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How Robots Should Approach People

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Making Appearances: How Robots Should Approach People

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To prepare for a future in which robots are more commonplace, it is important to know what robot behaviors people find socially normative. Previous work suggests that for robots to be accepted by people, the robot should adhere to the prevalent social norms, such as those related to approaching people. However, we do not expect that socially normative approach behaviors for robots can be translated on a one-on-one basis from people to robots, because currently robots have unique and different features to humans, including (but not limited to) wheels, sounds, and shapes. The two studies presented in this article go beyond the state-of-the-art and focus on socially normative approach behaviors for robots. In the first study, we compared people's responses to violations of personal space done by robots compared to people. In the second study, we explored what features (sound, size, speed) of a robot approaching people have an effect on acceptance. Findings indicate that people are more lenient toward violations of a social norm by a robot as compared to a person. Also, we found that robots can use their unique features to mitigate the negative effects of norm violations by communicating intent.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; *Laboratory experiments*;

Additional Key Words and Phrases: Social robots, human-robot interaction, interpersonal distance, robot approach, height, proxemics, personal space invasion, functional noise, velocity, social norms, robot navigation, human-robot collaboration

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1 INTRODUCTION

Our behavior in public spaces is governed by social norms: Unwritten rules and standards shared within a group, which specify how to behave in a certain social situation [10, 39]. On the one hand, we judge others based on their compliance to prevalent social norms. On the other hand, how we

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are perceived depends on our compliance to the social norms of others. Because impressions can be formed unconsciously in as little as 39 ms [2], the consequences of not adhering to prevalent social norms may lead to a (lasting) negative impression, and consequent interaction. We expect that this negative effect of the wrong first impression also occurs in human-robot interaction.

While increasingly deployed outside of factories, robots are not yet commonplace in society. Though forecasts state that the number of consumer robots will increase from 6.6 million to 31.2 million by 2020 [45]. As robots start are deployed in public spaces, it is important that their behavior is inline with the social norms that exist in the environment where the robot is to provide services [f.e. 3, 6, 36]. In the field of human-robot interaction (HRI), researchers have investigated elements of social robots' approach behaviors; i.e. what distance to keep from people [24, 50], from which direction to approach [43] and at what speed to approach [8, 12].

While the morphology of some robots can be described as humanoid, and robots can have humanoid elements such as a head and arms, they are still clearly distinguishable from people. We therefore do not expect that socially normative approach behaviors can be automatically transferred on a one-on-one basis from people to robots. For robots to effectively engage and interact with people, there are important questions that ought to be addressed. For example: Do people respond differently to robots approaching compared to other people approaching them? What aspects of a robot's design influence peoples' perception of, and attitudes toward a robot approaching them?

In this article, we present two complementary experiments in which we investigated people's responses to a robot's approach behavior. In the first experiment, we compared responses toward approaches by people and by robots (Section 3). In particular, the responses of people when an agent (a robot or person) got too close to them, and to what extent the agent's approach speed influenced participants' responses. The results showed that people responded more strongly to norm-violating approach behaviors by a person as compared to a robot. The goal of the second experiment was to investigate the impact of the features height, generated noise, and velocity on people's responses when being approached by a robot (Section 4). The results indicate that generated noise positively impacts participants' impression of the approach of the robot. Before presenting the two experiments, we will present theories and previous work related to the experiments in Section 2.

2 RELATED WORK

In this section, we will first explain how this article builds upon previous published preliminary findings. We will then introduce key theories and previous work related to this article. We will first describe research on people's interpersonal distancing behaviors when approaching other people (Section 2.1). This is followed by a presentation of related work in the field of HRI (Section 2.2). In Section 2.3, we will discuss work related to features of robots that may influence people's perception of a robot when it approaches people, such as speed and height.

It is important to note that the findings from this article divert from earlier-published preliminary results in [26]. The research methodology, in particular the set of nonverbal behavioral measures used in Experiment I, have been reported in [26]. We considerably extend our previous analysis of results with further quantitative analyses, resulting in a number of novel insights. Our new analysis reveals that participants show stronger compensatory responses to invasions of personal space by people as compared to robots. A reason for this discrepancy with our earlier results is a difference in the depth of the analysis. The preliminary results in [26] were based upon a Kruskal-Wallis test without further post hoc analysis as the aim was to present a set of measures along with a preliminary validation. Although this test yielded a significant difference between the groups, the conclusions drawn in [26] now turn out to be premature.

Table 1. Four Zones of Interpersonal Distance as Identified by Hall [22, p. 126]

Zone	Range	Situation
Intimate zone	0.00 to 0.45 m	Lover or close friend
Personal zone	0.45 to 1.20 m	Conversation between friends
Social zone	1.20 to 3.60 m	Conversation between non-friends
Public zone	3.60 m+	Public speech

With regards to Experiment II, the results reported in this article combine and extend previous results reported in [25, 31], allowing us to draw conclusions with respect to the combination of the features sound, height, and speed.

2.1 People Adhere to Strong Social Norms When Approaching Each Other

To have a better understanding of different norms that people adhere to in social situations, we will discuss work related to how people approach and distance from each other.

One aspect of approaching and interacting that has received the attention of researchers is the comfortable approach distance, closely related to one's *personal space*. Hall [22, p. 119] defined personal space as "a small protective sphere or bubble that an organism maintains between itself and others." According to Dosey and Meisels [14], the function of personal space is "to act (in part) as a buffer zone which serves as a protection against perceived threats to our emotional and physical well-being." Our personal space is therefore not only a physical but also a psychological buffer zone.

In this article, we will use the umbrella term "personal" space to refer to the comfortable distance two or more persons keep between each other. Hall [22] determined the distances that (North American) people generally keep from each other in various social situations (Table 1). The invasion of personal space occurs when the intimate space zone (between 0 and 45 cm) is being entered by someone who is not a close friend or relative. This has shown to be experienced as disturbing and uncomfortable [22]. The size of our personal space, the distance we keep from other people, is influenced by a multitude of factors, including cultural background, gender, and age. This distance is also influenced by observable behaviors between people interacting, e.g., posture, voice loudness, and odor strength [21].

When someone's personal space is invaded, he or she can act in several ways to compensate for this (unwanted) closeness. We will refer to these behaviors as compensatory behaviors. Physical reactions that serve to compensate for the invasion of personal space include flight behaviors, which occur within physical proximity: physically stepping away [23] or leaning away [32]. Subtler compensatory behaviors include reducing the eye contact between people [20], and showing negative facial expressions [7]. For the studies reported in this article, we considered these compensatory behaviors as a behavioral measure of people's perception of personal space invasion, whereas self-reported measures include assessment through, for example, questionnaires.

To summarize: people adhere to social norms when approaching each other, specifically in terms of how to approach and what distance to keep from others. From the literature it seems that people have an innate need to establish and maintain interpersonal distance to others. In the first experiment (Section 3), we investigated whether this social norm is similar when robots and people interact. First, we therefore discuss related work in HRI on approaching and distancing behaviors.

2.2 People Expect Robots to Adhere to Social Norms When Approaching

Research on social norms in HRI has largely been inspired by findings on patterns in people's interaction, e.g., the literature on personal space introduced in the previous section. A number of works have focused on socially aware navigation, for example by creating path planners that adhere to social conventions [30, 42, 46], legible avoidance maneuvers [33], and novel algorithms to appropriately approach people [28]. Before we can investigate what compensatory behaviors people display if their personal space is invaded, we need to know at what point during an approach a person experiences their personal space is invaded by a robot.

A topic that has received significant attention is the appropriate approach distance of robots to people. Several works have explored appropriate human-robot approach distance in HRI. Walters et al. [50] conducted an experiment with a PeopleBot in which participants were asked to approach a robot. In this experiment, 60% of participants positioned themselves either in Hall's [22] personal or social space zone (between 0.45 and 3.6 m). The remaining 40% stood closer to the robot, suggesting that they did not respond to the robot as to people. Similarly, Hüttenrauch et al. [24] conducted an experiment in which participants interacted with a PeopleBot as well, albeit in a more interactive scenario. The study found that almost all participants positioned themselves within Hall's personal space zone when interacting. Takayama and Pantofaru [44] conducted an experiment in which participants approached a PR2 robot and were approached by the same robot. Similar proxemics rules were found to apply to social robots as to people: Mutual gaze led to an increased distance between interacting partners when compared to an averted gaze. Furthermore, people familiar with robots maintained a smaller distance from the robot than people unfamiliar with robots. A study by Mead and Matarić [35] investigated how human-robot distances are influenced by the observable behaviors of gesture and speech, and showed that their model was consistent with the distances expected from the research of Hall [21, 22]. Similarly to being approached by robots, when a robot passes by a person, for example, in a hallway [38] or in a shopping mall [42], people show a preference for a robot that adheres to social conventions.

People have similar, but not necessarily equal proxemic expectations for robots as they do for people. Explained by theories such as the media equation [40] and anthropomorphism [15], it may be that the same unconscious rules apply to human-robot proxemics, as in human-human proxemics, but that the distances involved are different. There is some indication that people may allow robots to come closer than persons, implying that this particular social norm cannot be transferred exactly from people to robots. Because previous work in HRI has not yet compared responses to approaches from a person and a robot, we investigated this in the first experiment presented in this article (Section 3). Rather than investigating toward which distance people allow an agent (a robot or person) to approach, we investigated how people responded to an agent approaching them too close for comfort.

2.3 The Influence of Robot Features

Currently available robot platforms being developed for, and those already deployed in public spaces, contain design features that people do not possess. Examples of these features are wheels and motor noise generated by those wheels. There are three factors that are relevant to this article, these being auditory cues, speed, and robot height.

2.3.1 Auditory Cues: Sound and (Motor)noise. Research in HRI has addressed the use of sounds. Fischer et al. [19] poses that using sounds instead of speech to attract attention may be beneficial, since using speech may imply that a robot also understands speech. In a subsequent experiment, the authors found that people were more comfortable with a robot making a beeping sequence when approaching, compared to a robot not producing any acoustic signals.

An unexplored factor in HRI research that we consider in this article is the functional use of the sounds or noise generated by the robot. Auditory cues can signal that something or someone is approaching. In a survey about electric cars, participants expressed concerns over reduced auditory cues and the associated risk of accidents (e.g., not hearing a car in time) [52]. Following up on this, Nyeste and Wogalter [37] conducted an experiment in which participants evaluated videos of a Toyota Prius with six different types of sounds to render the car more prominent to pedestrians and bicyclists. An engine sound was considered the most acceptable sound for a car, preferred over a humming or whistling sound, a horn and a siren. As such it is interesting to investigate if different patterns of this engine sound can communicate different intentions, both for cars and social robots. In the second experiment reported in this article, we will investigate the influence of noise on people's evaluation of an approaching robot.

2.3.2 Speed. The speed at which a robot drives toward someone has been identified as an important factor in HRI. If a robot approaches too quickly, then this can be considered as threatening; if it approaches too slowly, it could signal a lack of social skills. Research in HRI has investigated the appropriate approach speed in various situations. Butler and Agah [8] manipulated a robot's approach speed and found that participants preferred slower approach speeds (0.25 and 0.4 m/s) over a faster approach speed (1.0 m/s). In an experiment by Dautenhahn et al. [12], the initial approach speed was 0.4 m/s, with the robot decelerating to 0.25 m/s when coming close to the participant; 60% of the participants indicated the final speed as generally being correct, while the remaining participants indicated the speed to be too slow. Compared to people's walking speed the average speed of robots is slower; e.g., Daamen and Hoogendoorn [11] report an average human walking speed of 1.34 m/s, while in lab studies, Enright and Sherrill [16] found averages between 1.37 and 1.6 m/s, depending on the gender of participants. This shows that a robot should approach slower rather than faster and on average drive slower than people would generally walk.

One possible reason for people's preference for a slower speed of robots may be that not all robots give a clear indication of when they will come to a halt. While people signal a range of nonverbal signals when approaching others [29, p.153], robots often lack a display of subtle cues. When robots convey their intentions, faster approaches may be more appropriate. One way of doing this is to equip robots with functional sounds; this has been discussed in Section 2.3.1. A second method for conveying a robot's intentions could be based on people's interpretation of the speed of the robot. These two factors will be addressed in the second experiment presented in this article.

2.3.3 Robot Height. A final factor that may influence the interaction between agents is height. In literature research has been reported on the relationship between a person's height and factors such as status, authority and income. Examples include Judge and Cable [27], who conducted a meta-analysis of studies investigating the relationship between height and workplace success, and showed that height is positively linked to intelligence, social esteem, performance and income. Case and Paxson [9] found height to be positively correlated with cognitive ability, which in turn is rewarded with higher income, and so on, and Young and French [53] found that historic U.S. residents who were perceived as "great" were significantly taller than those who were viewed as less significant. These studies indicate that height influences how we perceive others.

Height has also attracted the attention of researchers in HRI. Butler and Agah [8] manipulated robot height by adding a humanoid body to a robot platform to make it taller. The height of the robot varied between 35 and 170 cm, with the small robot being mechanical and the taller robot having a humanoid body placed on top of it. Results indicated that people felt more uncomfortable when the taller robot approached them. However, it is unclear whether this was due to the height, the variation in the degree of human-likeness, or a combination of these two factors. Walters [49] manipulated the appearance (humanoid vs. mechanical) and height (120 vs. 140 cm) of a robot in a within-groups experiment. Participants indicated that they had no overall preference for either the short or tall robot, nor did they have a significant preference for either the mechanical or humanoid appearance.

While there are studies that have explored robot height, their findings are not entirely conclusive. We cannot yet be sure whether a taller robot is perceived more positively upon approach, because people believe it to be more intelligent, in line with what we know about human interaction. Nor do we know if a smaller robot is perceived more positively because it appears less threatening. We will address this particular issue in the second experiment presented in this article.

To conclude: in this literature review section, we reviewed literature that showed that people adhere to the norm of personal space when approaching other people. When this norm is violated people employ so-called compensatory behaviors to reduce the physical or psychological distance between themselves. Examples of these behaviors include physically stepping away, or reducing gaze. Literature in HRI shows that people also adhere to this norm when interacting with a robot. What is still unknown is how people respond to violations of this social norm by robots compared to reponses to the same social norm violation by people, and we will investigate this in Experiment I. Robots after all are not people and have unique features (or modalities). In Experiment II, we will investigate the impact of several features on acceptance within a robot-human approach scenario.

3 EXPERIMENT I: WHAT HAPPENS WHEN A ROBOT OR PERSON INVADES PERSONAL SPACE?

In Experiment I, we examined participants' reactions to a person or robot approaching them closer than is generally assumed appropriate, i.e., invading their personal space. Previous research in HRI has been limited to investigating factors that influence the size of the personal space zone and comfortable approach distances (see Section 2.2; e.g., Hüttenrauch et al. [24], Takayama and Pantofaru [44]). This experiment, in contrast, set out to research the behaviors that can be observed when a robot invades someone's personal space. Compared to the work previously reported in [26], we will present a more in-depth analysis of the data.

3.1 Hypotheses

Based on the literature presented in Section 2, we formulated two hypotheses for this experiment. The first hypothesis is related to the agent: Based upon the results of the study reported by Walters et al. [50], we expected that people may allow robots to come closer than people. As a consequence, people may respond less negative way to the invasion of personal space by a robot as compared to by a person.

H1: People will respond more negatively when a person invades their personal space compared to when a robot does.

The second hypothesis concerned the agent's approach speed. As related work has shown, people appear to prefer a robot that approaches them at speeds slower than average human walking speed. This may be due to the subtle signals that people send when approaching [29, p. 153], which renders their intentions predictable. We therefore hypothesized that people respond more negatively to a robot approaching them at a higher speed, as compared to a person. As it will be difficult to determine whether a robot will adhere to social norms and stop in front of the participant, we hypothesized that compensatory behaviors toward personal space invasion would increase significantly for the robot in the faster approach condition.

H2: People will display more compensatory behaviors when being approached by a robot at higher speed, as compared to when a person approaches at a higher speed.

To test these hypotheses, we conducted a between-groups experiment in which we manipulated the agent (a robot or human confederate) and speed of both agents, which was either slow or fast.

Fig. 1. Where's Waldo poster used in experiment I.

3.2 Method

In this between-groups experiment ($N = 85$), we manipulated the agent (human confederate or robot) and the speed of the approaching agent (slow (0.4 m/s) or fast (1.0 m/s)). The preliminary results of this experiment have been reported in Sardar et al. [41].

3.2.1 Task. We designed a task in which participants remained standing in one position to allow the agents to approach them closely. However, we did not explicitly mention this to the participants beforehand. To reduce the potential anxiety of personal space invasion, we chose a museum-like setting. In such a setting it is more common that people stand close to each other to see artwork from the right angle.

During the task, participants were required to find figures on a "Where's Waldo" poster (Figure 1). To avoid the participants completing the task before being approached by the agent, two of the five characters were digitally removed from the poster and could therefore not be found.

3.2.2 Agents. The participants were either approached by a person or by a robot. The person was a confederate and fully aware of the experiment. To control for the effect of gender, we decided that the confederate should be of the same gender as the participant, and therefore, we employed multiple confederates. All confederates were of average height[1] and wore a white shirt, jeans and flat shoes. Prior to the experiment, confederates were trained to walk toward the position of participants at two different speeds (0.4 and 1.0 m/s). Training was conducted by the supervising experimenter using a stopwatch. The instructions to confederates included walking toward the participant and after having approached, ignoring the participant, keeping a neutral facial expression, and making no eye-contact.

The robot, a Nomad Scout, was given an outfit designed to look non-threatening (Figure 2). The robot had a diameter of 40 cm, a height of approximately 140 cm and was equipped with a range scanner in its stomach area for the purpose of measuring the distance between the robot and the legs of the participant when approaching. The robot was operated by a trained robot operator in

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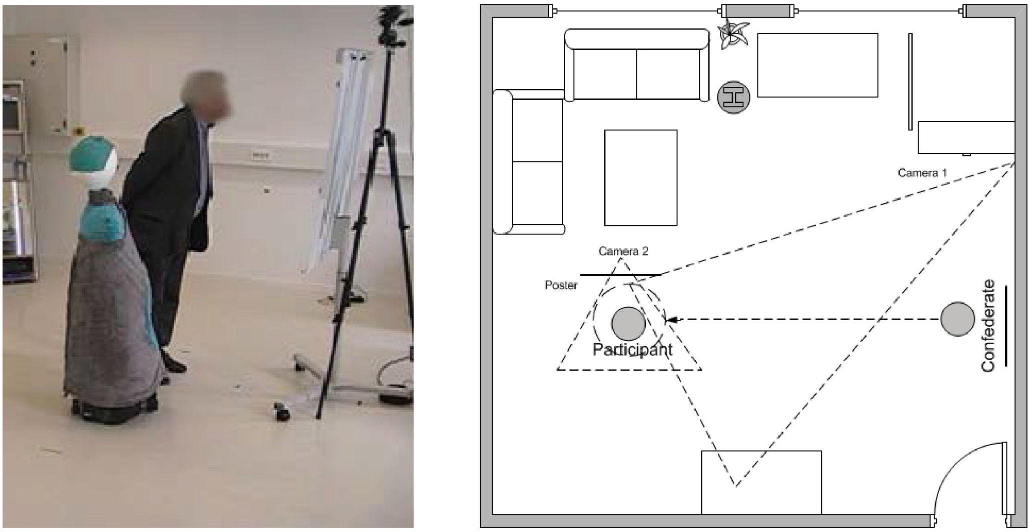
[1] According to Statistics Netherlands, the average height of Dutch men is 181 cm and women 168 cm. Source: http://www.cbs.nl/en-GB/menu/themas/gezondheid-welzijn/publicaties/artikelen/archief/2012/2012-3746-wm.htm?Languageswitch=on.



(a) Modified Nomad scout robot used in experiment I.

(b) Experiment room layout in experiment I (dashed lines indicate camera viewing angles.

Fig. 2. Robot and experiment room layout in experiment I.

a manner that reflected the behavior of the confederates: to approach participants at one of two different speeds (0.4 and 1.0 m/s).

3.2.3 Speed. The speed of both robot and confederate was either slow, at 0.4 m/s, or fast, at 1.0 m/s. The slower speed of 0.4 m/s was chosen as this speed was used in prior HRI experiments [8, 12]. The faster speed of 1.0 m/s was also used in prior research by Butler and Agah [8] and deemed less appropriate than a speed of 0.25 and 0.4 m/s. Both these speeds are lower than average human walking speed [11, 16], though at the time of the experiment, we were limited in two ways: First, it was not possible to driver faster with the current robot platform while simultaneously safeguarding the participants' safety. Second, the distance between the participant and the robot (and confederate) was limited due to space constraints. Within those constrains it would be impractical to further increase the maximum speed as the robot would have to immediately decelerate the moment it would have reached a speed of 1.4 m/s.

3.2.4 Measures. A self-reported questionnaire (subjective measure) and video data (objective data) were collected during the experiment. The questionnaire measured attitudes toward robots (12 items, $\alpha = 0.789$), physical (5 items, $\alpha = 0.820$) and social attractiveness (5 items, $\alpha = 0.777$), human likeness (7 items, $\alpha = 0.821$), and trust (8 items, $\alpha = 0.789$), as described in detail in Joosse et al. [26]. The task-specific manipulation checks (three items) and demographics (10 items) questions resulted in a 50-item questionnaire.

We used behavioral (objective) measurements to code the video data. The data were recorded by two cameras, one on top of the flipchart where the poster hung to record facial expressions and head posture, and one in the far corner of the room, providing an overview for recording full body movements such as stepping away (see Figure 2). Coders coded behaviors that were identified by social-psychological research as (observable) behavior occurring when personal space was invaded (see [26] for the underlying measures). The videos were independently coded by two coders using a 21-item coding scheme. Specifically, the coders indicated on a 5-point semantic differential scale whether or not they believed a particular response occurred. Joosse et al. [26] describes the underlying measures, as well as a principal component analysis that was conducted on the coded video data. The principal component analysis resulted in three components, which together explained 71.42% of the variance.

The three components containing avoidance behaviors are called negative emotional response, positive emotional response and physical avoidance behaviors. The negative emotional response ($\alpha = 0.87$) component is made up of items such as gazing at the confederate (which in this case we interpreted as a negative response to personal space invasion), looking surprised and behaving anxiously, distracted, or restless. Positive emotional response ($\alpha = 0.83$) includes positive responses on the part of users (e.g., pleasant facial expressions and leaning toward the agent). Items that loaded high on the physical avoidance ($\alpha = 0.80$) component include the step distance and number of steps that participants made away from the agent. These three components were coded on a 5-point scale.

3.2.5 Experiment Procedure. Prior to the experiment, the participant was taken into a briefing room. This room was isolated both visually and auditively from the experiment room. The experimenter delivered a short verbal briefing during which the participant was told that s/he was about to participate in an experiment about how people process visual information. After the verbal briefing, the participant was asked to sign a consent form and was taken to the experiment room (Figure 2). The agent was already in the experiment room. Before entering, the participant was asked not to pay attention to the “materials” (the robot) or the “other participant” (the confederate). The experimenter led the participant to the flipchart with the poster on it and provided final instructions on how to execute the task. The experimenter left the room as soon as the participant started searching for figures on the poster.

One minute after the experimenter had left the room and the participant had begun the task, the agent initiated the approach. The speed with which the confederate or robot approached the participant was either slow (0.4 m/s) or fast (1.0 m/s). Note that both these speeds were sufficiently slow for the purpose of moving safely toward participants. Based on the literature, the decision was made to approach from the right-hand side: research from Dautenhahn et al. [12] indicates preference for the left- or right-hand side is based on individual human preferences, though Dautenhahn et al. [12] found a slight preference for the right-hand side. All confederates and robot operators attempted to approach the participants’ intimate space zone. Once personal space invasion had occurred, the experimenter returned to the experiment room and led the participants to the briefing room, where they were asked to complete a questionnaire.

Once the above had been executed in full, the experimenter debriefed the participant and explained the true purpose of the experiment. The duration of each session was approximately 20 min.

3.2.6 Data Analysis. The data were partially normally distributed. In the case of normally distributed data, we calculated ANOVA’s and report main and interaction effects. In the case of non-normally distributed data, non-parametric tests were employed, in this case, Kruskal-Wallis tests followed by post hoc Mann-Whitney tests, as proposed by Field [18]. Unless stated otherwise, all reported significance tests were two-tailed tests. In addition, we report the effect sizes and statistical power of the tests.

3.2.7 Participants. A total of 85 participants (50 males and 35 females) took part in the experiment (see Table 2 for a distribution over conditions). All participants had functional knowledge of English and were primarily recruited on the premises of the University of Amsterdam. Participants’ age ranged between 18 and 70 years ($M = 25.14$, $SD = 9.82$). Most were of Dutch nationality (84.5%).

Table 2. Distribution of Participants, Experiment I

	Human confederate	**Robot**
Slow approach speed (0.4 m/s)	21 (14 M/7 F)	25 (17 M/8 F)
Fast approach speed (1.0 m/s)	21 (10 M/11 F)	18 (9 M/9 F)

Gender distribution in brackets; M = male participants, F = female participants.

The highest level of completed education among participants was university (45%), intermediate education (10%), and secondary school (45%). We excluded two participants whose personal space was not invaded during the experiment (due to technical errors) and five participants who did not notice the agent having approached them. As the robot shell was specifically built for this experiment, participants had never seen the current robot before. Forty-two percent of the participants who interacted with the robot indicated they had no prior experience with robots, 26% indicated they had seen robot before, 19% indicated they had played or worked with robots before, and 13% that they had built robots before. As such, the behavioral response of a percentage of the sample could be influenced by the fact that they had prior expectations and therefore different expectations.

3.3 Results

Two 7-point Likert scaled manipulation checks revealed that our manipulation of approach speed was successful. When asked to what extent the speed of the robot was slow,[2] the "slow" group rated the agent as moving significantly slower (M = 4.28, SD = 1.62) than the "fast" group (M = 3.21, SD = 1.67), U = 580.50, $Z = -2.84$, $p < 0.01$, $\eta_p^2 = -0.31$, $1\text{-}\beta = 0.28$. When asked the same question, but formulated differently ("The speed of the other participant/robot toward me was fast"[3]) the "fast" group indicated the robot moving faster (M = 4.46, SD = 1.62) than the "slow" group (M = 2.80, SD = 1.24), U = 396.50, $Z = -4.53$, $p < 0.01$, $\eta_p^2 = -0.49$, $1\text{-}\beta = 0.58$.

When comparing the two agents on the attitudinal measures a number of observations can be drawn. The human confederate was perceived as more socially credible (M = 4.43, SD = 0.72) than the robot (M = 4.31, SD = 0.94), *n.s.* Similar results were found for physical attraction as the confederate was rated as more attractive (M = 3.96, SD = 0.90) than the robot (M = 2.91, SD = 1.27), U = 418.50, $Z = -4.267$, $p < 0.01$. Also, the confederate was rated as being more socially attractive (M = 3.27, SD = 0.71) than the robot (M = 3.05, SD = 1.09), $t(83) = 1.078$, *n.s.* For participants who interacted with the robot additional attitudinal measures were collected. Prior experience with robots correlated negatively with perceived social attraction of the robot ($r = -0.493$, $p < 0.001$) and social credibility ($r = -0.295$, p = 0.055). Furthermore, a negative attitude toward robot correlated negative with perceived social attraction ($r = -0.647$, $p < 0.001$) and social credibility ($r = -0.609$, $p < 0.001$), indicating that participants who were more positive toward robots in general believed that the robot had higher social competence. None of the attitudinal measures were found to correlate significantly with either of the compensatory behaviors.

3.3.1 H1: Participants Respond More Negatively When Approached by a Confederate than by a Robot. For the first hypothesis, we predicted that people would respond more negatively, and thus display more compensatory behaviors when a confederate invaded their personal space as compared to a robot. When we considered the sum of compensatory behaviors (by summing up the

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[2] "The speed of the *other participant/robot* toward me was slow," 7-point semantic differential scale with 1 = "Strongly disagree" and 7 = "Strongly agree" with the statement.

[3] Formulated on a 7-point semantic differential scale with 1 = "Strongly disagree" and 7 = "Strongly agree" with the statement.

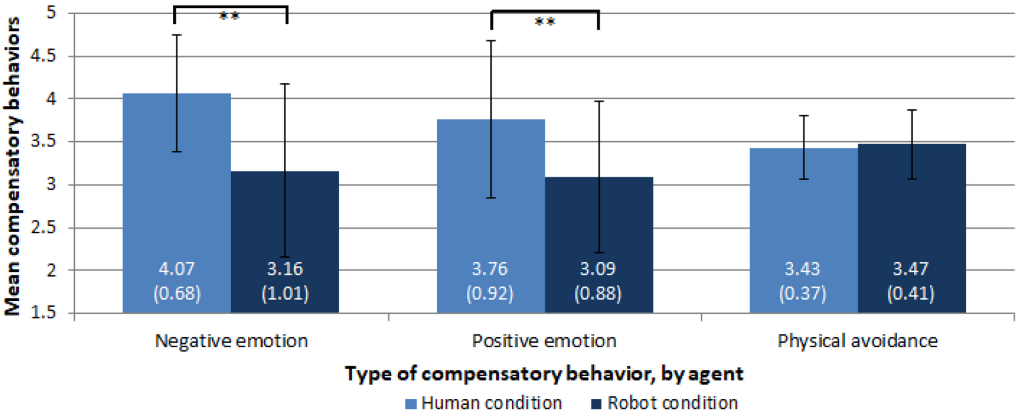


Fig. 3. Mean level of compensatory behaviors when approached by a robot or a confederate, coded from 1 to 5, with 1 = no compensatory behaviors at all and 5 = a lot of compensatory behaviors.

positive emotional, negative emotional and physical avoidance behaviors), we found that participants indeed displayed more compensatory behaviors when being approached by the confederate ($M = 11.26$, $SD = 1.57$) compared to the robot ($M = 9.71$, $SD = 1.77$), $U = 464.50$, $Z = -3.86$, $p < 0.001$, $\eta_p^2 = -0.42$, 1-$\beta = 0.46$.

Our analysis of the three individual components showed that participants displayed significantly more negative emotional responses ($U = 417.00$, $Z = -4.28$, $p < 0.01$, $\eta_p^2 = -0.46$, 1-$\beta = 0.53$) and positive emotional responses ($U = 532.00$, $Z = -3.27$, $p < 0.01$, $\eta_p^2 = -0.35$, 1-$\beta = 0.34$) when approached by a human confederate, as compared to a robot (Figure 3). This indicates that participants displayed less pronounced compensatory behaviors toward a robot invading their personal space than to a person, **supporting H1**. One interpretation could be that people are more lenient toward norm violations by robots. Physical avoidance behaviors were not influenced by the type of agent.

3.3.2 H2: People Display More Compensatory Behaviors When Being Approached by a Robot at Higher Speed. For the second hypothesis, we predicted that a faster approach speed would lead to more compensatory behavior when the robot invaded a person's personal space. Figure 4 shows that changes in approach speed of the confederate did not influence compensatory behaviors. A faster approach speed by the robot however, led to less negative emotional compensatory behavior, though this effect was not significant. Therefore, we **reject H2**.

3.4 Discussion of Experiment I

Our experiment showed that participants displayed significantly more positive and negative compensatory behavior when they were approached very closely by a human agent, compared to being approached by a robot. This is in line with our hypothesis based on previous work [50], which showed that people allow robots to approach them more closely than would be normative for people. There could be two explanations as for why people displayed more compensatory behaviors when being approached by a robot.

3.4.1 Perceived Awareness of Social Conventions. The first explanation could be that people are more lenient toward a robot versus a person violating a social norm; in this case, invasion of personal space. Perhaps the participants in our experiment were under the impression that the robot, unlike the confederate, is unaware of social conventions. Therefore, they had stronger

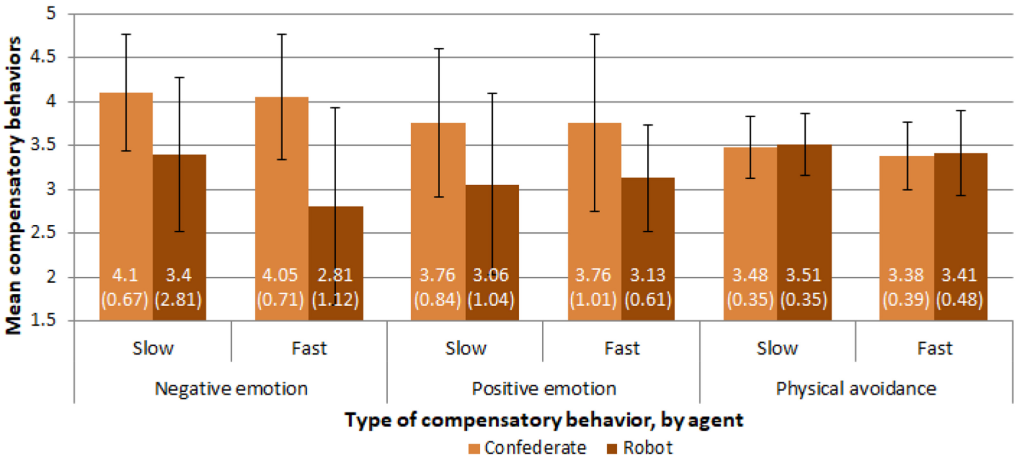


Fig. 4. Mean level of compensatory behaviors in the slow and fast speed conditions for confederate and robot.

reactions to people violating the personal space norm, who should have known better. This is perhaps comparable to parents forgiving younger children's impolite behavior as opposed to when they are older [13].

3.4.2 The Interplay of Motor Noise and Velocity. The second explanation relates to the robot's non-human features. A robot has unique features that could indirectly mitigate the negative response of people to the violation of personal space. In this case, we think that the sounds produced by the motors and wheels of the robot may have provided auditory cues to the participants. These cues may have allowed them to hear the robot approaching. In contrast, the approach by the confederates on sneakers may have been more surprising, accounting for the increased intensity of the response. This effect was enhanced as the experiment room was completely empty; thus, the only object that made any noise in the experiment room was the robot. Therefore, the motor noise may have in a way communicated the robot's intention to the participants. Based on this observation, we felt that this factor deserved more attention. Furthermore, with a height of 140 cm the robot platform was shorter than any of the confederates, who were of average height (about 170 cm). In previous research, robot platform height has been a factor that significantly influenced people's comfortableness when being approached [8]. Because this may also be a factor that explained people's responses, we investigated both motor noise, approach velocity and size in Experiment II.

3.4.3 Limitations. We designed a task that we believed mirrored a museum-like setting, in which it is common that people stand close to each other to see artwork from the correct angle. At the same time, participants may have attributed different meaning to the behavior of the confederate or robot, and thereby evoking specific compensatory behaviors. Replicating this experiment in a more natural environment may therefore yield different results. A similar argument could be made for the way the agent approached—in a straight line. A second limitation of the context of the study is that participants were potentially highly focused on the task (finding Wally) and therefore displayed less physical compensatory behaviors than they would otherwise. Finally, a limitation is that the effect sizes of the tests contributing to the acceptance of H1 were between −0.35 and 0.46, which can be interpreted as a medium effect of the agent on positive emotional behaviors, and a large effect on negative emotional behaviors. However, the statistical power of the results is not high, primarily due to the small sample size. A power analysis revealed that the necessary sample size for a 2 × 2 between-groups experiment should have been 136 compared with this study's 85 ($\alpha = 0.05$, $1\text{-}\beta = 0.80$, $\hat{f} = 0.25$, 2 measurements).

To investigate the interplay of motor noise and velocity on people's perception of a robot's approach, we conducted a second experiment, which is reported in the next section.

4 EXPERIMENT II: THE IMPACT OF NOISE, VELOCITY AND HEIGHT ON PEOPLE'S SUBJECTIVE RESPONSE

In Experiment I, we found that participants displayed less compensatory behaviors when their personal space was invaded by a robot, and that increased speed did not intensify these compensatory behaviors. We identified motor noise and height as potential confounds. Different from the human confederate, when the robot approached at a higher speed, the loudness of the robot's motor noise increased as well. As people use noise in everyday situations to make sense of speed, such as in encounters with cars [37, 52], we set out to investigate the interplay between motor noise and speed on people's evaluation of robot's approach behavior. To this end, we designed two motor noises and velocity patterns to communicate the robot's motion intentions. As a third factor, we included height in the design, as previous research has hinted that the height of the robot may influence the evaluation of said robot [8].

We conducted a 2 × 2 × 2 between-groups lab experiment in which a robot approached participants. The goal was to evaluate during which of the approaches of the robot was perceived most positively. Contrary to Experiment I, in which we compared responses to a human confederate and a robot approaching a person, in this experiment, we set out to investigate the potential confounds of Experiment I: robot height and robot motor noise. As such, we deemed it unnecessary to include a control condition with a human confederate, or to create a setting in which participants would be focused on a different task. We thus created a setting similar to previous HRI experiments [44, 50] in which participants were instructed in advance with respect to the robot approaching them. Initial results of this experiment have been reported in Lohse et al. [31] and Joosse et al. [25]. In this article, we combine both samples into one dataset, thereby allowing us to draw conclusions with respect to the influence of the height vs. motor noise and speed of a robot on acceptance.

4.1 Hypotheses

We investigated the use of noise as a modality for communicating the intention to accelerate, move and stop. By increasing the noise volume when the robot accelerates and decreasing when it slowed down, we created an effect similar to cars, where the volume becomes louder as a car approaches and softer as the distance from a person increases (see also Section 2.3.1). The possibility of using noise in an intentional way has not been explored in HRI to date. We use intentional noise (N^{in}) to refer to a noise pattern that communicates the robot's speed pattern, and unintentional noise (N^{un}) to a noise pattern that does not, as we will further explain in Section 4.2.1. As people send many multimodal signals when approaching others, functional noise can potentially add to a positive perception. This leads to the following hypothesis:

H3: A robot approaching with intentional noise will be more positively perceived than a robot approaching with unintentional noise.

Several previous studies have investigated appropriate robot speed, as reported in Section 2.2. While these studies concerned the evaluation of different approach speeds, they have not analyzed the possibility of communicating the robot's intention through different velocity curves. Similar to adding functional noise to the robot, we hypothesized that a robot accelerating and decelerating slowly (intentional velocity, V^{in}) will communicate its intentions better - such as when it will stop.

Therefore, this robot will be more positively perceived than a robot immediately accelerating to its maximum velocity and stopping abruptly (unintentional velocity, V^{un}).

H4: A robot approaching with an intentional approach velocity will be more positively perceived than a robot without intentional approach velocity.

Rather than a main effect based upon either of the two manipulations, hypothesis 3 poses that a robot showing congruent behaviors (in terms of velocity and noise) would be perceived more positively than a robot not doing so.

H5: A robot approaching with congruent noise- and velocity patterns will be more positively perceived than a robot approaching with incongruent noise- and velocity patterns.

A few studies in HRI have been conducted investigating the effect of appearance manipulations such as different robot height (see Section 2.3.3). Their findings have not been entirely conclusive; one reason could be that different robot heights were often combined with variations in robot morphology. Thus, with this experiment, we compared two robots with a similar (functional) design, but varying heights. A reason for including this factor was that there remain different opinions about a possible link between physical height and (perceived) intelligence, which will lead to a higher perceived social status [9, 27]. Judge and Cable [27] note that height equals power and therefore demands respect. If this carries across to HRI, then it may lead people to experience taller robots as more threatening, as well as more intelligent. Our final hypotheses relates to the effect of robot height. We predict that a smaller robot will be perceived as less intelligent, given that height could be correlated with social status, while at the same time being perceived more positively than the taller robot, because it appears safer and less threatening.

H6a: People will perceive a taller robot as more intelligent than a shorter robot.
H6b: People will feel safer when approached by a shorter robot than by a taller robot.

4.2 Method

To test the hypotheses, we have conducted a $2 \times 2 \times 2$ between-subjects experiment, in which we manipulated the robot's noise and velocity, and the robot platform itself. Participants were approached once by a robot, and afterwards completed a post-experiment questionnaire.

4.2.1 Independent Variables. We manipulated three factors, with each factor having two levels. An overview of the noise and velocity manipulations can be found in Figure 5.

Noise. We created two different noise patterns as we wanted to convey the robot's (velocity) intention by varying the level of noise. The loudness of the noise in the first pattern varied, thus using the noise in a functional way to convey information about the motion intentions of the robot. We called this pattern *"intentional noise"* (Figure 5, conditions $N^{in}V^{in}$ and $N^{in}V^{un}$). The second pattern did not vary in loudness, thus did not provide any cues about the velocity intention of the robot; we called this pattern *"unintentional noise"* (Figure 5, conditions $N^{un}V^{in}$ and $N^{un}V^{un}$). The noise was based on car engine noise and the volume was slightly higher than the motor noise of both robots in every condition.

Velocity. The robots were programmed to accelerate and decelerate, either slowly over time (0.1 m/s^2) and to drive "smoothly" or to accelerate and decelerate as fast as possible (1.35 m/s^2), and to drive in an "abrupt" manner. We labeled the first acceleration pattern *"intentional velocity"* (conditions $N^{in}V^{in}$ and $N^{un}V^{in}$ in Figure 5), meant to communicate the intention to approach and stop. The second acceleration pattern had a more constant speed and was therefore referred to as *"unintentional velocity"* (condition $N^{in}V^{un}$ and $N^{un}V^{un}$ in Figure 5). During the approach both robots reached a maximum velocity of 0.69 m/s.

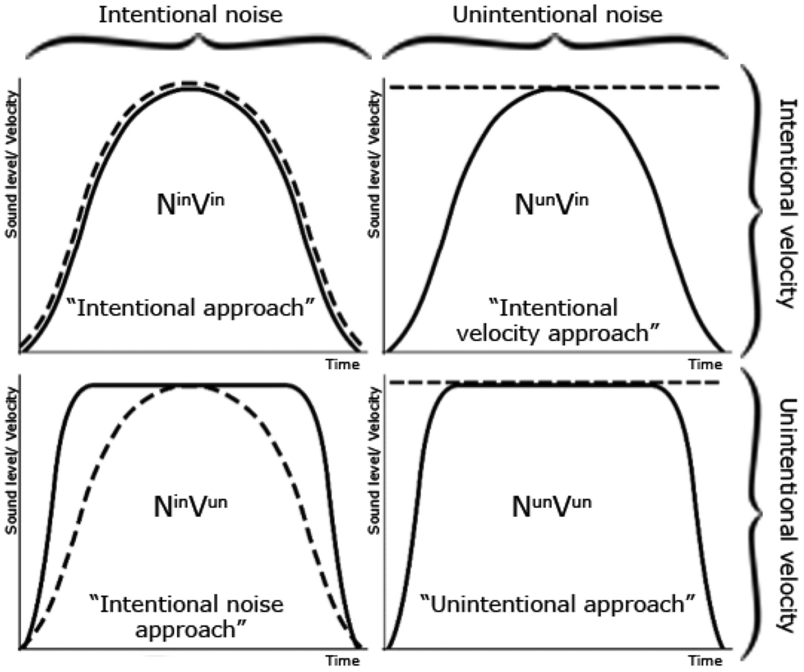
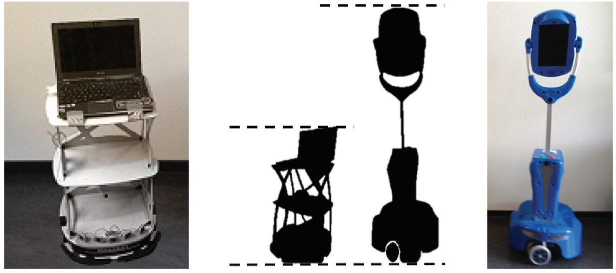


Fig. 5. Four approach conditions. Dashed lines represent volume of the functional noise, while the continuous line represent the velocity of the robot.



(a) 78 cm Magabot. (b) Height comparison of Magabot and Giraff. (c) 163 cm Giraff.

Fig. 6. Two robots with different heights were used in the experiment; a 78 cm Magabot, and a 163 cm Giraff.

The two manipulations resulted in four experimental conditions for each of the two robots, as shown in Figure 5. The four experimental conditions are labeled in this article as condition $N^{in}V^{in}$ (intentional approach), condition $N^{un}V^{in}$ (intentional velocity approach), condition $N^{in}V^{un}$ (intentional noise approach) and condition $N^{un}V^{un}$ (unintentional approach). $N^{in}V^{in}$ and $N^{un}V^{un}$ are the congruent conditions (the acceleration and level of motor noise are congruent) and $N^{un}V^{in}$ and $N^{in}V^{in}$ the incongruent conditions.

Robot height. Each participant experienced an approach by one of two robots: a Magabot (Figure 6(a)) or a Giraff (Figure 6(c)). The Giraff is a 163 cm high telepresence robot, whereas the Magabot is 78 cm high. The height was the main difference between the robots (Figure 6(b)). Overall, their appearance resembled a computer on wheels and they were both rather functionally

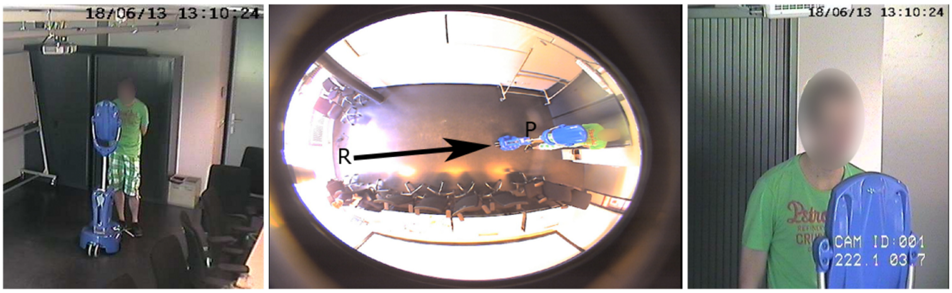


Fig. 7. Video data was collected using three different cameras: an overview of the situation (C1), top-down fish-eye camera (C2), and close-up of the participant (C3).

designed. On the screens of both robots, we displayed a pair of eyes, made up from static colored dots.

4.2.2 Measures. We used a 32-item post-experiment questionnaire to measure participants' subjective perceptions of the robot approach. In addition to four demographic questions, the questionnaire consisted of the Godspeed scales [4] measuring users' general perception of robots based on five constructs (24 items): anthropomorphism (5 items, $\alpha = 0.720$), animacy (5 items, $\alpha = 0.682$), likeability (5 items, $\alpha = 0.851$), perceived intelligence (5 items, $\alpha = 0.763$) and perceived safety (2 items, $\alpha = 0.827$). Using these scales, we measured whether or not a specific condition was perceived as more positive. All items were presented on a 5-point semantic differential scale and were randomized in order within and between scales in the questionnaire. A general evaluation of the approach behavior was obtained using four 5-point semantic differential scaled questions:

- The robot approach speed was... (1: too slow, 5: too fast)
- The final distance between me and the robot was... (1: too little, 5: too much)
- The robot sound was... (1: too quiet, 5: too loud)
- How helpful was the robot sound in terms of anticipating its actions? (1: not helpful, 5: very helpful)

4.2.3 Experiment Procedure. Participants were recruited from the premises of the University of Twente and informed that they were to participate in an experiment to evaluate human-robot approaches. Participants were aware that they would only be approached once by a robot. After signing a consent form, we explained the procedure to participants once more and introduced them to the robot. Participants were then asked to stand on a spot marked on the floor. They were not required to stand exactly in the middle of the spot, nor were they explicitly forbidden to move when the robot approached.

When the participants were in place, the experimenter initiated a script that made the robot drive from position R (see Figures 7 and 8) straight ahead to the position of the participant (P). Both robots were operated using predefined scripts to ensure that the approaches did not differ between trials. The approaches were recorded with three cameras: two cameras positioned in the corner of the experiment lab facing the participants (one close-up, one with a wider angle) and one fish-eye camera attached to the ceiling for recording the overall scene. The layout of the experiment lab and positioning of the cameras is shown in Figure 8. The video data were used to determine whether approaches needed to be excluded. After the robot completed its approach, the experimenter informed the participant that the experiment was over and asked them to complete the post-experiment questionnaire.

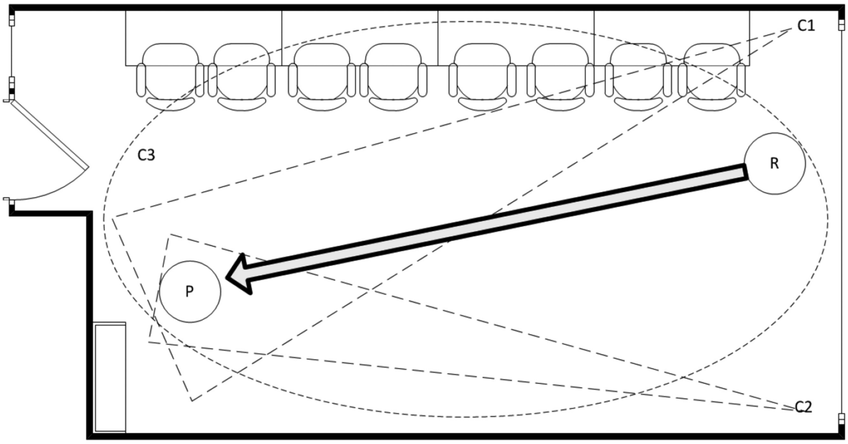


Fig. 8. Experiment room layout. Participants (P) were approached by a robot from the opposite side of the room (R). Data was captured with three cameras (C1, C2, and C3), dashed lines indicate viewing angle of the cameras.

4.2.4 Data Collection Events and Analysis. Two separate data collection events were conducted. Data from approaches by the short Magabot robot, which is reported in Lohse et al. [31] was collected in December 2012. Data from approaches by the taller Giraff robot was collected in June 2013 [25]. Both samples were similar in terms of participant age and gender distribution. To ensure that both samples were equal, a two one-sided test (TOST) was conducted with an equivalence margin (δ) of 0.5. The δ-value corresponds to 10% of the range of scores for the dependent variables. For a more detailed overview of the method, see Walker and Nowacki [48]. The two samples were found to be equal for all dependent variables (Godspeed scales and general evaluation questions). For each of the dependent variables, the lower and upper bounds were within the mean difference $\pm\delta$ margin. This indicated to us that the two samples could be analyzed together.

Prior to conducting further analysis, we checked for internal reliability of the scales we employed (reported in Section 4.2.2). Similar to Experiment I, we report ANOVAs and t-tests for which data were normally distributed, or else we report Kruskal-Wallis tests, followed by post hoc Mann-Whitney tests. Unless otherwise indicated, the tests for significance were two-tailed tests.

4.2.5 Participants. 98 participants participated in the study. A screenshot of the camera recording the wider angle view of participants was taken when the robot stopped and was used to decide whether the robot had stopped in the correct place (Figure 7, camera C1). This procedure led to the removal of the data from 18 participants.

The sample that was included in the data analysis consisted of 80 participants—45 males and 35 females, distributed over the four experiment conditions as shown in Table 3. The participants were aged between 18 to 43 years ($M = 21.1$, $SD = 3.37$).

4.3 Results

In general, when asked to evaluate the approach speed of both robots, the closeness with which it approached, the loudness of its functional noise and the helpfulness of the noise, participants reacted neither positively nor negatively. The mean rating of the approach speed was 3.14 ($SD = 0.59$), which can be interpreted as being generally appropriate. Closeness ($M = 2.78$, $SD = 0.97$), loudness of the noise ($M = 3.40$, $SD = 0.69$) and the helpfulness of sound ($M = 3.04$, $SD = 1.07$) were evaluated equally appropriate.

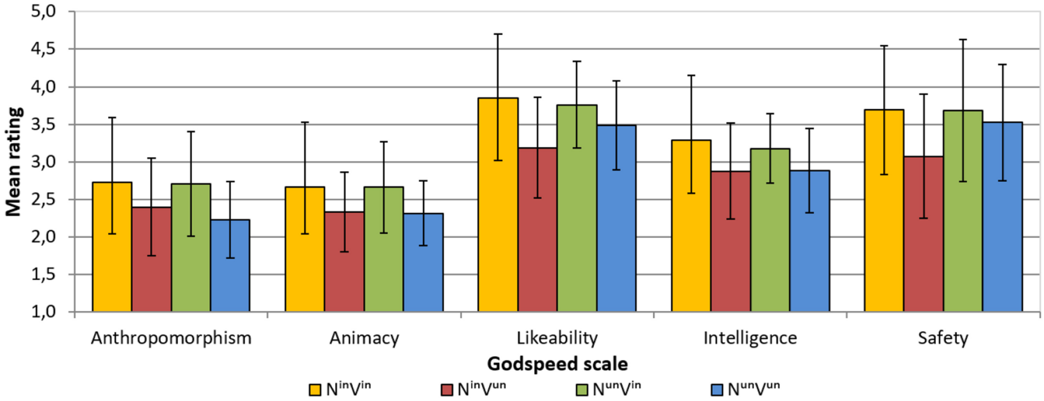


Fig. 9. Mean ratings for Godspeed scales by condition. All questions were formulated on 5-point Likert scales.

Table 3. Participant Distribution Experiment II

	Intentional approach (A) $N^{in}V^{in}$	**Intentional velocity approach (B) $N^{un}V^{in}$**	**Intentional noise approach (C) $N^{in}V^{un}$**	**Unintentional approach (D) $N^{un}V^{un}$**
Short robot (Magabot)	10 (5 M/5 F)	10 (5 M/5 F)	10 (5 M/5 F)	10 (5 M/5 F)
Tall robot (Giraff)	9 (5 M/4 F)	9 (6 M/3 F)	11 (7 M/4 F)	11 (7 M/4 F)

Gender distribution in brackets; M = male participants, F = female participants.

4.3.1 Intentional Noise Improves Evaluation of Approach Behavior. To test hypotheses 3 and 4, we conducted a $2 \times 2 \times 2$ MANOVA (all p's > 0.175). No interaction effect between the conditions was found; however, we found several main effects for functional noise.

The intentional noise conditions received higher ratings than the unintentional noise conditions, which we interpret as a more positive evaluation of the robot in these particular conditions, thereby **supporting H3**. We found significant main effects for functional noise on all but one of the Godspeed scales (Figure 10): anthropomorphism ($F(1,68) = 10.25$, $p < 0.01$, $\eta_p^2 = 0.13$, $1\text{-}\beta = 0.18$), animacy ($F(1,68) = 9.36$, $p < 0.01$, $\eta_p^2 = 0.12$, $1\text{-}\beta = 0.16$), likeability ($F(1,68) = 9.57$, $p < 0.01$, $\eta_p^2 = 0.12$, $1\text{-}\beta = 0.17$) and perceived intelligence ($U = 520.00$, $Z = -2.57$, $p < 0.01$, $r = -0.29$, $1\text{-}\beta = 0.24$).

Participants responses also indicated that intentional noise was significantly more helpful ($M = 3.35$, $SD = 1.12$) than unintentional noise ($M = 2.73$, $SD = 0.99$), $U = 546.00$, $Z = -2.55$, $p < 0.05$, $r = -0.28$, $1\text{-}\beta = 0.23$. These results provide support for H3, in which we stated that a robot with intentional functional noise would be perceived more positively, compared to a robot without intentional functional noise.

We did not find effects for approach velocity on any of the Godspeed scales, we therefore **reject H4**, which stated that an approach using intentional approach velocity would be more positively perceived than a robot approaching without intentional approach velocity. The p-values of anthropomorphism, animacy, likeability, perceived intelligence and perceived safety were all above the α-criterion of 0.05.

4.3.2 Congruent Behavior Effects Perception of Speed. We found a significant difference in the perception of velocity when it was congruent with noise (both intentional noise and velocity,

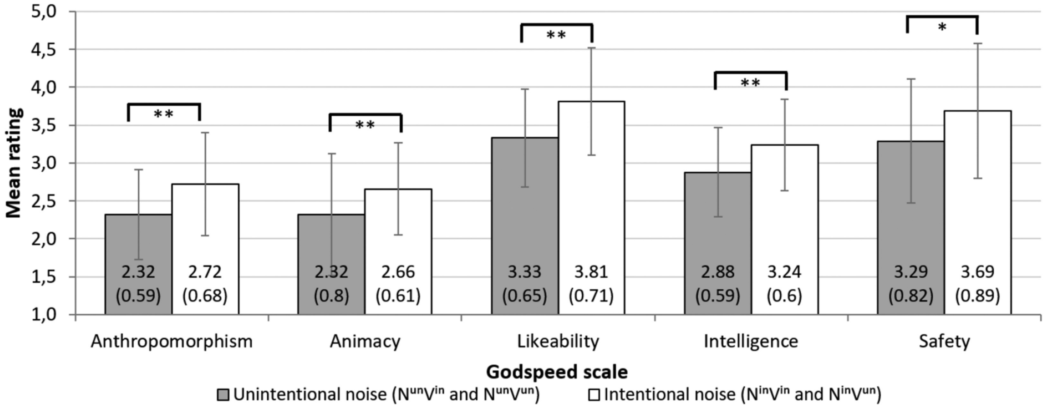


Fig. 10. Mean ratings of intentional and unintentional noise on the Godspeed constructs (*indicates significance at the 0.05 level, **at the 0.01 level).

or both unintentional noise and velocity), compared to when the behavior was not congruent (intentional noise with unintentional velocity, or unintentional noise with intentional velocity). In the congruent conditions, the robots were perceived as approaching at an appropriate speed (M = 3.00, SD = 0.60), while in the incongruent conditions, both robots were perceived as approaching slightly too fast ($M = 3.27$, $SD = 0.55$, $U = 618.5$, $Z = -2.05$, $p < 0.05$, $r = -0.23$, $1\text{-}\beta = 0.17$). There were no significant differences on the other dependent variables, this therefore does not warrant us to accept H5. While this does give an indication that people do potentially respond better to a robot with congruent multi-modal behaviors, we have to **reject H5**.

4.3.3 A Shorter Robot is Perceived as Being Safer. The height of the robot influenced perceived safety. Participants perceived the short Magabot ($M = 3.69$, $SD = 0.94$) as significantly safer than the taller Giraff ($M = 3.29$, $SD = 0.77$, $U = 611.00$, $Z = -1.85$, $p < 0.05$, $r = -0.21$, $1\text{-}\beta = 0.15$, 1-tailed), **supporting H6b**. None of the other dependent variables were influenced by the specific robot used. Since the taller robot was not perceived as being more intelligent, we **reject H6a**.

4.4 Discussion of Experiment II

The goal of Experiment II was to investigate the interplay between motor noise and speed on people's evaluation of robot's approach behavior. To this end, we conducted a 2 × 2 × 2 between-subjects experiment, where we manipulated the type of noise, velocity and robot height. The main finding of this study was that the intentional noise positively impacted participants' impression of the robot's approach. A second interesting finding was that approaches with incongruent noise and sound were perceived as being faster than congruent approaches. We assumed that the robot approach with mismatched noise and velocity would be rated lower, as it was less predictable. This proved to be partly true. For robot designers, this implies that the congruence of multimodal behaviors should be kept in mind, as these all contribute to the user experience.

We expected robot height to have an impact on participants' perception of the robot's intelligence, as related literature reports a correlation between human height and the perception of intelligence. However, we did not find such a relation, which may be explained by the fact that the robots in our experiment were more machine-like, rather than humanoid. This may explain why people did not make the same (unconscious) attributions of height and intelligence where robots were concerned as they would to people [9].

We can only speculate why functional noise had such a strong effect on participants' perceptions of the robot. The noise of new electric cars, or rather, the lack thereof, served as a starting point for our hypothesis and theoretical basis. Pedestrians rely on both visual and auditory cues to estimate an approaching car's distance, direction, speed [5], and motion path [1]. We believe these results indicate that participants used the decreasing loudness of the noise as an indicator that the robot would stop and because doing so conformed to their expectations. The decreasing noise pattern may have made the robot more predictable—similar to cars [37]. Even more so than Experiment I, the statistical power of Experiment II is limited. The impacts that were found pertaining to functional noise can only be classified as having a small effect (effect size under 0.3) and the power is limited ($1-\beta < 0.25$). To attain effects with high power a sample size of at least 184 would have been required.

There are two further limitations to Experiment II that we wish to discuss. The first relates to the task. Contrary to experiment I, in Experiment II, participants were aware that they would be approached by a robot. We argue that as participants were unaware of the conditions or manipulations of Experiment I, the experiment design was appropriate for testing the hypothesis at hand. In Experiment I it was necessary for participants to not know that they would be approached by an agent; in Experiment II, we were specifically interested in investigating participants' evaluation of robot approach behavior, and therefore we had to brief participants that they would be approached by a robot. Furthermore, the limited length of the approach path (about 5 m) limited the maximum speed at which either robot could approach participants. As such, this may explain why the approach speed pattern did not influence participants' evaluation.

The second limitation of Experiment II were the measures with which we operationalized the dependent variable (participants' evaluation of the different robot approaches), i.e., the Godspeed questionnaire. While measures such as the PANAS [51] and Source Credibility Scale [34] are more widely used (also in HRI), we chose to use the Godspeed questionnaire as a tool to compare different robot configurations, as suggested by Bartneck et al. [4]. We made this decision on the basis that this questionnaire was specifically developed for use in HRI; additionally, in this experiment, it showed moderate to high internal consistency.

In the next section, we address the general concerns of Experiments I and II, and their implications for researchers and the field in general.

5 GENERAL DISCUSSION AND CONCLUSION

Previous work in both psychology and HRI research showed that people expect other people, and robots, to adhere to the social norm of respecting one's personal space [8, 24, 44, 50]. The invasion of personal space can lead to negative responses to compensate for this intrusion, such as stepping away. Because we did not expect social norms (including adherence to personal space) to transfer exactly on a one-on-one basis from people to robots, we compared responses to the invasion of personal space by people and robots.

In the first experiment, we observed people's reactions to such a situation using both a human confederate and a robot, and found that people show less pronounced compensatory behaviors to invasion of their personal space when invaded by a robot, as compared to a person. We believe there are two explanations that could explain these results. First, it could be that people have lower standards when it comes to the compliance toward social norms by robots, as compared to people. People could be more forgiving toward robots when they exhibit inconsequential norm-violating behavior. In the same way as we might be for people who are unfamiliar with the norms in our social group, such as tourists, new colleagues, and children who still have to grasp the details of social norms. The second explanation relates to the motor noise generated by the robot, which increased as the robot approached at a higher speed, and decreased when it slowed down toward a halt. This increase could have communicated a sense of urgency or intent to the participants.

We believe the noise generated by the robot in Experiment I was more appropriate for the robot approach, compared to lack of the noise the person made when approaching participants. In Experiment II, we evaluated approach behavior in relation to noise and speed, and we evaluated whether it would be possible for a robot to communicate intent by approaching at a certain speed or while generating a certain level of motor noise. Experiment II shows that it is possible to design specific robot behaviors in ways that allow the robot approach to be perceived as more positive. Besides the exploration of the ways in which to appropriately approach people, related research in HRI investigated how to appropriately mitigate violations of social norms by a robot, and thereby creating a responsive way of approaching robots [47, p. 152–153]. Adapting approach behaviors to participants' preferences is also required as people's personal preferences and attitudes (including risk-aversion) could very well influence their behavior toward robots, as previously shown by [17]. As such, future research might investigate factors beyond social and cultural conventions, like for example the influence of personality traits on preferences for different robot approach behaviors.

For researchers designing behaviors and interaction for social robots, the results of these experiments imply that people do react to intrusions into their personal space, thus strengthening previous research in HRI pointing to the importance for robots to adhere to social norms. The second implication for designers is that robot features such as noise could be used to mitigate unwanted social behaviors, such as personal space invasion. In a way, the social (navigation) skills of a robot might not have to be as fine-grained as the social skills of a person before being deployed around people.

This research offers several future directions for HRI research. The first concerns compensatory behaviors people employ to compensate for an intrusion into their personal space. In Experiment I, we found physical avoidance behaviors to be less influenced by the behavior of the agent than we initially expected. Subtle compensatory behaviors that can be derived from facial expressions warrant additional research in this context. Second, it would be interesting to conduct experiments in a setting where people may not expect a robot to approach them, such as in a restaurant, shopping mall or public space. Replication in such a setting and with a robot that could safely approach people at a higher than average human walking speed [11, 16] could be interesting for both experiments. A third avenue for research includes the behaviors (such as sound) that a robot generates when approaching toward and interacting with people. Though previous research in HRI has investigated appropriate speed and approach behavior, we found in Experiment II that noise, for example motor noise, plays an important role in the expectations and first impressions people may have of a robot. For HRI researchers and robot (interaction) designers in general, this implies that auditory cues can be used to communicate motion behaviors, e.g., a robot's speed and direction. The type of auditory cue provide by a robot can also influence people's impressions of it; other auditory cue examples in HRI include beeping sounds [19], which may lead to different intentions being ascribed to the robot.

To conclude, for robots to seamlessly integrate into our society, it is important that they adhere to the social norms we hold robots to. These norms could very well be similar to norms we expect other people to adhere to. At the same time, it is more likely that these norms cannot be transferred on a one-on-one basis from people to robots. In this article, we investigated how robots should approach people. The studies reported in this article contribute to the HRI field in two ways. First, we have shown that people respond differently to invasions of personal space by people and by robots. In particular, people surprisingly displayed less pronounced compensatory behaviors when their personal space was invaded by a robot, as compared to a human confederate. In the second experiment, we showed that a robot can make use of modalities such as noise, to convey motion intent during approach and thus improve participants' subjective responses. Though people are highly trained in behaving in a manner that is considered acceptable, there are still situations in which they approach in a way that is considered too close for comfort. As robots start entering public spaces it is inevitable that they make those mistakes as well. Therefore, online adaptation to people's perception of a robot's approach are needed to mitigate social norm violations. Further work is needed to understand how to enable robots to communicate their motion intentions as clear as possible, and understand how people respond to the invasions of their personal space to detect those situations and respond accordingly.

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