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No Need for Speed? The Impact of Delivery Robot Speed on Passersby's Perceived Comfort and Safety and Preferred Signaling Distance

Heqiu Song[1] · Paul Preuschoff[2] · Benedikt Grzeschik[3] · Astrid M. Rosenthal-von der Pütten[1]

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Abstract

Autonomous robots have the potential to assist us in various everyday tasks, including driving and package delivery. In the case of autonomous delivery robots, efficiency and safety need to be guaranteed in order for them to be deployed in real-world settings. The speed of the robot and its signaling distance emerged as crucial research focus points, greatly influencing the perceived efficiency and safety of delivery robots. This study therefore investigates the impact of different robot speeds on participants' preferred signaling distance, perceived comfort, and safety during encounters. It also explores whether participants' prior robot experience or pet ownership influences these factors based on the literature. We conducted an online study with 48 participants who watched videos of encounters with delivery robots at different speeds. Participants indicated when they would step aside from the robot, defining the signaling distance. An additional real-life interaction study involved 11 participants. As expected, results indicated that as robot speed increased, participants preferred a larger signaling distance and felt progressively less comfortable and safe with higher robot speeds. However, there were no significant findings related to pet ownership or robot experience. We provide a formula to calculate the most adequate distance for signaling depending on robot speed. In conclusion, careful consideration must be given to robot speed and signaling distance to ensure that participants can react in time and have comfortable, safe interactions with delivery robots in various contexts.

Keywords Delivery robot · Speed · Signaling distance · Safe · Comfort

1 Introduction

Due to the increase in online purchases and, therefore, package delivery nowadays, the working hours of many delivery drivers have increased, whereas the working conditions have become challenging [25]. An additional help we can offer might be to deliver packages with the help of a delivery robot automatically, including indoor environment. However, this is only feasible if the operation of such delivery robots is efficient enough and still safe to use in the environment. Therefore, the speed of the robot is important.

Previous research has investigated the relationship between different robot speeds and the signaling distance for collision avoidance, however, the studies that focused on finding the relationship between these were done more than 15 years ago when the technology was far less advanced and the acceptance of new technologies was at a different level compared to now [2, 11]. Furthermore, their tested speeds

✉ Heqiu Song
heqiu.song@itec.rwth-aachen.de

Paul Preuschoff
preuschoff@cs.rwth-aachen.de

Benedikt Grzeschik
benedikt.grzeschik@rwth-aachen.de

Astrid M. Rosenthal-von der Pütten
arvdp@itec.rwth-aachen.de

1 Chair Individual and Technology, RWTH Aachen University, 52062 Aachen, Germany

2 Computer Media Group, RWTH Aachen University, 52062 Aachen, Germany

3 Department of Computer Science, RWTH Aachen University, 52062 Aachen, Germany

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were limited to 3.6 kph, which is still slower than the normal walking speed of a human (1.42 m/s, 5.11 kph). More importantly, a potential ceiling effect may have occurred due to the robot's relatively low speed. On the other hand, researchers have also investigated the relationship between robot speed, passing distance, and human comfort [15], human-robot proxemics in closed environments [13], safety parameters of autonomous cargo bike speed and distance to pedestrians [12]. As we can see, the relationship between robot speeds and the signaling distance for collision avoidance in a closed environment still lacks systematic investigation.

Moreover, while navigating through public spaces, it is common for delivery robots to encounter individuals who are not the intended users, referred to as Incidentally Co-present Persons (InCoPs), [22], who are not involved in the ongoing delivery process. Unlike the waiting consumers, they do not intend to engage with the robot. However, there is limited research focusing specifically on this target group and existing research is still on observation levels. We aim to address this research gap with two experimental studies. The first study adopted a within-subject design, employing videos of a robot approaching at different speeds in a hallway, with participants indicating the distance at which they would step aside. In the second study, we validated the results through a within-subject interaction study where participants encountered a real delivery robot in a corridor, replicating the same environment as in the video experiment. Beyond speed, several other factors influence the comfort of individuals in such interactions with robots, including pet ownership and prior robot experience [24, 27]. The research question *How do different robot speeds and personal factors (i.e., pet ownership and earlier experience with robots) impact the preferred signaling distance, comfort, and safety?* was investigated in the setting of a delivery robot encountering a human in a hallway.

2 Related Work

2.1 Distance and Speed

Robots will be expected to comply with social norms of movement if they get integrated into human environments [10]. The distance and speed of a robot are important factors that impact the success of interactions between individuals and robots, as they involve adjustments to the robots' paths and speeds when approaching people [29].

Previous studies have investigated the impact of robot speed and the distance between robots and humans within indoor settings such as corridors. For example, researchers pointed out that proximity and approach speed significantly influence people's trust levels toward robots [10]. In addition, researchers have examined the distance between a robot and an individual when the robot passes by the person [14, 15]. The findings indicated that comfort levels increased as distance extended. Furthermore, people showed greater tolerance for higher speeds and closer passing distances when robots clearly signal their intention to pass a person instead of expecting the person to yield [20]. Furthermore, it was revealed that the participants were less favorable toward approaching speeds of 40 inches per second (approximately 3.60 kph) or higher [3]. Notably, in a previous study, the preferred speeds were slower than the average human walking speed (1.42 m/s, 5.11 kph, [2, 11]). It's worth noting that this study is relatively dated, suggesting that participants at that time were likely less accustomed to mobile robots than they are today. More importantly, a potential ceiling effect may have occurred due to the robot's relatively low speed. The authors also speculate that users might become fatigued with slower speeds as they become more familiar with the robot over time.

In summary, the robot speeds used in earlier studies that investigated the relationship between robot speed and individual perception were between 0.72 kph and 3.60 kph, which would be very inefficient for delivering packages [3, 20, 24]. In addition, the highest speed resulted in the highest comfort, when operationalized as stopping distance, indicating that a ceiling effect might have been reached [19, 24]. In our present work, we therefore explore different speeds that exceed the speeds used in previous work to investigate whether prior work was limited by a ceiling effect. Moreover, we want to know how comfortable and safe participants feel when encountering faster robots. Finally, we explore the preferred signaling distance for communicating navigation intent (for instance, skirting behavior) and how this preferred distance changes with the speed of the robot.

2.2 Personal Factors

Personal factors play an important role in how users want to interact with robots. Many people who are not expected to interact with delivery robots will be the often-forgotten InCoPs who are not the intended users involved in the ongoing delivery process [22]. These are pedestrians who have unplanned interactions with a delivery robot in public spaces. Earlier studies have shown that personal factors influence how close people let a robot get into their vicinity, or how willing people are to move into the vicinity of a robot [24, 27]. Here the researchers have shown that people who have owned a pet before or had experience with robots would come closer to the robot than people who had no experience with robots, or have never owned a pet [20, 27]. Hence, we also integrated these two factors into our current study.

2.3 Research Questions and Hypotheses

As previously mentioned, earlier studies have investigated the preferred signaling distance, lateral distance, and speed for robot speeds up to 3.6 kph [20]. It has also been investigated that the personal factors of robot experience and pet ownership have a significant impact on the preferred lateral distance towards robots [27]. Investigating faster robots is highly relevant, since in the context of delivery tasks, a higher speed has a huge impact on the effectiveness of the robot. However, it has not been investigated yet whether the preferred signaling distance of the passerby changes with a higher robot speed and the relationship between the speed of the delivery robot and the preferred signaling distance of the passerby. Moreover, we look into how personal factors impact preferred robot speed or signaling distance.

Therefore, in this study, we focused on the following research question and hypotheses:

- **RQ**: How do robot speed and personal factors (i.e., pet ownership and earlier experience with robots) impact the preferred signaling distance, comfort, and safety?
  - **H1**: Robot speed and preferred signaling distance correlate positively, furthermore, robot speed can be used as a predictor for preferred signaling distance.
  - **H2**: Robot speed negatively correlate with comfort and safety. Participants feel more comfortable and safer with lower robot speeds. (Based on findings from [19] and [5])
  - **H3**: Pet owners (H3a) and participants with previous robot experience (H3b) have a lower desired signaling distance than the participants without pets or previous experience. (Based on findings from [27])

3 Study 1: Video-Based Lab Study

3.1 Study Design and Participants

We used a 7×4 within-subjects design with 7 different robot speeds each presented 4 times in this video-based laboratory study.

A total of 49 participants were recruited using convenience sampling and snowballing. One participant was excluded due to an incomplete questionnaire. Additionally, this study was repeated as part of a later interaction study. Participants who took part in the interaction study were subsequently invited to participate in this video-based study, resulting in additional data from 26 participants. In total, 76 participants' data was analysed (42 males, 31 females, and 1 prefer not to say). Participants' ages ranged from 19 to 71 years (M=27.59 SD=10.68).

3.2 Study Materials

3.2.1 Experimental Tools

We conducted our study using the digital survey tools SoSci Survey[1] and PsychoPy.[2] The presentation of videos and capturing of reaction times was done via PsychoPy, while for the questionnaires we used SoSci Survey.

3.2.2 Video Materials

For our study, we used a delivery robot constructed by the company ANONYMIZED (see Fig. 1) for recording the videos, which can travel at up to 7 mph (11.27 kph). In our study, instead of driving autonomously, the robot was teleoperated to drive in a straight line at a constant speed for the video recording.

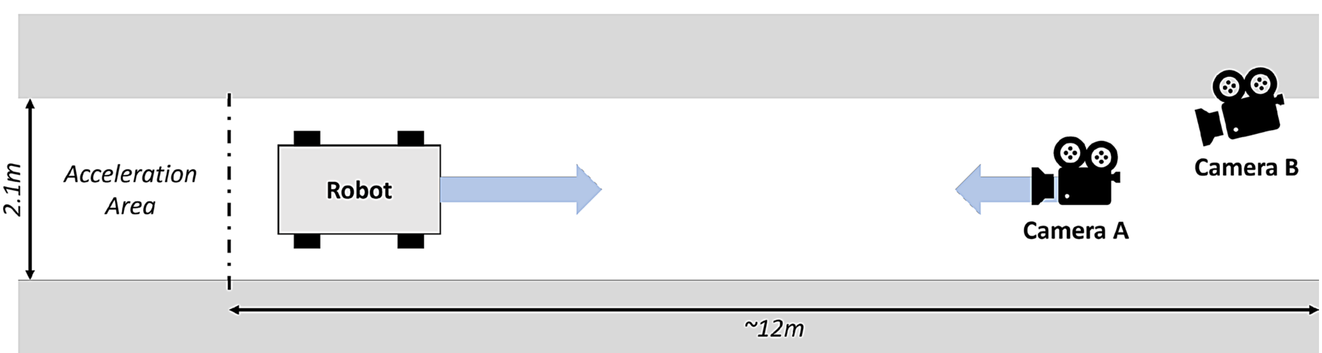

Fig. 1 Top view illustration of the video recording area

[1] https://www.soscisurvey.de/, accessed August 2023

[2] https://www.psychopy.org/, accessed August 2023

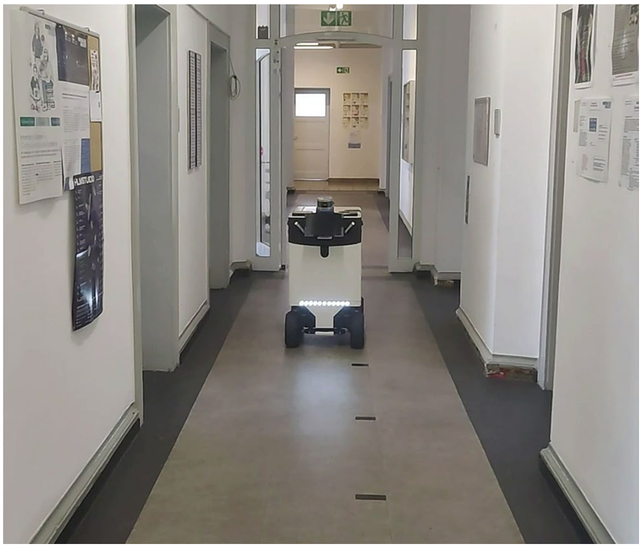

Fig. 2 The delivery robot in the hallway. This is a screenshot image from the videos shown to participants

The videos were recorded in a corridor that was about 12 meters long and 2.1 meters wide (see Fig. 2). The robot was placed at the end of the corridor, driving toward the camera. We made sure that the robot was at the desired speed at a predetermined point in the hallway. We edited the videos to start when the robot reached that point. This helped to increase the consistency between conditions. One camera *A* was hand-held and walking toward the robot at 0.84 m/s (3.02 kph, see Fig. 2). By using a metronome, we aimed to keep the step speed and thus the movement speed of camera *A* constant. We used a secondary camera *B* that was placed stationary in the hallway behind camera *A*. The footage taken by this camera was used to determine the distance between camera *A* and the robot by using the markings on the floor. Camera *A* and the robot moved at a constant speed, so we were able to calculate their distance when a participant pressed the button based on the timestamp of the video by using the time and speed. Only the videos captured by camera *A* were shown to the participants and 7 videos were made with a delivery robot driving at 7 different speeds (from 1 mph (1.61 kph) to 7 mph (11.27 kph), see Table 1).

3.3 Procedure

The study began with a standard informed consent procedure. Participants then answered some general questions about demographics (e.g., age, gender, etc.), pet ownership, and robot experience. Next, a practice session was presented by PsychoPy. In the practicing session, instead of a delivery robot, a human walked toward the camera. Participants needed to press a button as soon as they felt it was the correct time to adjust their path to avoid the collision, which is the same as they did in the experiment with a robot

Table 1 Means and standard deviations of signaling distance, comfort, and safety for each speed condition in the video-based study and the interaction study

	Video-Based Study						Interaction Study					
Speed	Distance		Comfort		Safety		Distance		Comfort		Safety	
(mph)	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1	5.05	3.27	5.48	1.62	6.30	1.07	1.48	1.09	5.48	1.40	6.33	1.07
2	5.28	1.59	5.58	1.27	6.01	1.06	2.02	1.08	5.77	0.96	5.73	1.16
3	6.38	1.65	5.40	1.18	5.58	1.18	2.40	0.99	5.31	1.23	5.10	1.38
4	7.36	1.81	4.98	1.37	5.08	1.39	3.15	1.22	4.27	1.50	4.08	1.53
5	8.07	2.04	4.46	1.37	4.35	1.47	3.36	1.14	3.31	1.69	3.27	1.70
6	8.75	2.28	3.88	1.61	3.76	1.62	4.30	2.02	3.27	1.50	3.12	1.51
7	9.12	2.40	3.57	1.66	3.37	1.65	4.56	2.33	2.84	1.78	2.60	1.85

later. This allowed participants to become familiar with the experimental setup. When they felt comfortable continuing, the main experiment was initiated. For each of the 7-speed conditions, participants were shown a corresponding video 4 times in random orders. After each video, they answered questions about their comfort and safety toward the delivery robot in the video on a 7-point Likert scale). At the end, participants were asked for their preferred speed condition and we collected some qualitative data on their preferences and reasoning for preferences. Finally, participants were debriefed and the experiment was terminated.

3.4 Measures

We measured participants' pet ownership by using the question "How many years have you owned a pet?" which can be answered in years, and a further indication question about how long they owned the pets. Participants' robot experience was measured with a 7-point Likert question "How familiar are you with robots?". As for the preferred distance, we calculated it with the timestamp when a participant pressed the button, speed of the camera A, and the speed of the robot.

Furthermore, to measure participants' comfort and safety, we asked questions: "To what extent the robot made you feel comfortable?" and "To what extent the robot made you feel safe?" on a 7-point Likert scale after they watched each video, adapted from the questions used in an earlier study [16]. Additionally, at the end of the study, we asked participants which of the speed conditions they preferred while showing them a side-by-side comparison of all videos.

3.5 Data Analysis

Data analysis was performed using SPSS. First of all, the data was restructured to be able to perform Pearson Correlation and Linear Regression due to the within-subject design. Pearson Correlation was used for investigating the correlations between robot speeds and preferred signaling distances. Linear regression was performed to explore whether robot speed can predict preferred signaling distance. Moreover, Repeated measure ANOVA was performed on the original dataset to check the effects of personal factors on participants' preferred signaling distance.

Table 2 Pearson correlation results between robot speed, signaling distance, comfort, and safety in the video-based laboratory study and interaction study (**: p<.001)

	Robot Speed	Distance	Comfort
Distance	0.47**		
	0.58**		
Comfort	−0.43**	−0.37**	
	−0.59**	−0.59**	
Safety	−0.59**	−0.40**	0.86**
	−0.67**	−0.63**	0.92**

3.6 Results

3.6.1 Relationship Between Robot Speed, Signaling Distance, Comfort, and Safety

To test whether robot speed and preferred signaling distance correlate positively (*H1*) and whether robot speed and comfort or safety correlate negatively (*H2*), we first performed Pearson Correlation on the restructured data. The results showed that the speed of the delivery robot is positively correlated with participants' preferred signaling distance, but negatively correlated with the comfort and safety of the participants (see Table 1). In other words, people preferred a longer signaling distance when the delivery robot was approaching at a higher speed, which supports H1. Furthermore, we also found that the faster the delivery robot was, the less comfortable and safe participants felt, which aligned with H2 (Table 2).

A fixed effect regression analysis was performed to test whether robot speed can be used as a predictor for preferred signaling distance (H1). Indeed, we found that robot speed can be a significant predictor of preferred signaling distance (R^2 = .22, F(1,488) = 135.74, $p <. 001$).

$$y = 4.34 + 0.65x$$

As shown in the formula, x is the robot speed in mph, and y is the signaling distance in meters.

3.6.2 Impact of Personal Factors

3.6.2.1 Pet Ownership A total of 34 out of 74 participants reported owning or having owned a pet. To test our hypothesis that pet owners and participants have a lower desired signaling distance than the others (*H3a*), we divided the participants into two groups, one group who has or had a pet, and the other group who never had a pet before. The repeated measure ANOVA showed no significant difference between pet owners and non-pet owners regarding the signaling distance, comfort, and safety ($p >. 05$). The result cannot provide supportive evidence for *H3a*.

3.6.2.2 Experience with Robot To test whether participants with previous robot experience (*H3b*) have a lower desired signaling distance, we first divide participants into 3 groups according to their answers to the question about the earlier experience with robots, which are *low* (who chose 1–2, n = 23 (31.1%)), *medium* (Who chose 3–4, n = 22 (29.7%)), and *high* (who chose 5–7, n=29 (39.3%)) levels of experience. However, we were not able to find a significant difference between the three groups of participants on distance, comfort, and safety ($p > .05$). These results could not confirm the *H3b*.

Furthermore, we explored the effect of age and gender on the desired signaling distance of passersby and found no significant results ($p > .05$).

3.6.3 Exploratory Findings - Preferred Speed

At the end of the study, we asked participants for their preferred speed, and participants' choices (see Table 3 for frequencies). The most preferred condition was 5 mph (8.05 kph). On average, participants preferred 3.63 mph (5.84 kph). This corresponds to a speed similar to normal human walking speed (3.2 mph, 5.15 kph) and faster than the speeds tested in prior work on robot speeds that were limited to 3.60 kph [2, 11].

Furthermore, we asked participants to elaborate on their preferred speed. Based on the distribution of preferences, we decided to present the results in three parts referring to *Slow Speed* (speed conditions 1 and 2), *Medium Speed* (speed conditions 3 and 4), and *Fast Speed* (speed condition 5–7). We summarized their responses (the numbers behind each statement are the frequency of the statements): participants preferred the slow conditions mainly because the lower speed of the robot gave them more time to react (6) and a fast-moving robot is scary (5). As for the medium conditions, participants reported that "it's not too fast or too slow" (16). Lastly, participants who preferred faster speed considered the robot was not too slow (4), but the robots in the slower conditions felt weird (4), and they seemed to have system errors (4).

4 Study 2: Interaction Study

4.1 Study Design and Participants

After the first video-based lab study, we were able to find a pattern that linked robot speed with preferred signaling distance. However, speed can be perceived differently through a video or in real-life situations, it has been investigated under the condition of simulated driving [7]. Therefore, it is necessary to validate the pattern we found in a real-world setting. That is why we conducted this interaction study and also replicated the video-based lab study after the participants took part in the interaction study. The interaction study was conducted in the corridor of the university, followed by a shorter replication of the same video-based lab study (each video was shown 2 times, instead of 4 times in the first study) and a semi-structured interview. This experiment was also conducted in a within-subject design. 26 participants participated in this interaction study (15 males, 11 females, 1 prefer not to say), ages ranging from 22 to 59 years old (M=28.23, SD=9.55).

4.2 Procedure

For each participant, researchers explained the experiment to them and asked for their consent to participate in the study. Then, participants were guided to stand in the middle of the corridor next to an open door to a room they could step into. This ensured their safety during the experiment. Next, a teleoperated delivery robot drove toward the participants 14 times at 7 different speeds (each speed twice in random orders, using the same speeds as in Study 1). Participants needed to step into the room when they felt the robot was too close to them, and felt uncomfortable or unsafe staying. After each trial, participants were asked to answer questions on a paper questionnaire regarding how comfortable and safe they felt with the robot (the same questions were also used in the video-based study, see Section 3). An extra question was added to ask how fast they feel the speed of the robot.

After the 14 interaction trials, participants were led to another room to finish the video-based study. Details of the procedure can be found in Section 3. The only difference is that participants only watched the video of each speed condition twice instead of four times.

4.3 Measurements and Data Analysis

We recorded each of the trails during the interaction study, the distance was calculated based on the timestamps, speed of the robot, and markers on the ground. We kept the other measurements the same as in the video-based study. The same analyses were performed to answer the research question and test the hypotheses. An extra ANOVA was performed to investigate the difference between the data from the interaction study and the online study.

4.4 Results

4.4.1 Interaction Study

4.4.1.1 Relationship Between Robot Speed, Signaling Distance, Comfort, and Safety We performed Pearson Correlation on the restructured data. Similar to our results in the previous study, we found that the speed of the delivery robot is positively correlated with participants' preferred signaling distance, but negatively correlated with the comfort and safety of the participants ($p < .001$, see Table 1).

The fixed effect regression also confirmed that robot speed can be a significant predictor of preferred signaling distance in the real-world setting (R^2=.34, F(1,180)=92.24, $p < .001$).

$$y = 0.93 + 0.53x$$

4.4.1.2 Impact of Personal Factors A total of 19 out of 26 participants reported owning or having owned a pet. The results of the repeated measure ANOVA showed no significant difference between pet owners, non-pet owners, and experienced, not experienced participants regarding the signaling distance, comfort, and safety ($p > .05$). Furthermore, our results also did not show significant differences between different gender groups ($p > .05$). We also have divided participants into three groups based on their age: age between 22 and 23 years old, between 24 and 27 years old, and above 28 years old. Based on these three groups, we found a significant interaction effect of age and speed on the safety perception of the robot ($F(2,23)=4.64$, $p=.02$). As we can see in Fig. 1, older participants (i.e., above 28) perceived robot with higher speed safer than the younger participants.

4.5 Comparison Between the Online Study and Interaction Study

We performed a 2 × 7 ANOVA to compare the preferred signaling distances from the two datasets (video-based study and interaction study) and the seven speeds of the delivery robot. As we can see in Fig. 3, significant differences were found between the two datasets (F (1,658)=395.36, $p < .001$) and speed conditions (F (6,658)=24.26, $p < .001$). More specifically, passersby accept closer distance in real-life situations than watching video-based materials if the delivery robot drives towards them at the same speed. Moreover, their accepted distance grows with the increase of the robot's speed (Fig. 4).

5 Discussion

In this paper, we present two studies, a video-based laboratory study ($n=74$) and an interaction study ($n=26$). In both studies, we measured the participants' preferred signaling distance and perceived comfort and safety when confronted

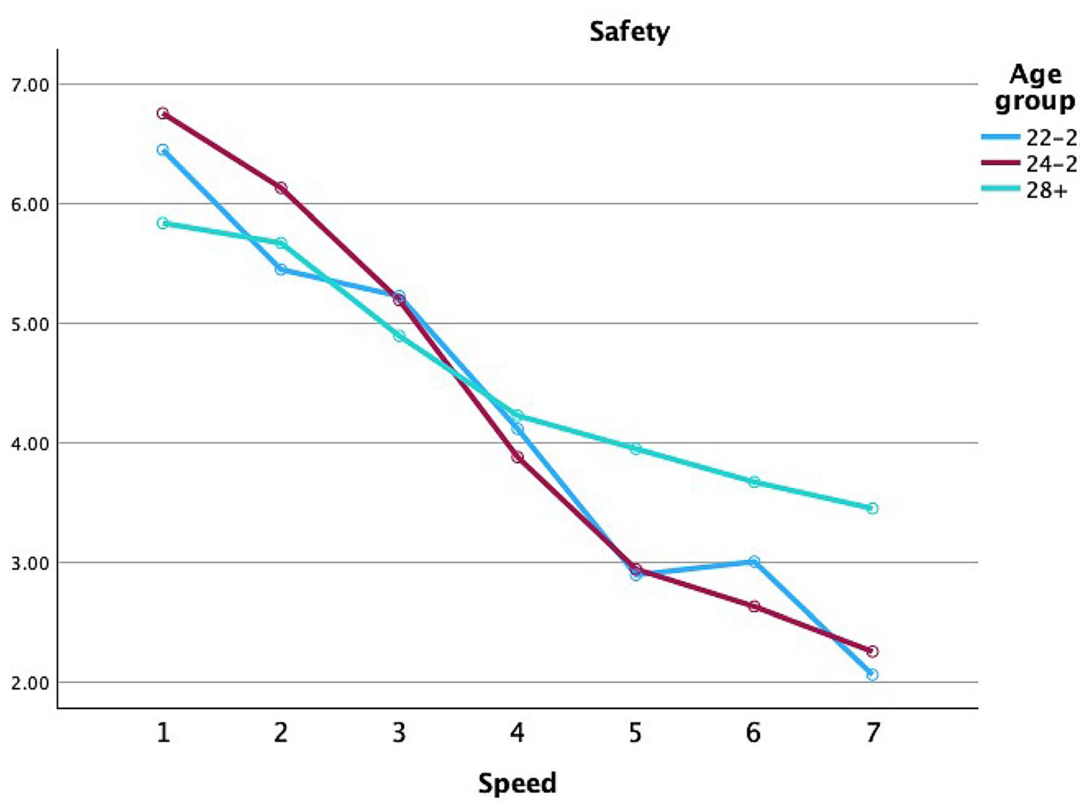

Fig. 3 Interaction effect between robot speed and age on passersby's safety perception in the interaction study

Fig. 4 Differences between two datasets on passersby's preferred signaling distance in different speed conditions

with a delivery robot at different speeds. The study results support our hypotheses that the robot's speed correlates with the preferred signaling distance and can be used to predict when a user would need a navigation cue from the robot to feel safe (H1). In addition, speed is correlated with perceived comfort and safety. However, we did not find significant results concerning participants' characteristics and influence on these processes (H3). Finally, our results suggest that human perceptions of speed through watching a video and watching it in real life are different. In the following, we discuss the results of both studies separately as well as in comparison.

5.1 Speed, Signaling Distance, Comfort, and Safety

In the results section, we demonstrated a significant influence of the robot speed on the preferred signaling distance, thus validating our initial hypothesis (H2). Ideally, we would want passersby to have a similar time frame for their reaction to an approaching robot for all possible robot speeds. To realize this, earlier signaling by the robot would be needed when the speed of the robot increases, otherwise, participants would need to react faster to move aside. The outcome was specific to each speed condition, which can be regarded as the minimum signaling distance, indicating that passersby should successfully perceive the signal before the robot reaches this distance. These insights directly inform the design and operation of delivery robots. For instance, robots can be equipped with adaptive signaling systems that adjust the timing and intensity of signals based on their speed. This may include visual cues [4, 8], such as flashing lights or projected paths, and auditory signals [21], such as beeps or voice alerts, that dynamically change to suit the robot's velocity. Furthermore, these findings encourage the integration of predictive algorithms that calculate optimal signaling distances in real time, ensuring smooth and safe interactions in various pedestrian environments. By incorporating these adaptive features, delivery robots can improve safety, improve user experience, and foster greater public trust in automated systems.

This observation also explains why, as speed increased, participants reported feeling less comfortable and less secure. In the qualitative data collection, participants mentioned that lower speeds made them feel more comfortable and safer because they had more time to react, and potential collisions would be less severe. However, a minority of participants also expressed discomfort with lower speed conditions, perceiving this behavior as *inefficient* and *slow them down*. One reason why this might be the case is that participants felt the need to linearly match their answers to the increasing speed they saw in the videos, which might also explain why the most comfortable and safe condition (condition 1) was not necessarily the most preferred (see Table 3).

Table 3 Preferred speed conditions by participants. Condition 5 is the most popular, followed by condition 4

Speed (mph)	Frequency (%)
1	5 (8.9)
2	11 (19.6)
3	10 (17.9)
4	12 (21.4)
5	13 (23.2)
6	2 (3.4)
7	3 (5.4)
Ave.	3.63 mph (5.84 kph)

Moreover, the difference we found between observing a robot's speed in videos and encountering it in real-life situations suggested potential misjudgments regarding the robot's speed in the video format. This finding not only provided insights for adjusting the formula derived from online data but also emphasized the importance of conducting interaction or field studies. It is important to note that in the videos that participants viewed, the camera maintained a constant forward speed, whereas, during the interaction study, participants were instructed to stand still and step away for safety reasons. Some participants even noted this distinction, which could explain the observed variations. In future research, we need to create a more identical real-world setting to conduct interaction studies, which means that participants should experience different speeds while also walking and potentially doing other things simultaneously. Passersby are not always fully focused on their environment, but look around, chat with someone accompanying them, or are occupied with their smartphones. In the next research step, the preferred signaling distances for pedestrians in inattentive states should be explored. Moreover, in the current study, participants only indicated when they would like to see a root signal but were not exposed to signals that should also be addressed in future work.

In a word, our results provide an initial version of a calculation tool that can serve as a reference for researchers and delivery robot designers to determine the minimal signaling distance needed for robots operating at various speeds.

5.2 Preferred Speed

In other literature on this topic, the most comfortable robot speed is usually under 3.6 kph [3, 19], leading us to suspect a ceiling effect. We discovered with our studies, that the preferred speed (3.63 mph, 5.84 kph) is around the average walking speed (3.2 mph, 5.15 kph [2, 11]). Still, above the limited speed tested in the previous studies [3, 19], which some participants indicated was chosen due to the fact that "it feels most like my own walking speed" or "it moves mostly like a human would do". The results might differ for several reasons. First of all, people usually like to take the middle ground when answering such questions [26], as can also be seen by previous literature investigating such an effect [3]. Furthermore, to our knowledge, this study represents the pioneering exploration of such high speeds, revealing a noteworthy contrast with slower speed settings. Consequently, this contrast could potentially raise the average preferred speed. Many participants explain their answer as "not too fast that it becomes unsafe, but not too slow that it is uncomfortable or inefficient". This sentiment aligns with participants' qualitative responses regarding their favored speed condition. Universally, participants conveyed that progressively higher speed values were perceived as less safe for use.

5.3 Impact of Personal Factors

Among the personal factors examined in this study, only one significant result was found in the interaction study: a significant interaction effect between age and speed on the perceived safety of the delivery robot. This is likely due to changes in human speed perception with age [17]. No significant results were found for pet ownership, experience with robots, or gender which contrasts with previous findings by [27]. Their study suggested that personal experience with pets and robots reduces personal space around robots. Additionally, they found that when a robot's head is oriented toward a person's face, it increases the minimum comfortable distance for women but decreases it for men.

There are several possible reasons why our study did not yield significant results regarding these personal factors: 1) Robot type and study context. The robot used in Takayama et al.'s study [27] was a mechanical-looking robot approximately 1.35 meters in height, whereas our study used a much smaller delivery robot. Previous research has shown that perceptions of safe speed vary significantly based on robot size and initial speed conditions [5]. A smaller delivery robot may have appeared less intimidating to participants. Additionally, the study context differed; our experiment took place in a corridor with the robot approaching participants at different speeds, while their study was conducted in a lab setting. 2) Changes in robot perception over time. There is a 15-year gap between the two studies, during which AI and robotics have become more integrated into daily life. Increased exposure to technology may have altered people's familiarity and comfort levels, influencing their perceptions of robots. 3) Limited sample diversity. A significant portion of our sample consisted of students from a technology-focused university. Compared to the general public, they are more likely to have regular exposure to advanced technology, which may have influenced their perceptions differently. These factors may explain why our results diverge from previous findings.

5.4 Limitations and Future Work

As mentioned above, we chose not to conduct an interaction study that precisely replicated the dynamic situations shown in the videos due to safety considerations. Future research could explore safer methods for conducting field studies that better reflect real-world scenarios, especially considering inattentive states of pedestrians, crowdedness, or conflicting signals such as a honking car. Additionally, employing a more comprehensive questionnaire could help explore more holistically the relationship between speed, safety, and comfort. Furthermore, it would be beneficial for the future design of such robots to investigate how different environmental contexts (e.g., indoor, outdoor, and public spaces) impact speed and the requirements for safety and signaling distance.

We asked participants a single question about pet ownership: "How many years have you owned a pet?" However, we did not collect information on the type of pet they owned, which could have influenced their perceptions. For example, attitudes toward delivery robots may vary between individuals who own a lizard versus those who own a dog.

In this study, we measured safety and comfort using semantic differential scales. The researchers also noticed an artifact of a fixed scale where participants respond relative to previous judgments in their study [14], furthermore, the choice of measures can shape the interpretation of what constitutes appropriate behaviour for a robot [13]. It's plausible that this method lacked sensitivity [28], and the distinction between these two concepts may not have been clear to all participants. Additionally, single-item measures are susceptible to measurement errors, which can compromise their reliability [1, 13, 18]. Future investigations should explore alternative behavioral measures to assess participants' comfort and safety. Moreover, beyond prior experience and pet ownership, other potential person characteristics are worth investigating such as age, having experience as a car driver, and others [23]. The existing literature has also examined the influence of robot size on individuals' perceptions of delivery robots, as robot size affects the distance people keep from the robot [9]. Replicating this study with various robot sizes could contribute valuable insights to the field, especially since the robot used in this study is larger than those used in previous work.

While this paper primarily focused on determining the minimal signaling distance, it's important to consider that if the robot signals its intention too early, participants may not notice or be able to interpret its intention because the robot is too distant [6]. Therefore, future research should aim to establish the maximum signaling distance, which would also depend on the type of signal employed.

6 Conclusion

Based on the findings presented in this study, we can draw several key conclusions. Firstly, there exists a positive correlation between the speed of the robot and the preferred signaling distance, meaning that as the robot's speed increases, passersby prefer a longer signaling distance between themselves and the robot. Conversely, there is a negative correlation between robot speed and perceived comfort and safety, meaning that higher robot speeds lead to decreased comfort and safety perceptions among passersby. Furthermore, the speed of the robot can serve as a reliable predictor for determining passersby's preferred signaling distance. This insight provides a valuable tool for researchers and robot designers specializing in delivery robots, as it enables them to anticipate the appropriate signaling distance based on the robot's speed.

Additionally, our findings indicate that the preferred speed for the robot, as perceived by participants, aligns closely with the average walking speed of a human passerby. It is therefore advisable for designers to consider this passerby-friendly speed range. Moreover, the signaling distance should be thoughtfully selected in accordance with this speed parameter to enhance safety and minimize the likelihood of potential collisions. These conclusions offer practical guidance for the design and deployment of delivery robots in real-world settings.

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Declarations

Ethics Approval This study was approved by the ethics committee (name withheld for anonymity).

Conflict of Interest The authors declare that they have no conflict of interest.

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Heqiu Song is a postdoctoral researcher in Human-Robot Interaction at RWTH Aachen University, Chair of Individual and Technology. She holds a Master's in Applied Psychology from Beijing Normal University and a PhD in Child-Robot Interaction from Eindhoven University of Technology. Her research focuses on the role of social robots in children's music education and the evaluation of human-robot interaction in diverse contexts, including delivery robots and mixed human-robot teams.

Paul Preuschoff is a doctoral researcher in Human-Computer Interaction at RWTH Aachen University, Media Computing Group. He holds a Master's in Computer Science from RWTH Aachen University. His research focuses on how recent technological advances in AI, VR and robotics should be used to stay human-centered and to support people in creative self-expression and fruitful collaboration. He also investigates the protection of users against deceptive design patterns on websites.

Benedikt Grzeschik holds a Bachelor's degree in Applied Mathematics and Computer Science from Fachhochschule Aachen. Alongside his studies, he completed vocational training as a Mathematical-Technical Software Developer. He is currently pursuing a Master's degree at RWTH Aachen University. His work focuses on interdisciplinary topics at the interface with computer science, currently in the field of bioinformatics as part of his thesis.

Astrid M. Rosenthal-von der Pütten is a Full Professor in psychology and director of the group Individual and Technology (iTec) at the Department of Society, Technology, and Human Factors at RWTH Aachen University. Her research explores interactions between people and AI systems ranging from algorithmic decision-support systems to social robots. She and her team are interested in how known social psychological phenomena and communicative processes evolve in human-AI interaction also going beyond dyadic laboratory interactions and focusing on groups and interactions in the field.