditions, and the vertical axis represents the score of the questionnaire. The boxes have lines at the lower quartile, median, and upper quartile values, and the notches in boxes show the minimum and maximum of the values. In Q3 and Q4, the average score tended to be A>B>C (Table 3), which indicates that the proposed two presentation behavior tends to give a good impression. For a comparison between conditions, the Steel-Dwass non-parametric multiple comparison test [31][32], was performed. Differences were considered statistically significant when $p < 0.05$. In Session 1, there was no significant difference between the conditions. The results of Session 2 showed significant differences between the conditions as follows.

Regarding the feeling that the robot is aware of the subject (Q1, Figure 9(a)), the average values under the conditions A and B where the robot behaved the noticed action were significantly higher than the condition C ($p < 0.05$ between A and C, A and B, Steel-Dwass test). There was no significant difference between A and B ($p = 0.997$). By presenting noticing action, the average value had increased significantly.

Regarding the understandability of the direction of the mobile robot (Q2), the feeling of safety (Q3) and the easiness to pass the robot (Q4), there were significant differences between conditions A, B, and A, C ($p < 0.05$ between A and C, $p < 0.05$ between A and C, Steel-Dwass test) (Figure 9(b)-(d)). There was no significant difference between B and C ($p = 0.166$ for Q2, $p = 0.558$ for Q3, $p = 0.366$ for Q4). By presenting the movement direction, the understandability, the feeling of safety, and the easiness to pass had increased significantly.

6.6 *Summary of the Analysis in Experiment 1*

In Session 1, no significant differences between conditions were detected. In Session 2, regarding hypothesis 1, in conditions B, the feeling of awareness (Q1) was significantly larger compared with conditions C. By considering the statistical analysis results, hypothesis 1 was supported. Regarding hypothesis 2, in condition A, understandability (Q2), feeling of safety (Q3), and ease of passing (Q4) were significantly improved compared with conditions B and C. By considering the statistical analysis results, hypothesis 2 was supported. These results suggest that people who understood the behavior of the robot in Session 1 could understand the behavior of the robot more easily in Session 2 and walk more easily.

7. Experiment 2

We carried out another experiment to compare the information presentation method using the face orientation with the method using blinkers, which many people are familiar with in automobiles. To compare the first impressions of the robot's behavior when the robot appeared around us, we conducted an experiment only once under each condition. Twenty five subjects (12 males and 13 females, whose average ages were 21.24) participated in our experiment.

7.1 *Hypothesis and Prediction*

Mobile robots can be designed to present information using blinkers. In contrast, the interface using the proposed face orientation is more intuitive and easier to understand for us. Based on these considerations, we made the following hypotheses:

Hypothesis 3: The proposed information presentation method using the face orientation will be evaluated more highly by pedestrians compared to the information presentation method using blinkers.

7.2 *Conditions*

To verify our hypotheses, we conducted an experiment to compare the information presentation method shown in Table 4. In condition B, blinkers (Figure 10) started blinking at the same timing as the direction presentation using the robot's face orientation in condition A.

7.3 *Measurements*

Subjective evaluation using the same questionnaire as in section 6.3 was carried out to investigate pedestrian impressions. Regarding the questionnaire items Q1, to clarify whether the subjects were aware of the robot's behavior, we removed the answer three that the subjective evaluation was "neither," and the answer to Q1 was in four levels. Then to objectively evaluate the walking comfort of the pedestrians, the movement trajectories of the pedestrians were analyzed based on the method described in Section 4. Values of $\alpha = 5$ and $L = 3$ were used in the analysis. The analysis focused on the movement trajectories of the pedestrians for three seconds around the avoidance start time. The trajectory analysis was performed offline after the experiment.

7.4 *Procedure*

The procedure is essentially the same as in section 6.4. Each subject experienced three passing, one for each of the conditions shown in Table 4. In Experiment 1, since the avoidance direction of the robot was determined according to the behavior of the subjects, the proportion of left-to-right avoidance directions was not the same. In Experiment 2, the future avoidance direction of the robot was randomly determined. When the time to collide with a pedestrian approaching from the front was less than three seconds, the robot started to avoid. Subjects completed an evaluation questionnaire about their impressions of the robot after completing all three passing walks.

7.5 *Results*

Subjective evaluations of the impression of the robot are shown in Figure 11. The horizontal axis represents the three experimental conditions, and the vertical axis represents the score of the questionnaire. For all question items, the average score tended to be A>B>C (Table 5), which indicates that presenting information using face orientation and blinkers give a good impression to the pedestrians. For a comparison between conditions, the Steel-Dwass non-parametric multiple comparison test was performed. Differences were considered statistically significant when $p < 0.05$.

Regarding all questionnaire items, there were significant differences between conditions A and C, and B and C ($p < 0.05$ between A and C, $p < 0.05$ between B and C, Steel-Dwass test) (Figure 11 (a)-(d)). There was no significant difference between conditions A and B ($p = 0.56$ for Q1, $p = 0.59$ for Q2, $p = 0.68$ for Q3, $p = 0.68$ for Q4, Steel-Dwass test). By presenting information from the robot, the subjective impression had increased significantly.

7.6 *Evaluation of Walking Comfort based on Trajectory Analysis*

Figure 12 shows the proposed velocity vector fluctuation index of the pedestrians that were averaged for each condition in Table 4. The horizontal axis represents time in seconds where

$t = 0$ represents the avoidance start time defined in Section 4.2. We focused on the index around the avoidance start time since pedestrians may decide how to avoid around the time. The vertical axis at the time t represents the index computed from the velocity vectors in 3 seconds of $t - 1.5 \leq t \leq t + 1.5$. We shifted this window by 0.05 seconds to obtain a time series of indicators. In condition A, the index at $t = 0$ tended to be lowest. In condition C, the index tended to be higher than other conditions.

7.7 *Relationship between the Subjective and Objective Analysis*

The results in previous subsection encouraged us to examine the relationship between the index at the avoidance start time and the subjective evaluation. We compare various subjective impressions under all conditions with an objective index based on movement trajectories. Figure 13 shows the relationship between the subjective evaluation and the proposed index. The horizontal axis shows the subjective evaluation for each question, and the vertical axis shows the index at the avoidance start time.

Focusing on the relationship between the ease of passing (Q4) and the index, the larger the subjective evaluation, the smaller the index (Figure 13(d)). The Pearson's correlation coefficient was $\rho = -0.49$ ($p = 0.000007$), showing a significant correlation. The negative correlation was most remarkable in the condition C of Q4 ($\rho = -0.72$,$p = 0.000039$). On the other hand, the data in the upper right of Figure 13 (d) are examples of good subjective impression but large index, many of which belong to conditions A and B.

We compared the proposed method with the discomfort function proposed in [26]. The discomfort function $f(\boldsymbol{x})$ in [26] evaluates the discomfort of a pedestrian when the robot is at $\boldsymbol{x}$. We calculated the $f(\boldsymbol{x})$ using the moving trajectories of the pedestrians and the robot measured in Experiment 2. We obtained the optimal parameters in the $f(\boldsymbol{x})$ by grid search that minimizes the average correlation coefficient between the subjective evaluation and the integration of $f(\boldsymbol{x})$ in the movement trajectory. Based on the optimal parameters, the time window that minimizes the correlation coefficient was selected in integrating the discomfort function.

Table 6 shows the Pearson's correlation coefficient between the subjective evaluation of the pedestrian and the indices. The larger the negative absolute value of the correlation coefficient, the more likely the index to represent the walking discomfort of the pedestrians. It is suggested that the proposed method reflects the subjective evaluation better than the methods in [26].

In Figure 13, there were cases in which the value of the vertical axis was large despite the high subjective evaluation. We further analyze the data with subjective ratings of 4 and 5 in Figure 13(d) from a different viewpoint. As another feature of trajectories, we focused on the avoidance distance that pedestrians avoided to the perpendicular to the traveling direction (Figure 14(d) shows the definition). The avoidance distance represents the maximum distance a pedestrian avoids in the direction perpendicular to the direction of the corridor between the initial position and the closest position to the robot. In Figure 14(a), we divided the data into those with the index larger than 0.6 (high index area, red rectangle) and those with smaller index (low index area, green rectangle). We found the trajectories that belong to the low index area avoided largely. Figure 14(b)(c) shows average avoidance direction in conditions A and B. This result shows one characteristic of the trajectories in the upper right area of Figure 13(d).

7.8 *Summary of the Analysis in Experiment 2*

Regarding hypothesis 3, the information presentation method using the face orientation explained in Section 3 tends to have a higher subjective evaluation average value than the method using blinkers, in terms of sense of awareness (Q1), ease of understanding (Q2), feeling of safety (Q3), ease of passing (Q4), but there is no significant difference.

As a result of the analysis of trajectories, a statistically significant negative correlation was found between the subjective evaluation and the proposed index, which tended to become smaller as the ease of passing was higher.

8. Discussion

8.1 *Contributions*

We showed the effectiveness of the proposed information presentation method using face orientation by the robot that passed by a pedestrian coming from the front. First, we showed that by turning the face to upward, the pedestrian in front of the robot had the impression that the robot was noticed him/her. Next, we confirmed that the behavior to convey two kinds of information to pedestrians, that is, the awareness of the pedestrian and the moving direction using face orientation, enhances ease of understanding the robot behavior, the feeling of safety, and the walking easiness of the pedestrians. We confirmed by asking the subjects who actually experienced the passing by the robot. Also, the effectiveness of the information presentation technique using face orientation was clarified by the comparison with the conventional technique using the blinkers.

Conventionally, the walking comfort of pedestrians passing by robots has been evaluated by subjective impressions using questionnaires. In this study, based on the analysis of the movement trajectory of the measured pedestrian, we proposed the index of the walking easiness using the fluctuation of the velocity vectors. We found a negative correlation between the subjective ease of passing and the variation of the velocity vector in the three-second window around the time that the pedestrian avoided the robot. This indicates that the lower the variation of the proposed index, the more the subject feels walking comfort. It suggests that the proposed index expresses a part of the subjective walking comfort.

8.2 *Comparison with the Blinkers*

By comparison between the method using face orientation and the method using blinkers, we showed that both methods of presenting information significantly improved the understandability, feeling of safety, and ease of passing of the robot. There were no significant differences between the two presentation methods. This result is different from [21] that the blinkers was preferred over face orientation. The difference from our result is that our robot turned its face up toward the pedestrian. It is possible this behavior improved the subjective impression.

8.3 *Evaluation of Walking Comfort based on Trajectory Analysis*

When the fluctuation of the velocity vectors is large, it is considered that the pedestrians do not walk smoothly. We proposed an evaluation index of the walking comfort based on the fluctuation of the velocity vectors. Although the magnitude of the correlation coefficient was not large, a significant negative correlation was found between subjective impression and the proposed index. We further investigated the data that are not negatively correlated, and the results suggest that the agreement with the subjective impression may be improved by considering another feature of the distance to avoid the perpendicular direction.

We compared the proposed index with the discomfort function in [26] according to their correlation coefficients with the subjective evaluation. The results showed that the proposed method has a negative correlation with a larger absolute value. The discomfort function in [26] tends to decrease exponentially with distance from the pedestrian, whereas the proposed index evaluates the change in the direction of the pedestrian, which may represent the discomfort of walking independently of the distance.

In the next step, we believe that it is important to reflect the behavior of the robot online based on the proposed index. Currently, we compute the index in the window of $L = 3$ seconds and velocity vectors of 1.5 seconds before and after a time is required to compute an index at the time. Since the computational cost of the index is small, the time required to reflect the motion of the robot online is 1.5 seconds. In the case the speed of the pedestrian is 1.1 m/s and the speed of the robot is 0.7 m/s, they approach 2.7m during that time. Therefore, the robot can change behavior after 1.5 seconds (2.7m) based on the computed index. The response time depends on the window length L.

8.4 *Passing with Multiple Pedestrians*

In this study, the effectiveness of information presentation using the robot's face orientation was shown in one-to-one passing by. When many pedestrians approach the robot in order, an effective method is to show awareness to the nearest person. When multiple pedestrians are walking side by side, it is more promising to face the average direction or to face one at a time in turn. The robot can point its face in the direction of each person to let them know that the robot has noticed each pedestrian. We are going to carry out experiments to verify the possibility of correspondence to multiple pedestrians in the next step.

In situations where it is difficult to avoid, such as when there is not enough room to pass in the real environment, it is safe for the robot to stop. Even in that case, it is effective to notify pedestrians from the early stage that the robot is aware of the pedestrians and will behave socially properly manner.

9. Conclusion

For the purpose that we can feel comfortable with mobile robots in our daily life environment, we proposed a new method for mobile robots to present information by turning their faces. To evaluate the comfort of pedestrians passing by a robot, in addition to subjective evaluation, we proposed an objective evaluation method of walking comfort by analyzing the movement trajectories of pedestrians.

Experimental results showed that the proposed robot's behavior gave a pedestrian the impression the robot noticed him/her. Our methods presented the robot's behavior more clearly and improved the feeling of safety and the ease of passing of the pedestrians. In comparison with the conventional method using blinkers, there was no statistically significant difference in the subjective impression, and we investigate the difference in the proposed objective index. We also investigated the relationship between subjective impressions and the proposed objective index and discussed the other objective features to be considered.

References

[1] Burgard W, Cremers AB, Fox D, Hähnel D, Lakemeyer G, Schulz D, Steiner W, Thrun S. The interactive museum tour-guide robot. In: Proc. 15th national conf. on innovative applications of artificial intelligence (AAAI). 1998. p. 11–18.

[2] Thrun S, Bennewitz M, Burgard W, Cremers A, Dellaert F, Fox D, Hahnel D, Rosenberg C, Roy N, Schulte J, Schulz D. MINERVA: a second-generation museum tour-guide robot. In: Proc. ieee int. conf. on robotics and automation (ICRA). 1999. p. 1999–2005.

[3] Murai R, Sakai T, Kawano H, Matsukawa Y, Kitano Y, Honda Y, Campbell KC. A novel visible light communication system for enhanced control of autonomous delivery robots in a hospital. In: IEEE/SICE Int. Symp. on System Integration (SII). 2012. p. 510–516.

[4] Yamashita S, Ikeda T, Shinozawa K, Iwaki S. Evaluation of Robots that Signals a Pedestrian Using Face Orientation Based on Moving Trajectory Analysis. In: Proc. IEEE Int. Conf. on Robot & Human Interactive Communication (RO-MAN). 2019. p. 1163–1170.

[5] Hall ET. The Hidden Dimension. Anchor. 1966.

[6] Kruse T, Pandey AK, Alami R, Kirsch A. Human-aware robot navigation: A survey. Robotics and Autonomous Systems. 2013;61(12):1726–1743.
[7] Rios-Martinez J, Spalanzani A, Laugier C. From Proxemics Theory to Socially-Aware Navigation: A Survey. International Journal of Social Robotics. 2015;7(2):137–153.
[8] Pacchierotti E, Christensen H, Jensfelt P. Human-robot embodied interaction in hallway settings: a pilot user study. In: Proc. IEEE Int. Symp. on Robot and Human Interactive Commun. (RO-MAN). 2005. p. 164–171.
[9] Pacchierotti E, Christensen H, Jensfelt P. Evaluation of Passing Distance for Social Robots. In: Proc. IEEE Int. Symp. on Robot and Human Interactive Commun. (RO-MAN). Ieee. 2006 sep. p. 315–320.
[10] Sisbot EA, Marin-Urias KF, Alami R, Siméon T. A human aware mobile robot motion planner. IEEE Transactions on Robotics. 2007;23:874–883.
[11] Helbing D, Molnár P. Social force model for pedestrian dynamics. Physical Review E. 1995; 51(5):4282–4286.
[12] Ratsamee P, Mae Y, Kamiyama K, Horade M, Kojima M, Arai T. Social interactive robot navigation based on human intention analysis from face orientation and human path prediction. ROBOMECH Journal. 2015;2(11).
[13] Lo SY, Yamane K, Sugiyama Ki. Perception of Pedestrian Avoidance Strategies of a Self-Balancing Mobile Robot. In: IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS). 2019. p. 1243–1250.
[14] Matsumaru T, Kusada T, Iwase K. Mobile Robot with Preliminary-Announcement Function of Forthcoming Motion using Light-ray. In: IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS). 2006. p. 1516–1523.
[15] Matsumaru T. Mobile Robot with Preliminary-announcement and Display Function of Forthcoming Motion using Projection Equipment. In: IEEE Int. Symp. on Robot and Human Interactive Communication (RO-MAN). IEEE. 2006. p. 443–450.
[16] Coovert MD, Lee T, Shindev I, Sun Y. Spatial augmented reality as a method for a mobile robot to communicate intended movement. Computers in Human Behavior. 2014;34:241–248.
[17] Ueda S, Kitazaki M. Collision Avoidance Affected by Walker's Head Direction in a Virtual Environment. In: HCI International 2013 - Posters' Extended Abstracts, CCIS 374. 2013. p. 727–731.
[18] Nummenmaa L, Hyönä J, Hietanen JK. I'll Walk This Way: Eyes Reveal the Direction of Locomotion and Make Passersby Look and Go the Other Way. Psychological Science. 2009 dec;20(12):1454–1458.
[19] Hayashi K, Shiomi M, Kanda T, Hagita N. Friendly patrolling: A model of natural encounters. Robotics: Science and Systems. 2011;7:121–128.
[20] Lu DV, Smart WD. Towards more efficient navigation for robots and humans. In: Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems. 2013. p. 1707–1713.
[21] May AD, Dondrup C, Hanheide M. Show me your moves! Conveying navigation intention of a mobile robot to humans. In: Proc. European Conf. on Mobile Robots (ECMR). 2015. p. 1–6.
[22] Khambhaita H, Rios-Martinez J, Alami R. Head-Body Motion Coordination for Human Aware Robot Navigation. In: 9th Int. Workshop on Human-Friendlly Robotics (HFR). 2016.
[23] Shiomi M, Zanlungo F, Hayashi K, Kanda T. Towards a Socially Acceptable Collision Avoidance for a Mobile Robot Navigating Among Pedestrians Using a Pedestrian Model. International Journal of Social Robotics. 2014;6(3):443–455.
[24] Kidokoro H, Kanda T, Brščic D, Shiomi M. Will i bother here?: a robot anticipating its influence on pedestrian walking comfort. In: 8th ACM/IEEE Int. Conf. on Human-Robot Interaction (HRI). 2013. p. 259–266.
[25] Watanabe A, Ikeda T, Morales Y, Shinozawa K, Miyashita T, Hagita N. Communicating robotic navigational intentions. In: Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS). IEEE. 2015. p. 5763–5769.
[26] Chi W, Kono H, Tamura Y, Yamashita A, Asama H, Meng MQ. A human-friendly robot navigation algorithm using the risk-RRT approach. In: Proc. Int. Conf. on Real-Time Computing and Robotics (RCAR). 2016. p. 227–232.
[27] Kollmitz M, Hsiao K, Gaa J, Burgard W. Time dependent planning on a layered social cost map for human-aware robot navigation. In: Proc. European Conf. on Mobile Robots (ECMR). IEEE. 2015. p. 1–6.
[28] Morales Y, Kallakuri N, Shinozawa K, Miyashita T, Hagita N. Human-comfortable navigation for an autonomous robotic wheelchair. In: Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS). 2013. p. 2737–2743.

[29] Thrun S, Burgard W, Fox D. Probabilistic Robotics. MIT Press. 2005.
[30] Kitazawa K, Fujiyama T. Pedestrian Vision and Collision Avoidance Behavior: Investigation of the Information Process Space of Pedestrians Using an Eye Tracker. In: Pedestrian and evacuation dynamics 2008. Berlin, Heidelberg: Springer Berlin Heidelberg. 2010. p. 95–108.
[31] Steel RGD. A Rank Sum Test for Comparing All Pairs of Treatments. Technometrics. 1960;2(2):197–207.
[32] Dwass M. Some k-sample rank-order tests. In: Olkin I, Al E, editors. Contributions to probability ans statistics. Standford University Press. 1960. p. 198–202.

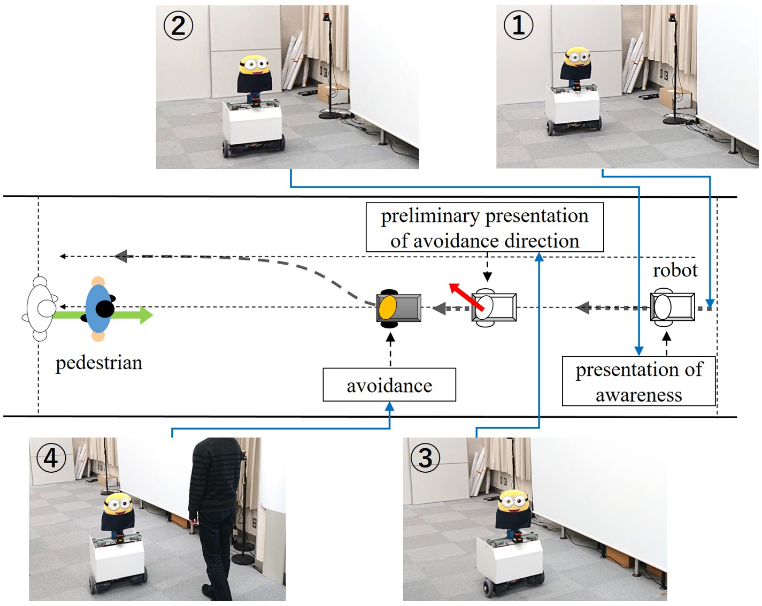


Figure 1. By turning the face orientation our robot presents that he noticed a pedestrian and the movement direction in advance.

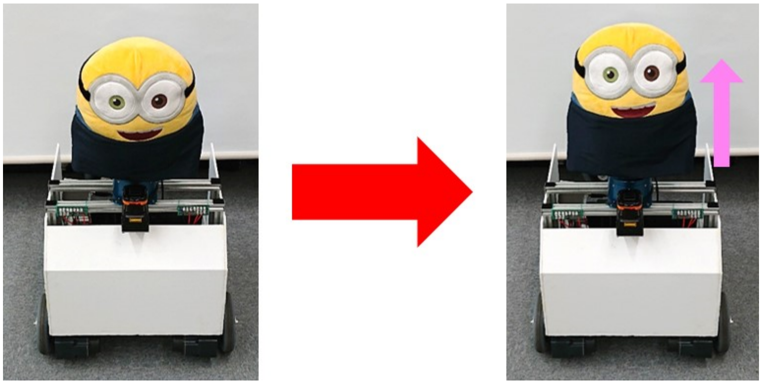


Figure 2. The robot raises his face to present that he noticed an opponent pedestrian.

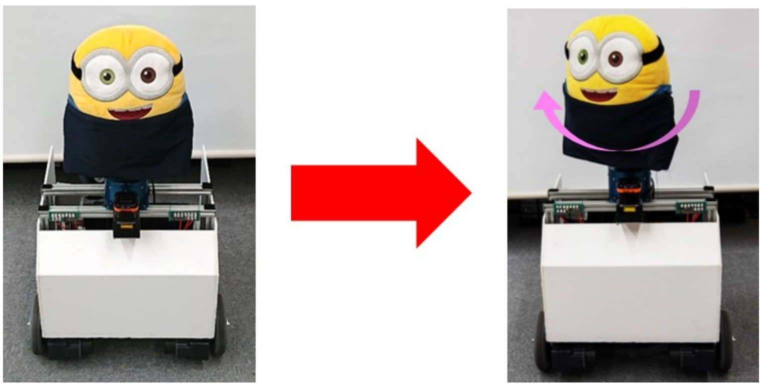


Figure 3. The robot turns his face to present the avoidance direction in advance.

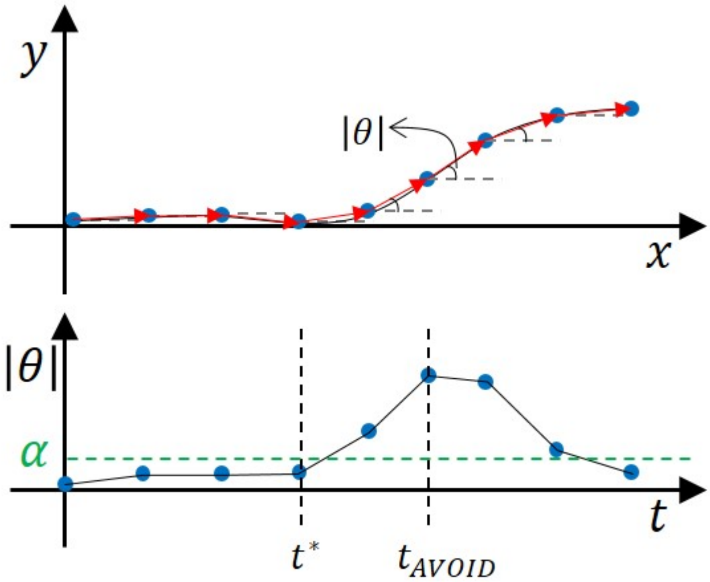


Figure 4. Start time of pedestrian avoidance

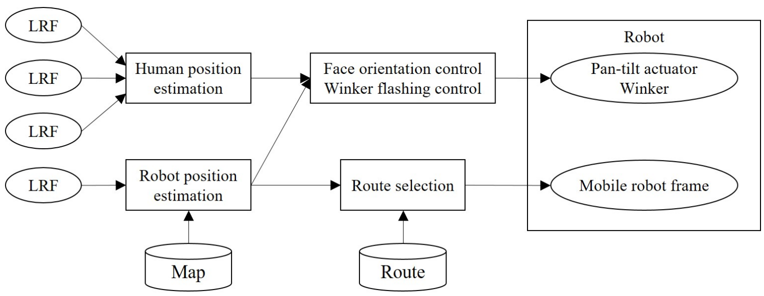


Figure 5. System overview

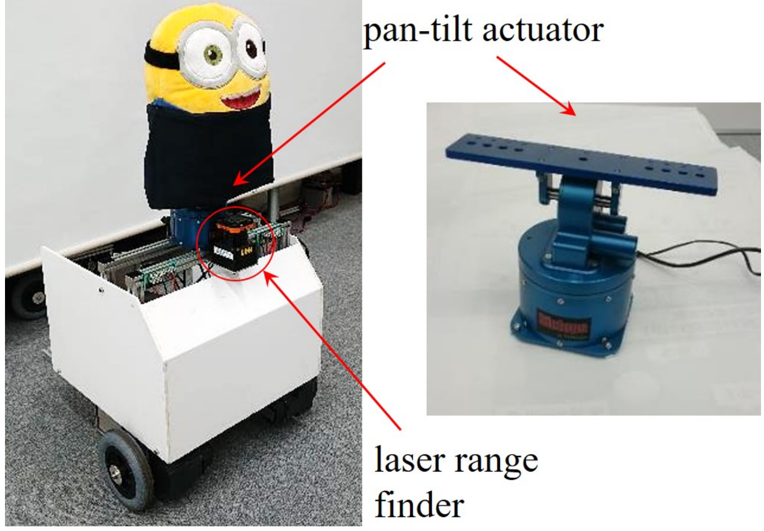


Figure 6. The robot used in the experiment

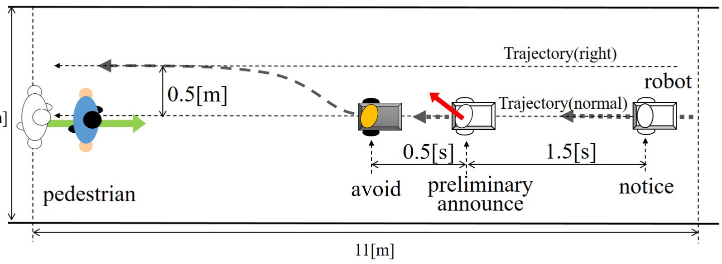
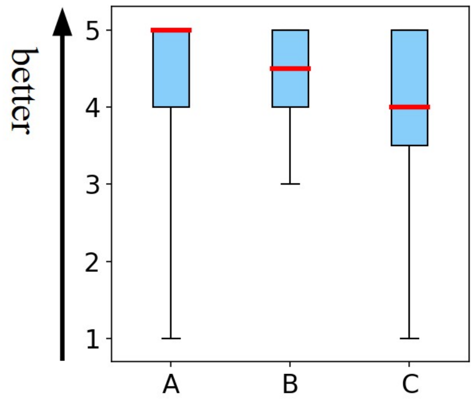
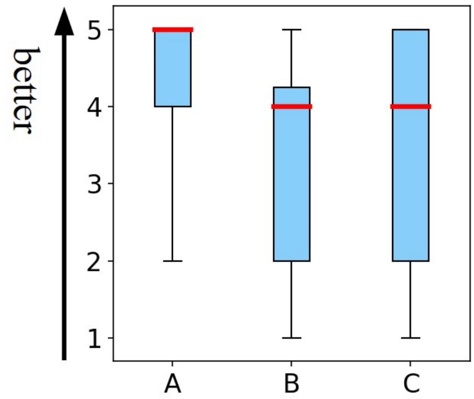


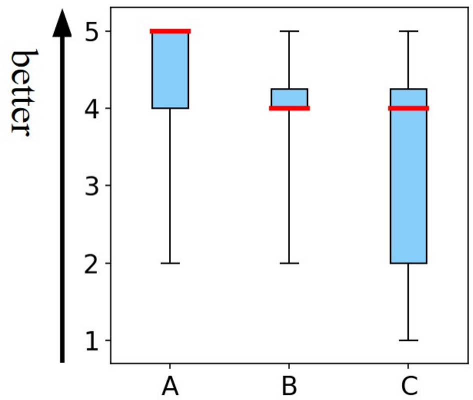
Figure 7. The time series of behaviors that the robot presents information and avoids. Actual avoidance occurs at a relative distance of 5 meters.



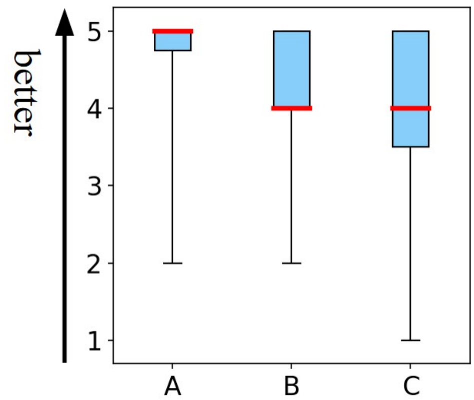
(a)Did you feel the robot is aware of you? (Q1)



(b)Did you understand that the robot moves straight ahead or to the left or right? (Q2)

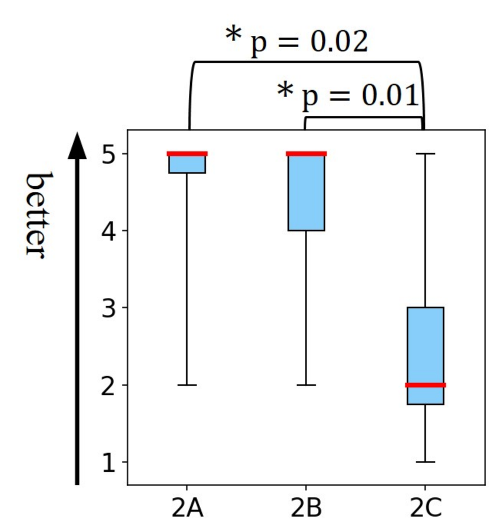


(c)Did you feel safe to pass by the robot? (Q3)

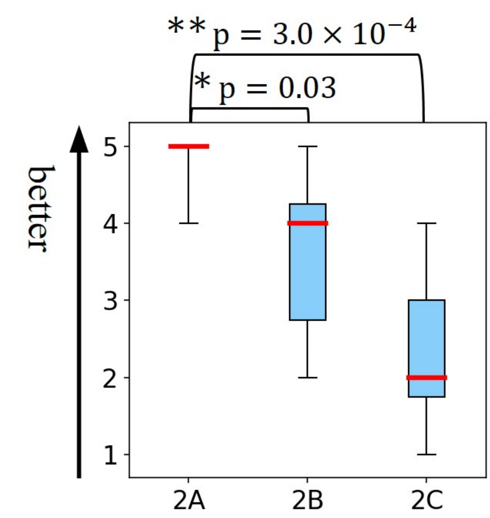


(d)Was it easy to pass the robot? (Q4)

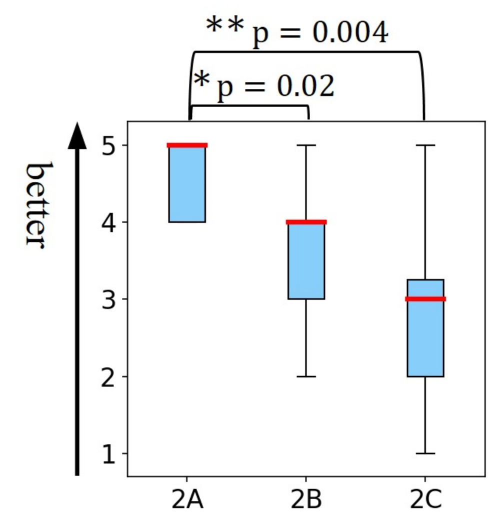
Figure 8. Results of the questionnaire on the impression of the robot (Session 1)



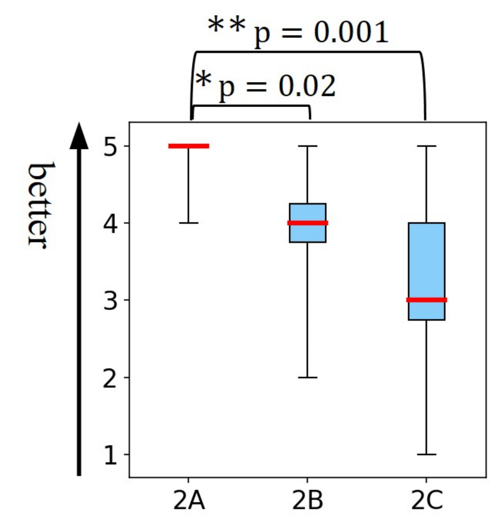
(a)Did you feel the robot is aware of you? (Q1)



(b)Did you understand that the robot moves straight ahead or to the left or right? (Q2)



(c)Did you feel safe to pass by the robot? (Q3)



(d)Was it easy to pass the robot? (Q4)

Figure 9. Results of the questionnaire on the impression of the robot (Session 2)

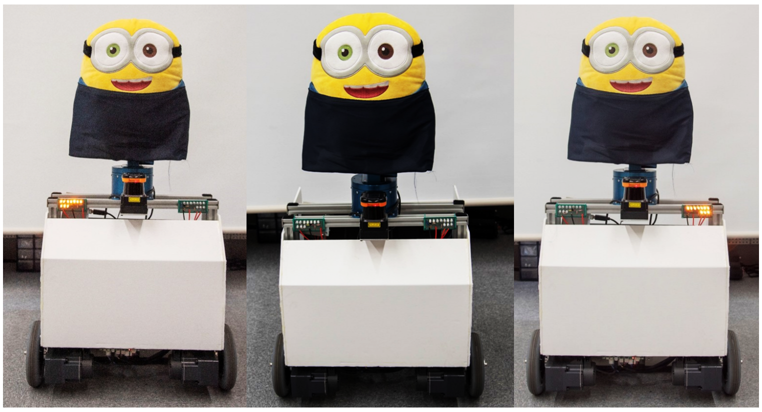
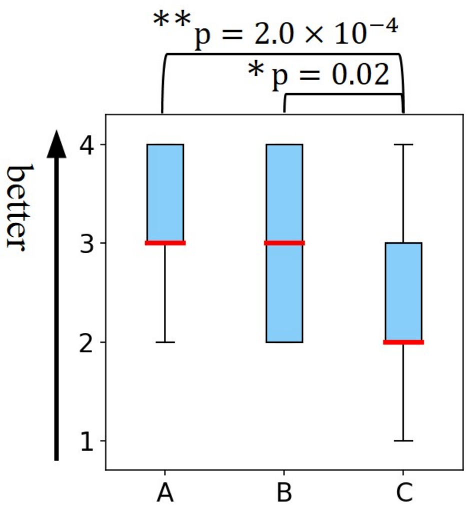
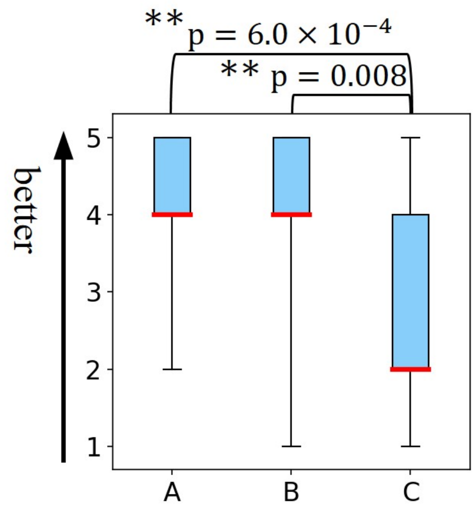


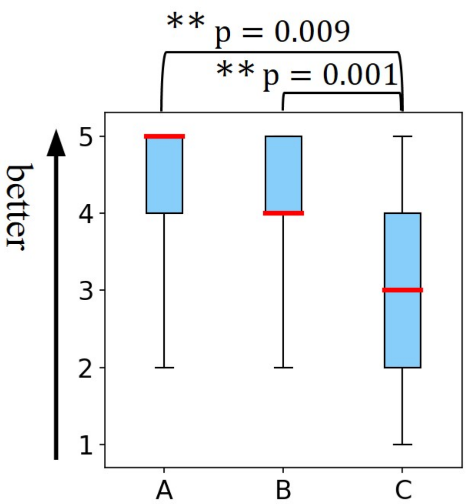
Figure 10. Presenting moving direction using a blinker in condition B.



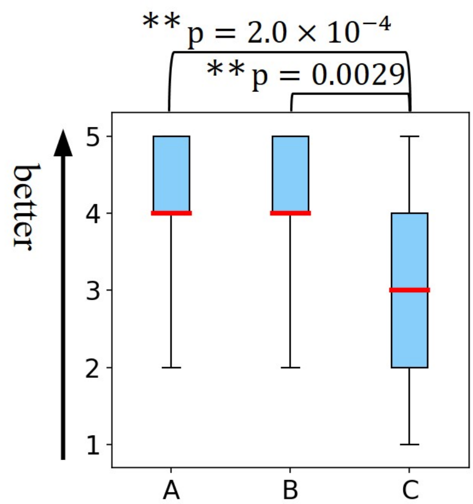
(a)Did you feel the robot is aware of you? (Q1)



(b)Did you understand that the robot moves straight ahead or to the left or right? (Q2)



(c)Did you feel safe to pass by the robot? (Q3)



(d)Was it easy to pass the robot? (Q4)

Figure 11. Results of the questionnaire on the impression of the robot

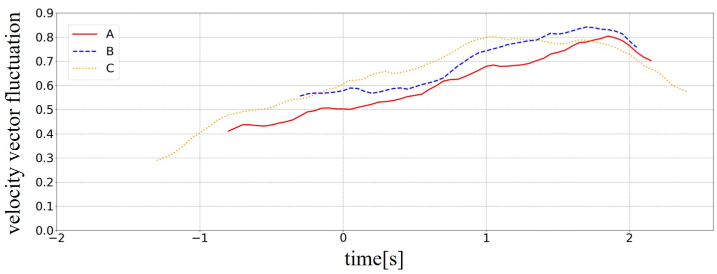
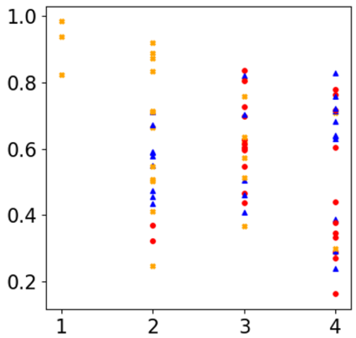
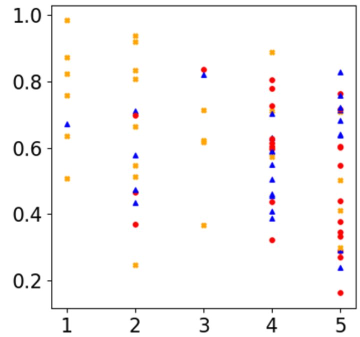


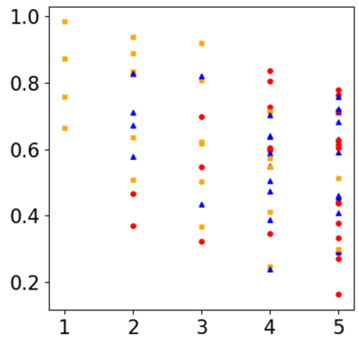
Figure 12. After shifting the index so that the avoidance start time is $t = 0$, the computed average is shown for each condition.



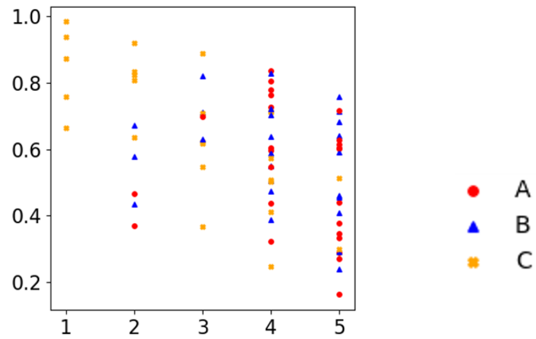
(a)Did you feel the robot is aware of you? (Q1)
$\rho = -0.280 (p = 0.01)$



(b)Did you understand that the robot moves straight ahead or to the left or right? (Q2)
$\rho = -0.330 (p = 0.003)$

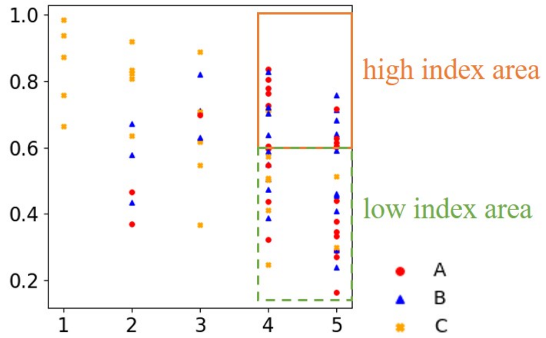


(c)Did you feel safe to pass by the robot? (Q3)
$\rho = -0.398 (p = 0.0003)$

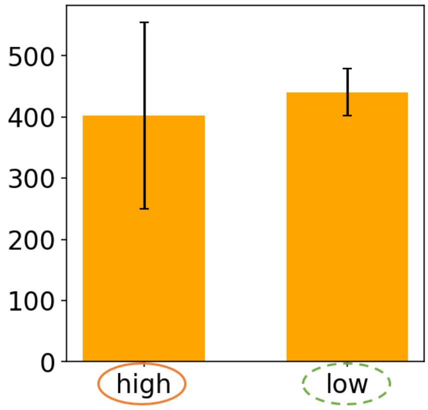


(d)Was it easy to pass the robot? (Q4)
$\rho = -0.491 (p = 0.000007)$

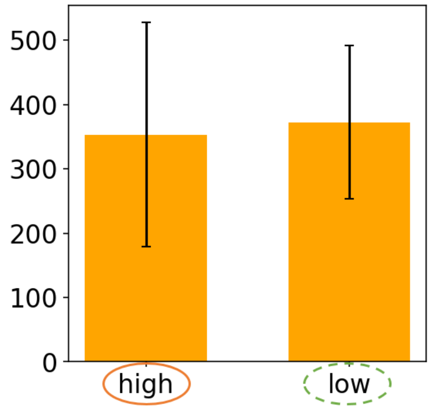
Figure 13. Results of the questionnaire on the impression of the robot. ρ represents the Pearson's correlation.



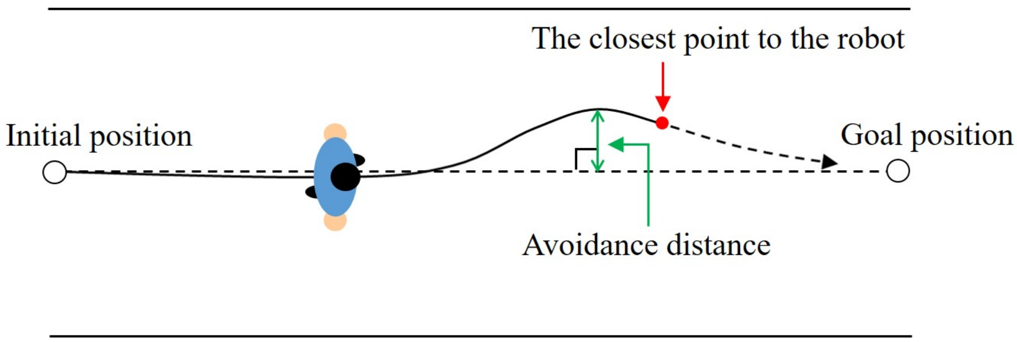
(a)Was it easy to pass the robot?



(b)avoidance distance in condition A



(c)avoidance distance in condition B



(d)definition of the avoidance distance

Figure 14. A survey of data with subjective ratings of 4 and 5 in Q4. These trajectories tend to avoid larger in the direction perpendicular to the traveling direction. (a) definition of high and low index area (b), (c) comparison of the avoidance distance to perpendicular direction. (d) avoidance distance is the maximum distance pedestrians avoided perpendicular to the direction of the corridor.

Table 1. Experimental Conditions 1

condition	presenting noticing pedestrian	presenting movement direction in advance
A	✓	✓
B	✓	
C		

Table 2. Questionnaires

Q1	Did you feel the robot is aware of you?
Q2	Is it easy to understand whether the robot goes straight or avoids left and right?
Q3	Did you feel safe to pass by the robot?
Q4	Was it easy to pass the robot?

Table 3. Average of Subjective Evaluation

	Section1			Section2		
	A	B	C	A	B	C
Q1	4.17	4.33	3.75	4.42	4.42	2.42
Q2	4.42	3.42	3.50	4.83	3.58	2.33
Q3	4.42	4.00	3.42	4.67	3.58	2.92
Q4	4.58	4.08	3.67	4.92	3.92	3.08

Table 4. Experimental Conditions 2

condition	presenting noticing pedestrian	presenting movement direction in advance
A	✓(face)	✓(face)
B		✓(blinker)
C		

Table 5. Average of Subjective Evaluation

	A	B	C
Q1	3.36	3.08	2.36
Q2	4.20	3.88	2.64
Q3	4.24	4.00	2.92
Q4	4.28	4.04	2.84

Table 6. Correlation between the subjective impression and walking comfort.

Questionnaire	Q3	Q4
Discomfort function [26]	-0.1174 ($p = 0.3157$)	-0.2222 ($p = 0.0554$)
Our method	-0.398 ($p = 0.0003$)	-0.491 ($p = 0.000007$)