Exploring Human Preferences for Adapting Inappropriate Robot Navigation Behaviors
A Mixed-Methods Study

Zhou, Yunzhong; Vroon, Jered; Kortuem, Gerd

DOI
10.1109/LRA.2024.3498432

Publication date
2024

Document Version
Final published version

Published in
IEEE Robotics and Automation Letters

Exploring Human Preferences for Adapting Inappropriate Robot Navigation Behaviors: A Mixed-Methods Study

Yunzhong Zhou, Jered Vroon, and Gerd Kortuem

Abstract—**In social environment navigation, robots inevitably exhibit behaviors that are perceived as inappropriate by humans. Current robots lack the ability to adapt to such human perceptions, leading to repeated inappropriate behaviors. This study employs a mixed-methods approach to explore human-preferred robot adaptations, combining qualitative data from a series of human-robot interactions and a semi-structured interview, and quantitative data from an online survey. 12 participants were recruited to interact with a mobile robot in an indoor setting, reporting 139 instances of inappropriate robot behaviors. The subsequent semi-structured interviews regarding these instances yielded 9 types of inappropriate behaviors and 10 major types of human-preferred robot adaptations, ranging from general ones, such as stopping the motion, to more specific ones, like moving away and then stopping. Additionally, 12 human-preferred adaptations were selected from the interview data and presented to the same participants through an online survey to evaluate their effectiveness in addressing the inappropriate behaviors previously identified. The results reveal the human preference for the robot to move to the side and then stop in most scenarios, which might serve as a general adaptation for addressing inappropriate robot navigation behaviors.**

Index Terms—**Social HRI, physical human-robot interaction, methods and tools for robot system design, human factors and human-in-the-loop.**

I. Introduction

ROBOTS play a vital role in social settings, from providing services and assisting in disaster recovery to transforming healthcare delivery. Central to these operations are socially aware navigation approaches, which enable robots to interpret and apply social rules such as proxemics [1] and human priority, thus respecting human safety and comfort during navigation [2]. In addition, robots can predict human trajectories and plan paths to avoid interfering or colliding with humans [3]. Robots also respond to human social signals such as emotions by controlling their distance from humans [4].

Some studies have tried to resolve challenges that emerge during navigation. Conflicts have been a significant challenge in socially aware navigation. According to Mirsky et al.: "A conflict between a robot and [...] pedestrians is a situation in which if there is no change of direction or speed by at least one of the parties, they will collide" [5]. One common strategy for resolving conflicts is for the robot to adjust its path or speed based on the inferred intentions of humans [6]. Other studies enhanced the robot's communication capabilities using direct visual signals (e.g., lights or projections) or sounds, thus preventing conflicts [7]. Some studies have tried to address the "freezing robot problem (FRP)" [8], which occurs when a robot navigating a crowded environment becomes paralyzed or stuck. One method, Frozone, computed a deviation velocity that avoids the Potential Freezing Zone (PFZ) to ensure smooth and collision-free navigation [9]. Additionally, a recent work addressed the FRP by employing deep reinforcement learning by integrating spatial-temporal reasoning and real-time pedestrian speed information [10]. Narrow spaces pose a distinct challenge for robots, as they provide limited room for both the robot and humans to move freely. Senft et al. found that humans generally favor robots that rotate their bodies to clear the path, as opposed to a sliding motion [11]. In an effort to understand the impact of robot behavior on humans, Koay et al. conducted human-robot interaction studies and identified a set of potentially discomforting robot behaviors, such as getting too close or blocking paths [12]. However, all these works did not investigate human perception of robot behaviors, which is crucial for pinpointing truly inappropriate behaviors. Vroon et al. introduced "perceived appropriateness" (PA) [13], which refers to an individual's subjective perception of how appropriate a robot's behavior appears. However, their work only investigated the PA of robot positioning, ignoring other aspects such as path blockage or acceleration.

In conclusion, existing studies have 2 gaps that this study seeks to bridge. The first gap is the limited understanding of how humans perceive inappropriate robot navigation behaviors. We propose to address the research question: **RQ1: "How do humans perceive the appropriateness of robot navigation behaviors, and which factors influence robot inappropriate behaviors?"** This question further breaks down into specific sub-questions: **RQ1.1: "What factors contribute to the emergence**

Received 6 May 2024; accepted 14 October 2024. Date of publication 14 November 2024; date of current version 25 November 2024. This article was recommended for publication by Associate Editor M. Frego and Editor A. Peer upon evaluation of the reviewers' comments. This work was supported by China Scholarship Council (CSC) under Grant 201906260279. *(Corresponding author: Yunzhong Zhou.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Human Research Ethics Committee TU Delft under Application No. 2996, and performed in line with the TU Delft Regulations on Human Trials.

The authors are with the Faculty of Industrial Design Engineering, Delft University of Technology, 2628CE Delft, The Netherlands (e-mail: y.zhou-13@tudelft.nl; j.h.vroon@tudelft.nl; g.w.kortuem@tudelft.nl).

This letter has supplementary downloadable material available at https://doi.org/10.1109/LRA.2024.3498432, provided by the authors.

Digital Object Identifier 10.1109/LRA.2024.3498432

TABLE I
EXPERIMENTAL PROCEDURE, INCLUDING THE PURPOSE, DATA COLLECTION, AND RESEARCH QUESTIONS FOR EACH STEP

Step	Purpose	Data Collection	RQ
1. Human-Robot Interactions	Report inappropriate robot behavior	"Press the button in your hand if you perceive that the robot behaves inappropriately". Multiple button presses in close succession are treated as a single instance.	
2. Semi-Structured Interview	Robot behavior factors	Q1.1: What occurred before you pressed the button?	1.1
	Inappropriate behavior	Q1.2: Which aspect of the robot's behavior was inappropriate?	1.2
	Concern	Q1.3: Why did the robot's inappropriate behavior concern you?	1.3
	Preferred adaptation	Q2.1: After pressing the button, how would you have preferred the interaction to continue?	2.1
	Evaluation of the Robot's Next Action	Q2.2a: What did the robot do after the button press? Q2.2b: (-2 to 2, 5-point scale): How appropriate did you find the robot's behavior after the button press?	2.2
3. Online Survey	Evaluation of 12 Adaptations	Q2.3 (-2 to 2, 5-point scale): For each of the following adaptations, how appropriate would you find it in this situation?	2.3

of inappropriate robot navigation behaviors?"RQ1.2: "How do humans perceive inappropriate robot navigation behaviors?"RQ1.3: "Why are humans concerned with inappropriate robot navigation behaviors?" The second gap is a lack of knowledge regarding how humans prefer robots to adapt their inappropriate behaviors. We propose to address the research question: **RQ2: "How should robots adapt to resolve inappropriate behaviors?"** This question further breaks down into specific sub-questions: **RQ2.1: "How do humans prefer the robot to adapt its inappropriate navigation?"RQ2.2: "How do humans evaluate the appropriateness of the robot's action after it behaved inappropriately?"RQ2.3: "What adaptations do humans prefer for each type of inappropriate robot navigation behavior?"**

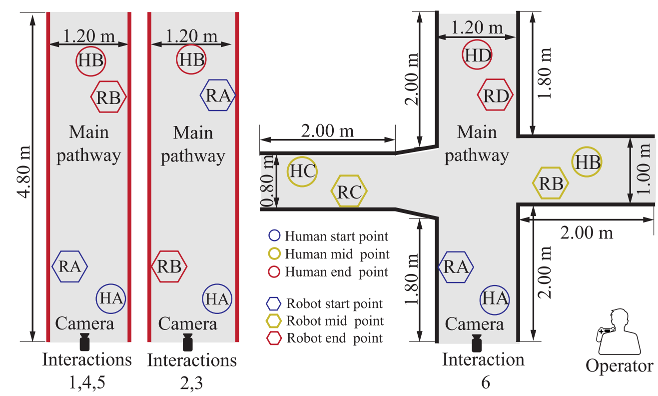

Fig. 1. Overview of the designed setting.

II. METHOD

A. Sampling and Recruitment

A purposive sampling strategy was employed for participant recruitment. 12 participants (mean age: 28.8 years, standard deviation: 6.0 years; 8 females and 4 males) were recruited for the experiment. Participants with experience in design were selected, as their expertise in interactions and problem-solving is crucial for exploring adaptations to inappropriate robot behaviors. The participants were neither associated with the researchers' laboratory nor briefed on the specific research hypotheses beforehand. The research protocol was approved by the university's Human Research Ethics Committee.

B. Experimental Procedure

The experimental procedure, outlined in Table I, follows a mixed-methods approach with three steps: human-robot interactions, a semi-structured interview, and an online survey. This framework combines qualitative insights with quantitative survey data, providing both depth and statistical support [14].

1) Step 1. Human-Robot Interactions: Upon arrival, participants were briefed on the study, consent was obtained, and they were introduced to the experiment, which involved walking within a crossroad region in an indoor lab with designated start and end points 6 times (see Fig. 1), each time interacting with a Clearpath Jackal robot (0.51 m × 0.43 m × 0.25 m). During interactions, they were instructed to press a button in their hands whenever they perceived the robot as behaving inappropriately [13].

These 6 interactions altogether exposed the participants to at least 21 distinct robot actions, as shown in Table II, along with the protocols for the operator and tasks for the participants for each interaction. The main pathway, with a length of 4.8 m and a width of 1.2 m, was designated for interactions 1-5, covering actions A1-A17. The entire region (including the main pathway), with pathways of varying widths (0.80 m, 1.00 m, and 1.20 m), was used for interaction 6, covering actions A18-A21 [15], [16].

The robot was controlled by a skilled operator via a Bluetooth PS4 controller, employing the Wizard of Oz protocol [17]. The operator's station, which included a standing desk, a chair, and a laptop, was located in a corner of the room. The interactions were recorded by a camera positioned to face the main pathway. The teleoperator was trained in all 6 interactions, and practiced controlling the pre-set speed range and acceleration according to the specifications in Table II. After completing the training, the interactions were recorded, and actions were extracted. Both the primary author and an external expert in human-robot interactions independently coded these actions. The inter-coder agreement yielded a Cohen's kappa value of 0.81 [18], indicating high reliability. This confirmed the consistent identification of the robot's actions by different coders. Actions related to speed and acceleration specifications (A1, A2, A3, A5, A6, and A16) were analyzed further, and computed values fell within the required ranges.

TABLE II
SUMMARY OF 6 INTERACTIONS, ROBOT ACTIONS, AND PROTOCOLS FOR THE OPERATION

Interaction	Action	The protocols for the operator and tasks for the human. The robot's and the human's points are visualized in Fig. 1. RA, RB, RC, and RD refer to the robot points, while HA, HB, HC, and HD refer to the human points. For each interaction, both the robot and the human start moving simultaneously.
1: Follow	A1: Follows at < 0.6 m/s [19] A2: Follows at $0.6 - 1$ m/s [19], [5] A3: Follows at $1 - 2$ m/s [5] A4: Blocks the human from the front [12] A5: Accelerates ≤ 3 m/s^2 [20], [21] A6: Moves at < 0.6 m/s [22] A7: Is overtaken by the human [23]	The robot travels from RA to RB and back, the human HA to HB and back, each completing 1 round trip in the main pathway. The robot moves slowly towards point RB to allow the human to overtake it (A1, A4, A6, A7), then accelerates to catch up (A2, A3, A5). At point RB, the robot turns and repeats this sequence: waiting for the human to pass (A1, A4, A6, A7) and then accelerating to catch up (A2, A3, A5).
2: Avoid	A8: Avoids from the side [12] A9: Avoids by retreating [12]	Both the robot and human make 2 round trips between RA and RB and HA and HB respectively in the main pathway, with 4 encounters. The robot alternates moving aside and retreating (A8 & A9) for each encounter.
3: Get close	A10: Violates personal space [12] A11: Suddenly stops when close [12] A12: Slowly stops when close [12]	Both the robot and human make 2 round trips between RA and RB and HA and HB, respectively in the main pathway, with 4 encounters. The robot alternates stopping quickly (A11) and slowly (A12) when near the human (A10).
4: Sudden motion	A13: Narrows human path [23] A14: Approaches the human [20] A15: Suddenly changes the direction [22]	Both the robot and human make 2 round trips between RA and RB and HA and HB, respectively in the main pathway, with 4 encounters. Each encounter, the robot narrows the path (A13), approaches the human (A14), and suddenly changes direction (A15).
5: Overtake	A16: Moves fast at $1 - 2$ m/s [8], [5] A17: Overtakes the human [23]	The robot travels from RA to RB and back, the human HA to HB and back in the main pathway, each completing 1 round trip with 2 encounters. The robot alternates moving fast and overtaking the human (A16, A17) for each encounter.
6: Random motion	A18: Moves towards the human [12] A19: Blocks the human from the side [12] A20: Changes the direction [20] A21: Stops for a long time [8]	The robot and human each navigate 4 points through the whole pathway until the 3-minute timer alarms. The robot follows the sequence RA to RD and back repeatedly, while the human follows the same pattern from HA to HD. The robot randomly changes speeds and directions (A18, A19, A20) and stops for a long time (A21).

2) Step 2. Semi-Structured Interview: After 6 interactions in Step 1, the participants were shown the recorded videos, which contained timestamp information to align with the timestamps of their own button presses. This allowed them to identify and review each interaction corresponding to their button presses. For each button press, they were interviewed concerning the robot behavior factors (Q1.1), inappropriate robot behavior (Q1.2), their underlying concern (Q1.3), preferred robot adaptation (Q2.1), and the evaluation of the robot's next action (Q2.2). The answers to Q2.1 were coded and analyzed, and 12 preferred adaptations were selected to proceed to Step 3, which includes the 11 most frequently reported adaptations and 1 baseline adaptation of "continue".

3) Step 3. Online Survey: One week after completing all interactions and the interviews, the 12 participants were invited back for a follow-up online survey. The online survey included recordings of the participants' own interactions with the robot, along with the timestamps of their button presses. This enabled them to pinpoint and review each instance of their own button press. They were asked to imagine that each of the 12 adaptations would occur immediately after their button press. Explanations were provided for each adaptation to assist the participants in understanding them. They then rated how appropriate each adaptation would be for the inappropriate robot behaviors they had previously identified (Q2.3, 5-point scale, from strongly inappropriate to strongly appropriate).

C. Data Coding and Theme Extraction

The interview data were transcribed verbatim into Microsoft Word and systematically analyzed using ATLAS.ti, following Braun & Clarke's six-phase inductive approach to thematic analysis [24]. Initially, the primary researcher, Yunzhong Zhou (Y.Z.), became familiar with the data by reading the transcripts multiple times and noting initial ideas and reflections. In the second phase, Y.Z. generated initial codes by identifying meaningful segments throughout the data. To enhance coding reliability, 10% of the randomly selected data was coded by an external expert in human-robot interactions. Discrepancies were discussed and resolved, which further refined the coding framework. Cohen's kappa values ranged from 0.71 to 1.00, indicating substantial to perfect agreement [18]. Third, Y.Z. grouped related codes into potential themes. These themes were then collaboratively reviewed and refined with Jered Vroon (J.V.), resulting in a preliminary thematic map. The fourth phase involved a comprehensive review of these themes, assessing them against the coded extracts and the entire dataset. This review led to the modification of some themes, including merging related themes and redefining others. Themes were defined and named through iterative discussions involving Y.Z., J.V., and another researcher, Gerd Kortuem (G.K.). Finally, a scholarly report was produced.

The objective robot-huma relative poses in the recorded videos were also coded, and each encounter was associated with a timestamp. As the precise timing of participants pressing the button varied (i.e., some pressed it after the encounter, some during), a combination of the video and the interview was used to pick the precise moment to code (within 2 seconds of the timestamp, at exactly the timestamp if unclear). Specifically, the robot's relative poses to the participants were coded, including relative position and orientation [25].

The coding and the results from the interview and videos are presented in Table III. Through the interview, participants altogether reported 139 instances of inappropriate robot

TABLE III
CODING DATA OVERVIEW. K DENOTES COHEN'S KAPPA VALUE [18], AND NUM DENOTES THE NUMBER

Purpose	**Source**	**Type**	**Num**	**K**
Robot behavior factors	Videos	Objective	139	0.76
	Interview (Q1.1)	Subjective	139	0.73
Inappropriate behavior	Interview (Q1.2)	Subjective	139	0.85
Concern	Interview (Q1.3)	Subjective	203	0.71
Preferred adaptation	Interview (Q2.1)	Subjective	148	0.79
Robot's next action	Interview (Q2.2a)	Subjective	139	0.81
Evaluation of the robot's next action	Interview (Q2.2b)	Subjective	139	1.00
Evaluation of 12 adaptations	Online survey (Q2.3)	Subjective	139	1.00

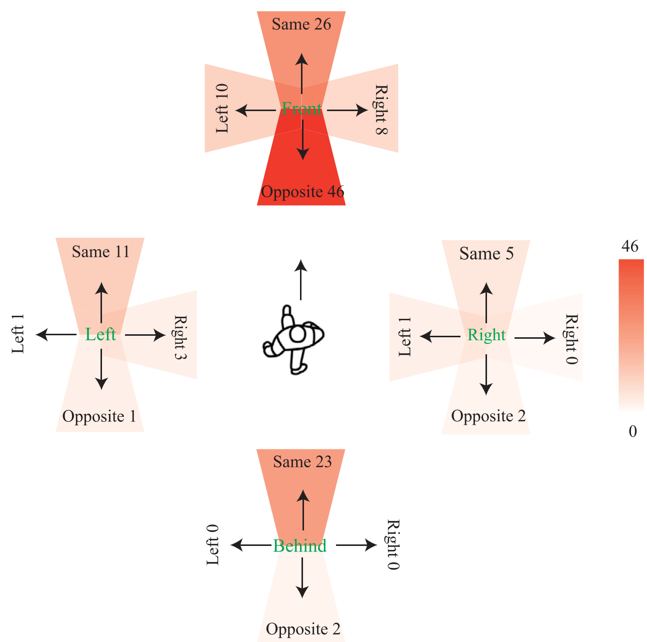

Fig. 2. Number of reported inappropriate robot navigation behaviors across different robot-human relative poses.

behaviors. Typically, participants provided 1 answer per instance for most questions, except for their concerns in Q1.3 and the preferred adaptations in Q2.1. This resulted in 139 instances of robot behaviors, PA, and evaluations of the robot's next action, alongside 148 instances of preferred adaptations and 203 instances of concerns.

III. Results

A. Inappropriate Robot Navigation Behaviors (RQ1)

1) Robot Behavior Factors (RQ1.1): Factors include both objective robot-human relative poses and subjective reports from the participants.

In our coding, the robot-human relative poses consist of 16 types, including combinations of different positions (front, behind, left, right) and orientations (same, opposite, left, right). As can be seen from Fig. 2, the relative poses strongly influence the number of reported inappropriate robot behaviors, especially

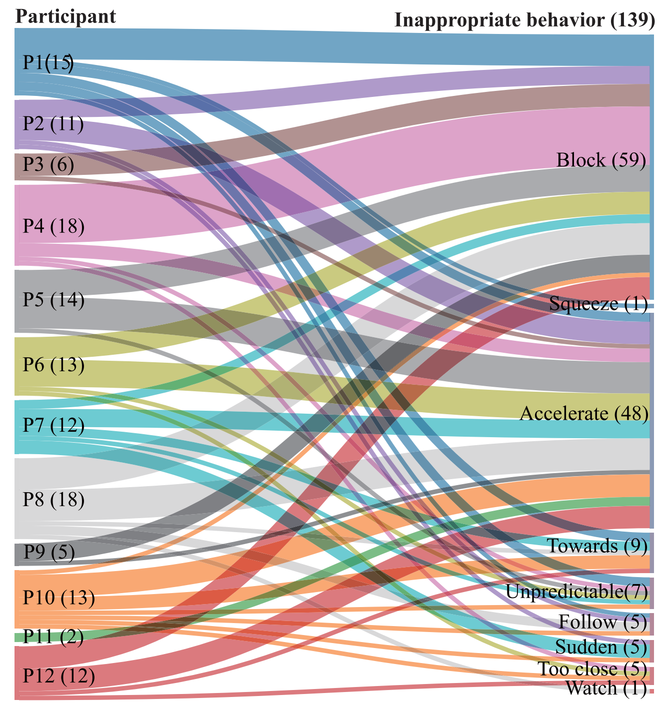

Fig. 3. Inappropriate behaviors, including their types and numbers.

when the robot approaches the participants, particularly from the front.

Furthermore, without being directly asked in Q1.1, the participants reported 3 key robot behavior factors that influenced inappropriate robot behaviors: acceleration (43 instances), smoothness (42 instances), and speed (14 instances). Regarding acceleration, feedback primarily focused on the robot accelerating (37/43) rather than decelerating, especially when the robot approached or followed the participants from the front (35/37). The smoothness factor, described by the participants as "random", "unpredictable", or "jerky", was majorly mentioned when the robot was either in front of or behind the participants (35/42). The speed factor was often associated with the robot moving too slowly or remaining stationary (12/14) rather than moving too fast.

2) Inappropriate Behaviors (RQ1.2): Fig. 3 shows 139 instances of inappropriate robot behaviors reported by 12 participants, categorized into 9 types. The number of instances reported by each participant ranges from 2 (P11) to 18 (P4 and P8). The reports of inappropriate robot behaviors vary among participants. Participant 11 reported only inappropriate acceleration, whereas participants 4 and 9 reported over 65% blocking and less than 15% acceleration problems. Among different types of inappropriate behaviors, "Block" was the most reported (59/139) and happened mostly when the robot was in front of the participants (48/59), especially in parallel (same or opposite) orientation (36/48). "Accelerate" was also frequently reported (48/139), especially when the robot was behind (20/48) or in front (17/48). Other behaviors include the robot moving "Towards" the participants, exhibiting "Unpredictable" or

TABLE IV
NUMBER OF CONCERNS

Concern	Number
Safety	79
Interfere	38
Confuse	33
Disrespect	25
Comfort	13
Efficiency	5
Privacy	5
Cognitive load	5

TABLE V
NUMBER OF PREFERRED ADAPTATIONS

Preferred adaptation	Number
Away	60
Stop	37
Slow	19
Away, stop	11
Slow, speak	9
Stop, speak	7
Predictable	3
Away, speak	1
Continue	1
Stop, light	1

"Sudden" movements, "Follow", getting "Too close", "Watch", or "Squeeze" the participants' path.

3) Concerns (RQ1.3): Table IV shows 203 instances of concerns reported, categorized into 8 types. The most common were "Safety" (79 instances) concerns, which were mostly related to the robot being on a collision course with the participants (relative poses: front & opposite (25 instances), behind & same (16 instances), and front & same (12 instances)). The concern of the robot "Interfere" with their walking paths (38 instances) was also frequently reported, especially when the robot was in the front (relative poses: front & opposite (15 instances), front & same (9 instances), and front & right (4 instances)). "Confuse" concerns (33 instances) mostly arose when the robot was in the front (relative poses: front & opposite (12 instances), and front & same (9 instances)). Other concerns include "Disrespect", "Comfort", "Efficiency", a violation of "Privacy", and increased "Cognitive load".

B. Adapting Inappropriate Robot Navigation (RQ2)

1) Preferred Adaptations (RQ 2.1): Table V shows 148 instances of preferred adaptations categorized into 10 major types. The most common was for the robot to move "Away" (60 instances), especially when the robot was in the front, with a relative orientation of opposite (25 instances) or same (12 instances). The second most frequently reported was to "Stop" (37 instances), especially when the robot was on a collision course with the human (relative poses: front & opposite (8 instances), behind & same (7 instances)). Others include for the robot to "Slow down", "Away, stop", "Slow, speak", "Stop, speak", make "Predictable" behavior, "Away, speak", "Continue", or "Stop, light". Interestingly, although Q2.1 openly asked about the interaction as a whole, all 139 instances reported solely on robot adaptations without mentioning their own adaptations. We conducted a binomial test with the null hypothesis that preferences for robot and human adaptations are equally likely ($p = 0.5$). The test yielded a p-value of $p \approx 2.87 \times 10^{-42}$, which is below the significance threshold of 0.05. This suggests a human preference for robot adaptations.

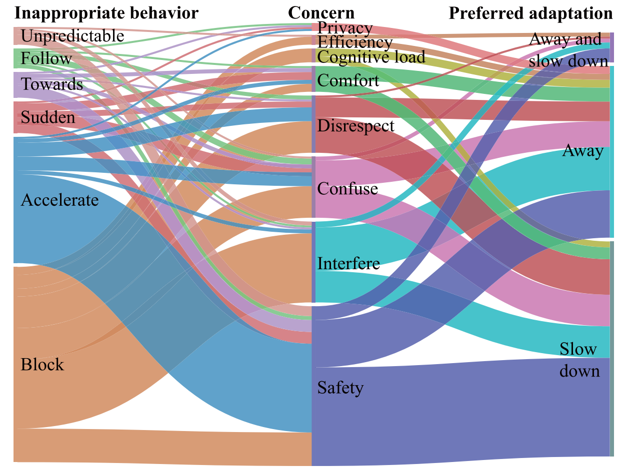

Fig. 4. Relations between inappropriate behavior, concern, and preferred adaptation.

The relationships between inappropriate behaviors, concerns, and preferred robot adaptations have also been analyzed and presented as a Sankey diagram in Fig. 4. For analytical clarity and focus, only sub-categories with at least 5 instances were included, collectively representing over 95% of the cases for each category. Additionally, the preferred adaptations were clustered into 3 categories to facilitate a clear understanding: move "Away", "Slow down", and move "Away and slow down". "Block" triggered a wide range of human concerns, particularly "Interfere", increased "Cognitive load", and "Efficiency". "Safety" concerns, on the other hand, were dominantly triggered by inappropriate "Accelerate". Others were associated with various concerns, such as "Sudden" behavior causing concerns of "Safety", "Confuse", or "Comfort".

Different concerns also influenced humans' preferred robot adaptations, as evidenced by a human preference for the robot to "Slow down" rather than to move "Away" when having "Safety" concerns or the preference for the robot to move "Away" rather than to "Slow down" when having "Interfere" concerns. For other concerns, participants showed a relatively balanced preference for the robot to either move "Away" or "Slow down".

2) Evaluations of the Robot's Next Action (RQ2.2): The participants also reviewed and evaluated the appropriateness of the robot's next action. Interestingly, the participants often perceived the robot as adapting its behavior (96 instances), although the operator did not receive any feedback from the participants and thus did not adapt accordingly. This included "Slow down", "Turn", "Stop", "Jerky", "Accelerate", and "Follow". In only 43 instances was the robot perceived as "Continue" its previous behavior.

The mean ratings for the robot's next actions are presented in Table VI. The robot's next actions were generally rated

TABLE VI
AVERAGE EVALUATION OF THE ROBOT'S ACTUAL ACTIONS PERFORMED AFTER THE BUTTON PRESS, ALONG WITH THE NUMBER OF INSTANCES

Inappropriate behavior type (#)	The robot's next action (#)						
	Continue (43)	Slow down (27)	Turn (27)	Stop (13)	Jerky (13)	Accelerate (12)	Follow (4)
Block (59)	-0.86 (22)	0.40 (5)	-0.12 (16)	0.50 (4)	-0.75 (8)	-1.00 (3)	0.00 (1)
Accelerate (48)	-1.29 (7)	0.00 (19)	-0.20 (5)	-0.17 (6)	-0.67 (3)	-1.17 (6)	-1.00 (2)
Towards (9)	-1.33 (3)		0.00 (2)	0.33 (3)		-2.00 (1)	
Unpredictable (7)	-1.00 (4)	0.00 (1)	-2.00 (1)				1.00 (1)
Sudden (5)	1.00 (1)		0.00 (1)		0.00 (1)	1.00 (1)	1.00 (1)
Follow (5)	-1.00 (2)	-1.00 (2)	1.00 (1)				
Too close (4)	-1.00 (3)		0.00 (1)		-1.00 (1)		
Watch (1)						-2.00 (1)	
Squeeze (1)	-1.00 (1)						
Overall (139)	-0.47 (139, std: 0.98)						

Values range from strongly inappropriate (-2, deep red) to strongly appropriate (+2, deep blue).

The list of actions was derived from answers to Q2.2a.

TABLE VII
AVERAGE EVALUATIONS OF DIFFERENT ADAPTATIONS IMAGINED BY THE PARTICIPANTS FOR EACH INAPPROPRIATE BEHAVIOR TYPE, CALCULATED BASED ON THE NUMBER OF INSTANCES CORRESPONDING TO THAT INAPPROPRIATE BEHAVIOR TYPE

Inappropriate behavior type (#)	Adaptation (#)											
	Continue (139)	Away (139)	Slowly away (139)	Retreat (139)	Retreat ,stop (139)	Aside (139)	Aside, stop (139)	Stop (139)	Quickly stop (139)	Slow (139)	Slow, inform (139)	Predict -able (139)
Block (59)	-1.31	1.10	0.92	0.34	0.42	1.08	1.17	0.03	-0.15	-0.12	0.12	0.86
Accelerate (48)	-1.66	0.60	1.00	0.51	0.96	0.98	1.30	0.21	-0.11	0.04	0.21	0.62
Towards (9)	-1.48	0.91	0.99	0.37	0.55	1.02	1.21	0.08	-0.10	0.00	0.18	0.73
Unpredictable (7)	-1.29	0.86	0.86	0.14	0.14	1.00	1.14	-0.40	-0.40	0.00	0.00	0.60
Sudden (5)	-1.40	0.80	1.20	0.40	0.40	0.80	1.00	-0.40	-0.40	0.00	0.00	0.60
Follow (5)	-1.42	0.76	0.88	0.30	0.43	0.97	1.14	-0.20	-0.34	-0.09	0.08	0.64
Too close (4)	-1.25	0.75	1.00	0.25	0.25	1.50	1.25	0.00	0.00	0.00	0.25	0.50
Watch (1)	-1.00	1.00	2.00	1.00	1.00	2.00	1.00	0.00	0.00	1.00	0.00	1.00
Squeeze (1)	1.00	1.00	1.00	-1.00	-1.00	1.00	1.00	-1.00	-1.00	0.00	0.00	1.00
Overall (139)	-1.43	0.85	0.93	0.35	0.54	1.01	1.19	0.06	-0.16	-0.03	0.16	0.76

Values range from strongly inappropriate (-2, deep red) to strongly appropriate (+2, deep blue).

The list of adaptations was derived from answers to Q2.1.

negatively by the participants, with a mean score of -0.47 and a standard deviation of 0.98. Participants who reported that the robot continued its inappropriate behavior evaluated this action negatively. The average evaluation score is -0.91 with a standard deviation of 0.32. This score was calculated using the formula:

$$\text{Average Score} = \frac{1}{N}\sum_{i=1}^{N} X_i \quad (1)$$

In (1), X_i represents the evaluation score for the i-th instance where "Continue" was reported, and N is the total number of such instances. Other actions received mixed ratings depending on the context. For example, "Slow down" following the "Block" was rated slightly positively (mean: 0.43, standard deviation: 0.51), whereas "Slow down" following "Follow" was evaluated negatively (mean: -0.33, standard deviation: 0.47). "Slow down" following "Sudden" motion was generally evaluated positively (mean: 0.50, standard deviation: 0.63).

3) Evaluations of 12 Robot Adaptations (RQ2.3): Average participant evaluations of 12 adaptations concerning their own identified inappropriate behavior instances through the online survey are shown in Table VII. The adaptations and their explanations are presented as follows: "Continue" means the robot continues its current motion; "Away" means the robot moves away from the participants; "Slowly away" means the robot moves away at a slow pace; "Retreat" means the robot backs off; "Retreat, stop" means the robot backs off and then stops; "Aside" means the robot moves to one side of the pathway; "Aside, stop" means the robot moves to one side and then stops; "Stop" means the robot stops its motion; "Quickly stop" means the robot stops abruptly; "Slow" means the robot slows down without stopping; "Slow, inform" means the robot slows down and informs its next action; and "Predictable" means the robot moves in a predictable manner, such as in a straight line.

Across almost all inappropriate behavior types, the robot that "Continue" its behavior consistently received negative evaluations (mean -1.43, std 0.42), underscoring the imperative for the robot to make adaptations. Adaptations such as "Slowly away", and moving "Aside" or "Aside, stop" generally received positive evaluations across all inappropriate behavior types, which might indicate human preferences for these adaptations. Among the 12 adaptations, "Aside, stop" received the highest average evaluations across most inappropriate behavior types (mean 1.19, std 0.35). Although it did not receive the highest score in every inappropriate behavior situation, it consistently ranks among the top and receives the highest average score overall. Due to the non-normal distribution of the data, a Mann-Whitney U test was conducted to compare "Aside, stop" with other adaptations [26]. The results revealed statistical differences between "Aside, stop" and all other adaptations, with Bonferroni-corrected p-values well below the adjusted significance level of 4.5×10^{-3} [27]. This might indicate the human preference for the robot to adapt its inappropriate behavior by moving "Aside, stop".

IV. Discussion

A. Inappropriate Behaviors (RQ1)

This study identifies 9 types of inappropriate robot navigation behaviors (Fig. 3), especially "Block" and "Accelerate", which deserve more attention due to their dominant frequencies. This finding extends beyond the work of Vroon et al., which solely identified inappropriate robot positioning [13]. Furthermore, it emphasizes the necessity for current studies to resolve conflicts to avoid inappropriate "Block" and "Towards" behaviors [5], [7], optimize smooth paths to avoid inappropriate "Accelerate", and mitigate "Sudden" and "Unpredictable" motion [2], [28]. To note, participants only reported inappropriate behaviors after all interactions, using timestamp information to synchronize their button presses with the video recordings. This helped mitigate recall biases, but the external point of view and the delay of the reports may still cause bias issues. Future studies could explore real-time data collection methods, such as a "think aloud" approach, to collect inappropriate behaviors more accurately and minimize such biases. Furthermore, while this study employs manual operations to achieve the desired interaction efficiently and explore the richness of interactions, this approach introduces limitations, such as potential inconsistencies and reduced repeatability of the robot behaviors. Future research could build on these findings by programming the robot behaviors, enabling more meaningful comparisons.

This study advances the understanding of how robot behavior factors influence human perception of robot navigation behaviors, extending beyond the previous work that focused solely on robot positioning behaviors [13]. These factors include the robot-human relative poses (as shown in Fig. 2), and robot motion smoothness, acceleration, and speed. Given its exploratory nature, this study collected a small data sample and did not impose strict controls on parameters such as speed and acceleration, limiting the ability to draw conclusive findings on how these parameters affected inappropriate robot behaviors. Participants primarily perceived the robot's inappropriate acceleration and blocking behaviors. To gain a more comprehensive understanding, future research should involve more controlled interactions with finer adjustments to robot motion parameters, including speed and acceleration rates. Additionally, increasing the number of inappropriate behavior instances with more human-robot interactions would facilitate rigorous quantitative analyses. These would enhance our understanding of the dynamics in human-robot interactions, thereby providing deeper insights into the robot behavior design.

Contrary to the findings of Koay et al. [29], which reported discomfort among subjects when a robot approached within 3 meters, and in contrast to the principles of proxemics applied in socially aware navigation [1], the participants in this study only reported 5 out of 139 instances of the robot being "Too close". This discrepancy could be attributed to the relatively less open space in the experimental setting (path width ranging from 0.8 m to 1.2 m, as depicted in Fig. 1), which may cause the participants to tolerate closer proximity due to the necessity of passing by the robot [11]. Furthermore, Fig. 4 shows that the participants prefer the robot "Slow down" over moving "Away" even when they have "Safety" concerns, which might further indicate an acceptance of closer proximity in less open spaces. These findings might suggest that proxemics rules can be adapted to account for path width, enabling robots to make more context-aware decisions in varying environmental conditions.

Participants have also reported various types of concerns underlying the inappropriate behaviors (see Table IV). Many such concerns have already been widely studied in socially aware navigation, such as understanding and optimizing human safety, comfort, efficiency, legibility, and avoidance of interference [2], [3], [4], [28], [30]. However, there have hardly been studies investigating human concerns of "Disrespect" and "Cognitive load", which deserve further attention.

B. Human-Preferred Robot Adaptations (RQ2)

Unlike previous studies, which assumed cooperative navigation between humans and robots–where humans continuously predict, interpret, and adapt to robot behaviors [31]–this study reveals a human preference for robots to adapt their behaviors when perceived as behaving inappropriately, allowing humans to continue their current behavior. This is indicated by the fact that all 139 instances reported solely on preferred robot adaptations without mentioning their own adaptations (binomial test: $p \approx 2.87 \times 10^{-42}$), despite Q2.1 openly asked about the interaction as a whole (see Table I). Therefore, it is suggested that when a robot is perceived as behaving inappropriately, it should change its own motion while assuming that humans continue their previous behaviors.

This study provides insights into human evaluations of various robot adaptations under different types of inappropriate navigation behaviors (see Table VII). Participants rated the robot making certain adaptations better than the robot continuing its inappropriate behavior. This finding emphasizes the necessity of detecting inappropriate robot navigation behaviors, thus paving the way for the robot to make adaptations [13]. Among the 12 adaptations, the robot moving "Aside, stop" is identified as the most preferred adaptation overall and is statistically different from all other adaptations. This might indicate that robots could move to the side of the pathway and then stop when perceived as inappropriate by humans, especially in narrow spaces. Note that this experiment is conducted in a relatively narrow space to explore inappropriate behaviors and preferred adaptations effectively and efficiently. This might explain why humans prefer the robot to move "Aside, stop", and as such, its applicability might not extend to open spaces. Furthermore, the evaluations of the 12 adaptations depend on participants imagining hypothetical scenarios to assess the appropriateness of each adaptation. Although this yields useful insights for designing robot adaptations, it does not fully capture real-world conditions. Future research could benefit from employing the "think aloud" approach to report preferred adaptations in real-time, thus enabling the robot to adapt accordingly and allowing direct comparisons of different adaptations in real-life scenarios.

V. Conclusion

This study investigated human-preferred adaptations for inappropriate robot navigation behaviors by conducting a series of human-robot interactions, a semi-structured interview, and an online survey. Firstly, participants interacted with a mobile robot in a designed lab setting and identified robot behaviors they perceived as inappropriate. Then, a semi-structured interview was conducted to identify inappropriate robot navigation behaviors and the corresponding preferred adaptations. Additionally, all the participants were invited back to evaluate the appropriateness of 12 selected robot adaptations for addressing inappropriate robot behaviors. The coding of the interview and survey revealed 9 inappropriate behavior types. These were influenced by robot-human relative poses, as well as the robot's speed, acceleration, and motion smoothness. Furthermore, the study revealed a negative human perception of the robot continuing its inappropriate navigation behaviors. As for adaptations, the robot moving to the side of the pathway and stopping was preferred and evaluated positively, reflecting its generalizability in addressing inappropriate robot navigation, at least in less open spaces. Despite the controlled laboratory setting, the small and homogeneous participant sample, and the potential bias from having participants identify inappropriate behavior types after all interactions, these conditions were instrumental in allowing a focused exploration of human-robot interactions. Future work will address these limitations by involving a more diverse participant pool and conducting real-life comparisons of different adaptations to assess their effectiveness in addressing inappropriate robot navigation behaviors.

References

[1] E. T. Hall, et al., "Proxemics [and comments and replies]," *Curr. Anthropol.*, vol. 9, no. 2/3, pp. 83–108, 1968.

[2] E. Cancelli, T. Campari, L. Serafini, A. X. Chang, and L. Ballan, "Exploiting proximity-aware tasks for embodied social navigation," in *Proc. IEEE/CVF Int. Conf. Comput. Vis.*, 2023, pp. 10923–10933.

[3] T. Smith, Y. Chen, N. Hewitt, B. Hu, and Y. Gu, "Socially aware robot obstacle avoidance considering human intention and preferences," *Int. J. Social Robot.*, vol. 15, no. 4, pp. 661–678, 2023.

[4] A. Bera et al., "How are you feeling? multimodal emotion learning for socially-assistive robot navigation," in *Proc IEEE 15th Int. Conf. Autom. Face Gesture Recognit.*, IEEE, 2020, pp. 644–651.

[5] R. Mirsky et al., "Conflict avoidance in social navigation—a survey," *ACM Trans. Hum.-Robot Interact.*, vol. 13, no. 1, pp. 1–36, 2024.

[6] A. Favier, P. T. Singamaneni, and R. Alami, "An intelligent human avatar to debug and challenge human-aware robot navigation systems," in *Proc. 17th ACM/IEEE Int. Conf. Hum.-Robot Interact.*, IEEE, 2022, pp. 760–764.

[7] Q. Qiu, S. Yao, J. Wang, J. Ma, G. Chen, and J. Ji, "Learning to socially navigate in pedestrian-rich environments with interaction capacity," in *Proc. 2022 Int. Conf. Robot. Automat.*, IEEE, 2022, pp. 279–285.

[8] P. Trautman and A. Krause, "Unfreezing the robot: Navigation in dense, interacting crowds," in *Proc. 2020 IEEE/RSJ Int. Conf. Intell. Robots Syst.*, IEEE, 2010, pp. 797–803.

[9] A. J. Sathyamoorthy, U. Patel, T. Guan, and D. Manocha, "Frozone: Freezing-free, pedestrian-friendly navigation in human crowds," *IEEE Robot. Automat. Lett.*, vol. 5, no. 3, pp. 4352–4359, Jul. 2020.

[10] B. Xue, M. Gao, C. Wang, Y. Cheng, and F. Zhou, "Crowd-aware socially compliant robot navigation via deep reinforcement learning," *Int. J. Social Robot.*, vol. 16, no. 1, pp. 197–209, 2024.

[11] E. Senft, S. Satake, and T. Kanda, "Would you mind me if i pass by you?: Socially-appropriate behaviour for an omni-based social robot in narrow environment," in *Proc. 15th ACM/IEEE Int. Conf. Hum.-Robot Interact.*, IEEE, 2020, pp. 539–547.

[12] K. L. Koay, K. Dautenhahn, S. Woods, and M. L. Walters, "Empirical results from using a comfort level device in human-robot interaction studies," in *Proc. 1st ACM SIGCHI/SIGART Conf. Hum.-Robot Interact.*, 2006, pp. 194–201.

[13] J. Vroon, G. Englebienne, and V. Evers, "Detecting perceived appropriateness of a robot's social positioning behavior from non-verbal cues," in *Proc. IEEE 1st Int. Conf. Cogn. Mach. Intell.*, IEEE, 2019, pp. 216–225.

[14] R. B. Johnson, A. J. Onwuegbuzie, and L. A. Turner, "Toward a definition of mixed methods research," *J. Mixed Methods Res.*, vol. 1, no. 2, pp. 112–133, 2007.

[15] R. S. Shahrezaie, L. B. Manalo, and D. Feil-Seifer, "Knowledge-based reasoning for navigation in public spaces," in *Proc. RSS Workshop Social Robot Navigation*, Jul. 2021. [Online]. Available: https://rrl.cse.unr.edu/en/pubs/?pub=112/

[16] F.-A. Moreno, J. Monroy, J.-R. Ruiz-Sarmiento, C. Galindo, and J. Gonzalez-Jimenez, "Automatic waypoint generation to improve robot navigation through narrow spaces," *Sensors*, vol. 20, no. 1, pp. 240–159, 2019.

[17] N. Dahlbäck, A. Jönsson, and L. Ahrenberg, "Wizard of oz studies: Why and how," in *Proc. 1st Int. Conf. Intell. User Interfaces*, 1993, pp. 193–200.

[18] J. Cohen, "A coefficient of agreement for nominal scales," *Educ. Psychol. Meas.*, vol. 20, no. 1, pp. 37–46, 1960.

[19] R. Guldenring, M. Görner, N. Hendrich, N. J. Jacobsen, and J. Zhang, "Learning local planners for human-aware navigation in indoor environments," in *Proc. 2020 IEEE/RSJ Int. Conf. Intell. Robots Syst.*, IEEE, 2020, pp. 6053–6060.

[20] A. V. Taylor, E. Mamantov, and H. Admoni, "Observer-aware legibility for social navigation," in *Proc. IEEE 31st Int. Conf. Robot Hum. Interactive Commun.*, IEEE, 2022, pp. 1115–1122.

[21] A. Ollman, "Implementation of pose estimation algorithms on the clearpath jackal UGV," B.E. (Honours) thesis, Dept. College Eng. Comput. Sci., The Australian Nat. Univ., Canberra, Australia, 2019.

[22] T. Kruse, P. Basili, S. Glasauer, and A. Kirsch, "Legible robot navigation in the proximity of moving humans," in *Proc. 2012 IEEE Workshop Adv. Robot. Social Impacts*, IEEE, 2012, pp. 83–88.

[23] R. Peddi and N. Bezzo, "An interpretable monitoring framework for virtual physics-based non-interfering robot social planning," *IEEE Robot. Automat. Lett.*, vol. 7, no. 2, pp. 5262–5269, Apr. 2022.

[24] V. Braun and V. Clarke, "Using thematic analysis in psychology," *Qualitative Res. Psychol.*, vol. 3, no. 2, pp. 77–101, 2006.

[25] X.-T. Truong and T.-D. Ngo, ""To approach humans?": A unified framework for approaching pose prediction and socially aware robot navigation," *IEEE Trans. Cogn. Devel. Syst.*, vol. 10, no. 3, pp. 557–572, Sep. 2018.

[26] H. B. Mann and D. R. Whitney, "On a test of whether one of two random variables is stochastically larger than the other," *Ann. Math. Statist.*, vol. 18, no. 1, pp. 50–60, Mar. 1947.

[27] S. Holm, "A simple sequentially rejective multiple test procedure," *Scand. J. Statist.*, vol. 6, no. 2, pp. 65–70, 1979.

[28] A. Bellarbi, A.-i. Mouaddib, N. Achour, and N. Ouadah, "A new approach for social navigation and interaction using a dynamic proxemia modeling," *Evol. Intell.*, vol. 15, pp. 2207–2233, 2022.

[29] K. L. Koay, M. L. Walters, and K. Dautenhahn, "Methodological issues using a comfort level device in human-robot interactions," in *Proc. RO-MAN IEEE Int. Workshop Robot Hum. Interact. Commun.*, IEEE, 2005, pp. 359–364.

[30] Y. Gao and C.-M. Huang, "Evaluation of socially-aware robot navigation," *Front. Robot. AI*, vol. 8, 2022, Art. no. 721317.

[31] H. Khambhaita and R. Alami, "Viewing robot navigation in human environment as a cooperative activity," in *Proc. Robot. Res.: 18th Int. Symp. ISRR*, Springer, 2020, pp. 285–300.