Human-Robot Interaction: Testing Distances that Humans will Accept Between Themselves and a Robot Approaching at Different Speeds

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Abstract Service robotics has great potential for helping people to live independent lives in their own homes. However, if this potential is to be fully exploited in the near future, research and development cannot limit itself to solving the technological challenges involved. The only way to develop service robots that people will accept is to get potential users involved in the process as early as possible. With that in mind, this study investigates human-robot interaction from the perspective of a service robot approaching the user at varying speeds. We developed an empirical study to measure the distance that humans will accept between themselves and a robot when approached by that robot. The results show that the robot's speed and the test subject's body position significantly affect the accepted distance. We also found that the physical appearance of humanoid service robots has no substantial bearing on the accepted distance.

Keywords Human-robot interaction · Service robot · Acceptance · Speed

1 Introduction

While the use of robots is accepted practice in many areas of industry today, service robotics still has many problems to overcome. To date, the spectrum of tasks performed by service robots has been limited to providing simple services. Current research (e.g. ARMAR, Care-O-bot® 3, DESIRE, Justin and RIBA),

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however, is developing and testing ways of having robots perform complex tasks. These projects are increasingly focusing on health and nursing care. In domestic settings, mobile service robots have great potential for helping people live independent lives in their own homes for longer. This might include transferring physically strenuous activities to the robot, or using the robot to compensate for existing impairments in the user's mobility.

Unlike industrial robotics, service robotics is oriented towards humans. It is therefore important to know as much as possible about what potential users want from the technology, and to pay sufficient attention to these needs when developing the systems. Developers must take account of user requirements concerning, for example, the kind of human-robot interaction that necessarily occurs when using a robot. In an industrial setting, humans and robots often work in separate areas. But this is often impossible for the kinds of tasks a service robot carries out. To perform their tasks, service robots move around freely within their user's living space. As a result, the design of human-robot interaction plays a decisive role in whether or not users accept the technology.

One of the first steps in human interaction with server robots is the user seeing the machine and identifying it as a robot. Next, the user will apply their own mental models to produce expectations about the robot's function and behaviour. The way that these first steps unfold depends largely on the physical appearance of the robot.

Robot designs are generally classified according to how much they resemble a human. The two ends of the spectrum are "machine-like" and "human-like". The "uncanny valley", a qualitative model often used in the design of service robots, describes familiarity as a function of the degree of human-likeness in relation to movement or lack of movement [1]. Because a causal relationship exists between familiarity and acceptance, the literature often speaks specifically about how a robot's appearance or behaviour affects whether or not a user accepts it [2]. A recognised goal in robot development is to positively influence acceptance by producing an anthropomorphic appearance [3]. However, anthropomorphism does not always benefit acceptance—it can actually confuse users [4]. A robot's appearance can therefore affect acceptance or familiarity to differing degrees.

Alongside appearance, behaviour is also important when it comes to developing effective robots [5]. According to the "uncanny valley" model, these are the two main factors influencing familiarity. Depending on how human-like it is, a mobile robot can produce a much higher or lower level of familiarity than a stationary robot [1]. With regard to acceptance, robot behaviour is considered more important than key physical aspects (e.g. its size and design) and more important than its ability to produce facial expressions and gestures [4].

If a person likes a robot's overall appearance but rejects its behaviour, this can result in a certain level of disappointment [6]. Unlike robot appearance, the field has yet to succeed in producing authentic anthropomorphic robot behaviour (e.g. gestures, facial expressions and motor functions). A robot that closely resembles a human will thus disappoint users when they interact with it, since its behaviour does not back up the expectations that its appearance creates. To avoid this kind of disappointment in the following empirical study, we deliberately chose a robot that did not look human.

For service robots to be able to perform their tasks satisfactorily, they must interact with humans in the same space.

With this in mind, Walters et al. investigated the distance that people considered comfortable to maintain when approaching a stationary robot to interact with it [7].

Irrespective of that distance, service robots must be able to come within reach of humans when performing fetch-and-carry tasks. These are especially important for people with limited mobility. As a result, the way in which a robot approaches a person is a crucial factor to consider when designing human-robot interaction. The following section will present the current state of scientific knowledge on the effects of various robot-human approaches, and will use this information to develop research questions and relevant hypotheses.

Our aim was to develop and carry out an empirical study investigating the factors that influence the distance that people will accept between themselves and a service robot approaching them.

2 Current State of Scientific Knowledge

A further study by Walters et al. shows that about 40 % of subjects tolerated shorter distances between themselves and an approaching robot than they did between themselves and another person (human–human interaction) [8]. We can therefore assume that these subjects did not perceive the robot as a social being [8]. This finding shows that it is important to consider a robot's appearance when setting the distance at which humans and robots will interact. Another study, this time by MacDorman, showed that the degree of human-likeness affects how eerie or familiar a person considers a robot to be [9].

In the study's conclusion, however, MacDorman says that the perceived human-likeness is not the only factor affecting how eerie or familiar a person finds the robot [9]. Therefore, in what follows, we will present other factors that might influence the accepted distance.

The study by Walters et al. measured the spatial distance at which 28 test subjects of varying ages became uneasy in the presence of an approaching, non-humanoid robot [8]. However, the distance sensor stopped the robot automatically when it was 0.5 m away from the subject. This means that the study was unable to investigate the human response to the robot at close range. If we compare the results of this study with those produced by humans approaching a stationary robot, we find that there are differences in the distances measured. Mizoguchi et al. investigated different speeds of approach and found that the faster the robot approached the person, the larger the acceptable distance was [2]. They also found that when the robot approached at the same average speed but with different speed profiles, it affected the level of familiarity that subjects felt towards the robot [2].

The appearance and speed of a robot affect user acceptance. It is therefore important that even at the stage of developing the technology for service robots, sufficient consideration is given to the design of their appearance and behaviour. The standard DIN EN ISO 9421-210 describes a process for designing usable interactive systems. It recommends taking the intended use as the starting point for developing these kinds of systems, and to pay attention to it throughout the entire process. In ambient assisted living situations, a variety of scenarios exist in which service robots could conceivably help humans. In these scenarios, the user might be standing, sitting or lying down. Different body positions alter people's perceptions. For example, if the angle of the head changes, it can cause a person's subjective judgement of the vertical to deviate from the objective situation [10]. The position of the body also affects the time needed to get out of the way of an approaching robot. If a person is lying down, it will take more time and effort to move out of the robot's path than it would if they were standing up. This influence on the distance that a person will accept between themselves and an approaching robot can be described as perceived safety. Developing safety mechanisms to protect humans from harm is an important issue in the field of human-robot interaction as a whole [11–13]. It has also been shown that robot behaviour affects the way in which users perceive safety [14].

Furthermore, it makes sense to consider that age might affect a user's ability to interact with technological systems. Numerous effects of this nature have been found to apply to computers. The effects can be the result of age-related changes in physical and mental abilities [15]. Well-known factors include a person's attitude to technology [16], their knowledge and experience of technological systems [17], and their technology-related self-efficacy [18]. The interaction of these elements is underpinned by the individual's overall affinity for handling electronic devices [19]. A final hypothesis will therefore address how age affects the accepted distance between human and robot.

To summarise, research in the field of human-robot interaction relating to robot approaching human should focus on the following:

- Influence of different, non-anthropomorphic physical appearances of robots
- Influence of different speeds and speed profiles
- Influence of the intended use on interaction with the robot

Past studies were carried out as Wizard of Oz experiments, which could have had a non-quantifiable impact on the results. The investigator stopped the robot when the subject expressed that wish. The distances measured in this way do not reflect the actual accepted distances, which is why we optimised the methodology for our study. Further, existing studies have mostly been unable to investigate human-robot distances of less than 0.5 m, even though the robot must enter this space if it is to come within reach of the person.

3 Acceptance

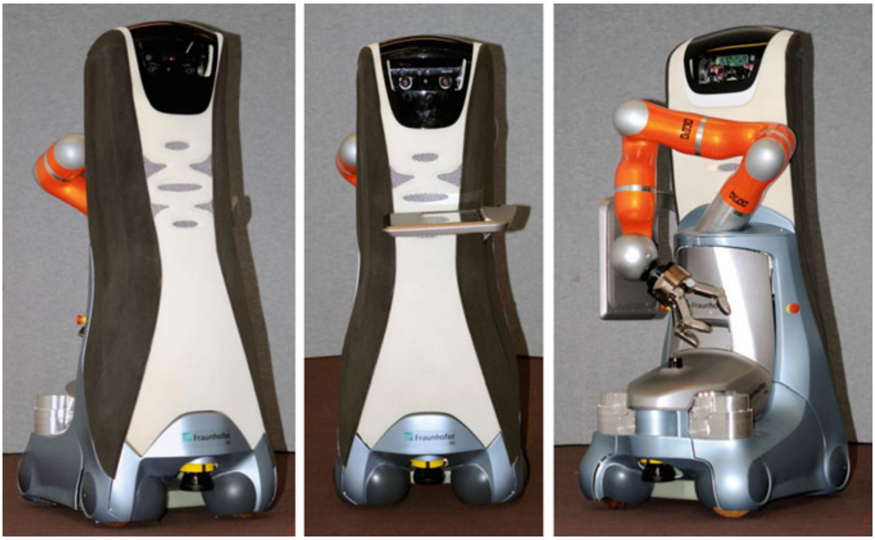
In this context, acceptance means the active willingness of the person in question to make use of a state of affairs that they perceive to be new. This state of affairs, or innovation, includes complete services, ideas, products and processes—as well as specific characteristics (e.g. design, quality, interfaces and behaviours). The decision on whether or not to accept a given innovation can vary depending on who is judging the situation. The crucial factor here is how the person processes information [20], as this helps them compare their expectations with the way specific characteristics actually appear. Decisions on whether or not to accept individual characteristics culminate in an overall decision on whether or not to accept the innovation. This means that changing a single characteristic can affect overall acceptance. And because the expectations that a person has of the innovation can change over time, these too can affect overall acceptance [21]. Most of the changes can be represented by the different phases of acceptance [22]. These phases are divided into: motivation, awareness, first contact, and use. If, for example, a person in the awareness phase sees a very human-like robot, they will have significantly higher expectations of witnessing anthropomorphic behaviour in the subsequent phases (cf. Sect. 1).

For developers to design the characteristics of an innovation in such a way as to ensure optimal acceptance, they must be aware of the factors that determine acceptance. Depending on the innovation in focus, the literature discusses a variety of influences that can affect acceptance [23–25]. Overall, the terms (perceived) usefulness and (perceived) ease of use are posited as the primary factors that determine acceptance.

The test subjects in the following study assumed the role of a user of a service robot. We selected subjects who had no experience with the service robot in question, and little experience with robots in general. This meant that the empirical study covered the phases of motivation, awareness and first contact.

4 Methodology

Our empirical study investigated, for a number of variables, the distance that subjects would accept between themselves and an approaching robot. We used the Care-O-bot® 3 (Fig. 1), a service robot that performs tasks which require it to interact with humans. It can fetch and carry household items and drinks, lay the table, and open drawers and doors. The Care-O-bot® 3 is not humanoid—its design deliberately avoids human attributes. The robot's functions are split between the front and back. The "working side" faces away from the user and houses all the technical components (e.g. its manipulator) that cannot be covered. The "serving side", which has no visible technical components, is where the human–machine interaction happens. This side has a fold-away tray, which



working side with folded away tray

working side with unfolded tray

serving side with folded away tray

Fig. 1 Three views of the Care-O-bot® 3

functions as the main interface between the user and the robot. In addition to transporting objects, the tray also has an integrated touchscreen which is used for inputting and outputting information. The Care-O-bot® 3 is approximately 1.45 m tall and occupies a 0.6 m diameter floor space [26].

4.1 Task and Test Subjects

To carry out the task, subjects were given a button which they could use to stop the robot. The subjects held the button in both hands as the robot approached them. They were asked to press the button as soon as they felt that the distance between themselves and the robot was unacceptable.

Thirty test subjects aged between 20 and 75 ($\bar{x}$: 43.33a; SD:19.01a) took part in the empirical study. The participants, 17 women and 13 men, were divided into three age groups. AG_1 had 15 subjects between 20 and 39, AG_2 had eight subjects between 40 and 59, and AG_3 had seven subjects between 60 and 75. Asked to state their highest educational qualification, 13 subjects said that they held university degrees, while 11 said it was their *Abitur* (university entrance examination taken at German secondary schools). Two held doctorates, and two had completed an apprenticeship. Two other subjects said that their highest qualification was the *Mittlere Reife* (roughly equivalent to GCSEs in the UK or a high-school diploma in the US) and, respectively, a qualification from the *Handelsschule* (vocational business high school). Eleven subjects said that they work in the field of technology or science. Ten subjects said that they work or used to work in the field of social studies or the humanities. Nine said that they work or used to work in business or administration.

4.2 Independent and Dependent Variables

The following independent variables were considered as within-subject factors: the robot's appearance (e), the robot's speed (v), the subject's body position (k) and the robot's task (a). The age group, also an independent variable, was considered as a between-subject factor.

The distance that the subjects accepted between themselves and the approaching robot was measured as a dependent variable.

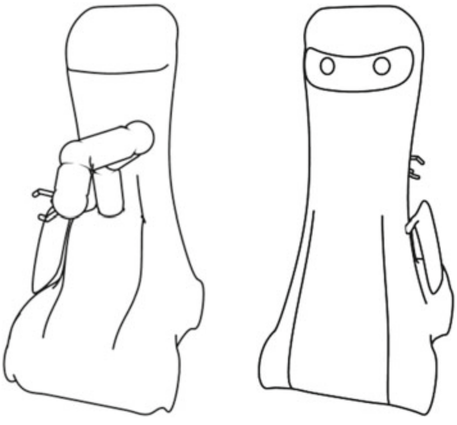
4.2.1 Robot Appearance

The front and back of the robot look different and serve different purposes. To see how each side influences the user, the investigators had the robot approach the subjects with each side showing in turn. As Fig. 2 demonstrates, neither side is humanoid in appearance. One side is more aesthetic, while the other looks more technical.

4.2.2 Robot Speed

Section 2, which dealt with the current state of scientific knowledge, discussed how the speed and speed profile affect the distance that subjects are willing to accept between themselves and the robot. Therefore, it seemed sensible and

Fig. 2 Factor levels in the robot's appearance



e_1 = working side e_2 = serving side necessary to consider both of these variables. With this in mind, we carried out the empirical study with three constant speeds and two speed profiles.

The robot's top speed is 0.75 m/s. DIN EN ISO 10218-1 considers 0.25 m/s to be a safe speed if the robot is making hazardous movements. At the moment, this standard only applies to industrial robots. But DIN EN ISO 13482, which is currently being drafted, will expand it to apply to non-industrial, non-medical household and assistive robots. We therefore used 0.25 m/s as the minimum speed for our service robot. The third constant speed (0.5 m/s) is the mean of the maximum and minimum speeds. The robot's maximum acceleration is 0.8 m/s^2. This means that it covers:

- 0.04 m to accelerate to 0.25 m/s
- 0.16 m to accelerate to 0.5 m/s
- 0.35 m to accelerate to 0.75 m/s

At all three of these speeds, which are shown in Fig. 3, the robot travels in a uniform motion.

We used the two speed profiles to investigate whether subjects would accept less distance between themselves and the robot when it had a non-uniform motion than they would when it moved in a uniform way, where the average speed was the same in both cases. To make it theoretically possible to reduce the accepted distance, we developed the speed profiles so that the robot travelled at a higher speed when it was further away from the subject and at a lower speed when it got closer. We achieved this by reducing the robot's speed as it approached the subjects. The difference between the two speed profiles was based on the following considerations. One profile was smooth so that it would protect the technical components in the drivetrain (e.g. electric motors and fan belts) and thereby extend the robot's lifetime or make it possible to produce relatively cheap drivetrain parts for service robots in the future. The other profile was graduated so that the subjects could clearly see that the robot was slowing down. Both profiles had an average speed of 0.5 m/s. This meant we could compare the results with those for the constant speed of 0.5 m/s.

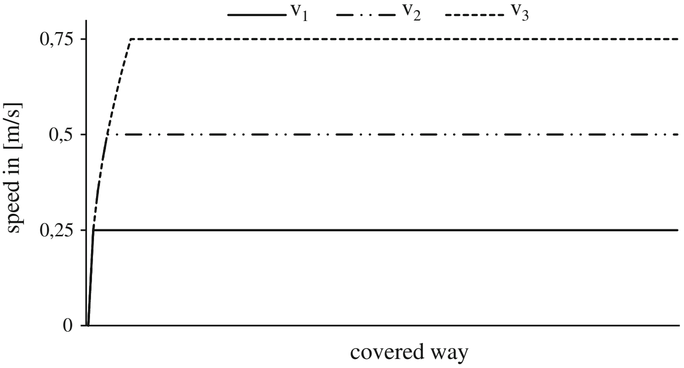


Fig. 3 v-s graph of the three constant speeds

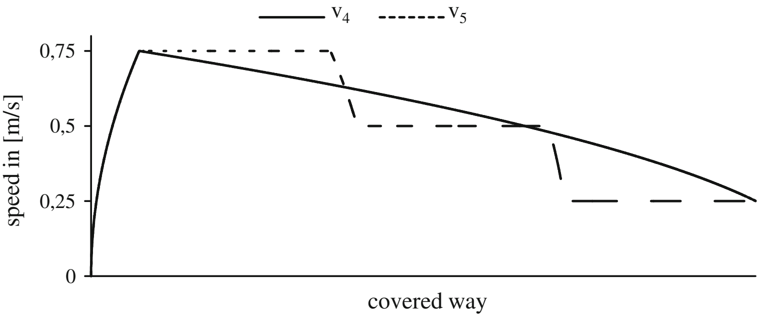


Fig. 4 v-s graph of the two speed profiles

For both profiles the robot's maximum acceleration was 0.8 m/s^2. At the start, the robot accelerated to the maximum 0.75 m/s. It covers about 0.35 m before it reaches that speed. We calculated the speed profiles for the remaining distance to the subject. In the smooth profile, the robot decelerated evenly from 0.75 to 0.25 m/s. The graduated profile involved three equal stages of motion at speeds of 0.25, 0.5 and 0.75 m/s. Between these, there were two downward "ramps" where the robot decelerated at 0.8 m/s^2. Figure 4 shows the two speed profiles.

The five factor levels of the independent variable speed are described as follows:

- Speed $v_1 = 0.25$ m/s
- Speed $v_2 = 0.5$ m/s
- Speed $v_3 = 0.75$ m/s
- Speed profile v_4 = smooth
- Speed profile v_5 = graduated

4.2.3 Body Position of the Test Subjects

With regard to an ambient assisted living environment we considered the positions standing, sitting and lying (Fig. 5) to be best-suited to testing the most common scenarios in which a service robot would support its user.

4.3 Procedure

We conducted the empirical study in four stages:

- Preliminary interview
- Introduction
- Distance measurement
- Concluding interview

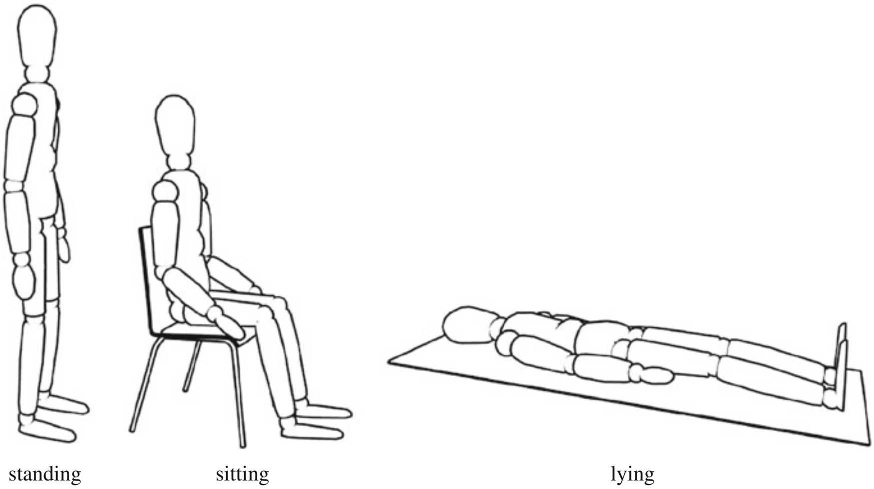


Fig. 5 Factor levels of the body positions adopted by test subjects

The preliminary interview, which we conducted before introducing the robot, established the subjects' demographic details, their experience with robots and their affinity for technology [21].

During the introduction stage, the subjects were allowed to inspect the robot. In a structured interview, the subjects discussed how they felt about the robot and were encouraged to think about how it works. At the end of the introduction stage, the test subjects had all received the same information on how the robot works and on the tasks it performs.

During the distance measurement stage, we recorded the extent to which the independent variables affected the distance that the subjects would accept between themselves and the approaching robot. The subjects were positioned—either standing, sitting or lying—so that each of them began the test at the same distance from the robot's starting position. As shown in Fig. 6, a desk for two investigators was set up to the left of the test subject. One investigator was tasked with starting the robot and recording the distances. The other investigator was responsible for safety during the test.

The safety plan consisted of three separate levels. First, the speeds and speed profiles were programmed in such a way that the robot would automatically stop as soon as it got within 0.1 m of the test subject. Second, a distance sensor would stop the robot if it got closer than 0.1 m to the subject. Third, the investigator responsible for safety could use an emergency stop button to abort the test manually. The robot began approaching each of the subjects from five metres away. The subject pressed a button to stop the robot when they felt it got too close. The distances recorded reflect the shortest distance that the subjects accepted

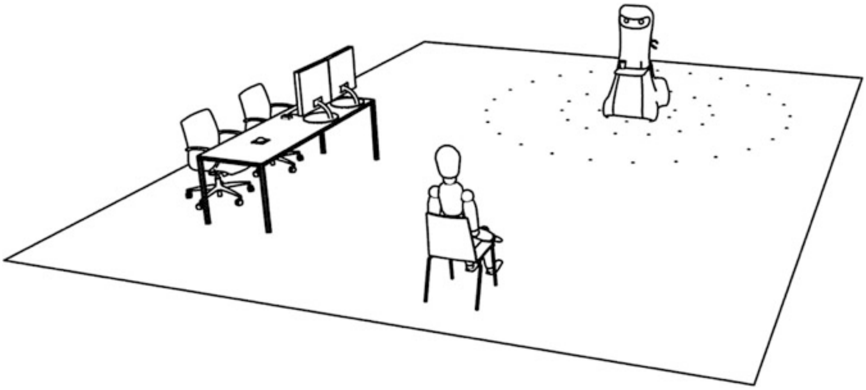


Fig. 6 Test set-up for distance measurement

between themselves and the robot. The distances were measured via the robot's sensors, which have an overall accuracy of ±0.02 m. The independent variables were altered one by one during the course of the experiment. To avoid knock-on effects, the changes were made according to a Latin square design. Thus, the two factor levels for the robot's appearance, five for its speed and three for the subject's position gave a total of 30 different approaches. The robot carried these out with the tray folded away.

In the concluding interview, subjects answered questions about their impressions of the robot and, again, about their affinity for technology [21]. They also evaluated the speeds and speed profiles.

4.4 Hypotheses

Based on research into the current state of scientific knowledge, we posit the following hypotheses:

H_1: The robot's appearance significantly affects the distance that the subject will accept between themselves and the robot.
H_2: The robot's speed significantly affects the distance that the subject will accept between themselves and the robot.
H_3: The subject's body position significantly affects the distance that the subject will accept between themselves and the robot.
H_4: The subject's age group significantly affects the distance that the subject will accept between themselves and the robot.

Table 1 Influence of reaction time ($t_{reaction}$) on the distance travelled by the robot during this time ($s_{reaction}$) as a function of the subject's age (A) and gender (G), and of the robot's speed

A	G	v (m/s)	$t_{reaction}$ (s)	$s_{reaction}$ (m)
20	Female	0.25	0.203	0.051
20	Female	0.75	0.203	0.152
20	Male	0.25	0.170	0.043
20	Male	0.75	0.170	0.128
75	Female	0.25	0.305	0.076
75	Female	0.75	0.305	0.229
75	Male	0.25	0.285	0.071
75	Male	0.75	0.285	0.214

4.5 *Accounting for Age-Related Differences in the Measured Distances*

The sensors on the Care-O-bot® 3 allowed the investigators to record the distances at the point in time when the subjects pressed the button. But this does not precisely reflect the actual distance that they accept, as it takes a little time for them to react and press the button. Reaction time is the time it takes a person to react to a given stimulus. A stimulus can come in a variety of forms and can target different receptors or senses. In the case of our study, a visual stimulus (distance) triggered a motor response (pressing the button). The reference value for the average reaction time for a motor response triggered by a visual stimulus is 220 ms [27]. However, because reaction times change throughout a person's life and because this study included people of different ages, we considered the reaction times differently depending on age. Following Haas [28], we recorded the reaction time for each person based on their age and gender. The distance that the robot covered within that time ($s_{reaction}$) was calculated for each subject at each speed and then subtracted from the distance measured for a given approach. Table 1 shows some examples of the distance travelled in the reaction time.

Therefore, the effects of age on human performance, which primarily concern reaction time in this empirical study, do not affect the dependent variable because this was accounted for in the distances measured.

5 Results

The results from the distance measurement stage are presented separately to those from the preliminary and concluding interviews.

5.1 Accepted Distance Between Human and Robot

The three null hypotheses (H_{01}, H_{02} und H_{03}) were checked using a multifactor analysis of variance with repeated measurements, as the subjects were tested multiple times in the various factor levels. The null hypothesis was rejected at a significance level of $\alpha = 0.05$. We investigated the influence of the three factors appearance (e), speed (v) and body position (k).

All the requirements for a multifactor analysis of variance were fulfilled, with the exception of sphericity [29]. Mauchly's sphericity test found that only the factor concerning body position fulfilled the sphericity requirement. For the other factors, we used the Greenhouse-Geisser correction to degrees of freedom. Table 2 shows the results of the multifactor analysis of variance. There were no significant interactions between appearance (e), speed (v) and body position (k).

The analysis shows that the appearance factor (i.e. whether the robot approached the subject with its serving side or working side showing) had no significant influence on the distance ($F(1.29) = 0.197$, $p = 0.660$, $\eta_p^2 = 0.007$). This means that we cannot reject null hypothesis H_{01}.

The results for the factor speed ($F(2.077; 60.235) = 237.175$, $p < 0.001$, $\eta_p^2 = 0.891$) show that the speed significantly affected the distance that the subjects would accept between themselves and the robot. Thus, we can reject null hypothesis H_{02} and adopt the alternative hypothesis H_2. The post hoc tests with a Bonferroni correction show that all the speeds, except v_1 and v_4, differed significantly ($p < 0.001$). Speed v_1 ($\bar{x} = 0.821$) and speed profile v_4 ($\bar{x} = 0.830$) produced near-identical mean distances. The mean distance of speed profile v_5 ($\bar{x} = 0.71$) is actually significantly ($p < 0.001$) shorter than the mean distance of

Table 2 Results of the three-factor analysis of variance with repeated measurements for the distance that subjects will accept between themselves and the approaching service robot

Source	Sum sq.	df	F	p	η_p^2
e	0.18	1	0.197	0.660	0.007
Error:	2.599	29			
v	31.287	2.077	237.17	<0.001	0.891
Error:	3.826	60.235			
k	9.845	2	13.665	<0.001	0.320
Error:	20.894	50.431			
e * v	0.023	2.759	0.399	0.737	0.014
Error:	1.695	80.025			
e * k	0.016	1.467	0.145	0.799	0.005
Error:	3.270	42.551			
v * k	0.202	5.281	1.854	0.102	0.060
Error:	3.158	153.16			
e * v * k	0.049	4.529	0.482	0.772	0.016
Error:	2.942	131.355			

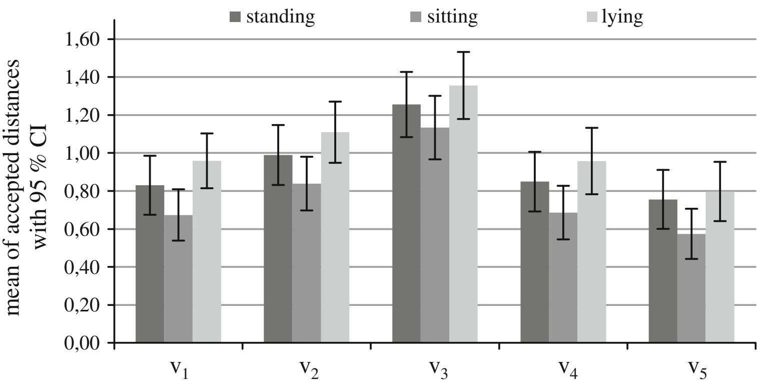


Fig. 7 Mean distances for the effects speed and body position

the slowest constant speed, v_1 ($\bar{x} = 0.821$). On average, the slower the robot approached, the closer the subjects allowed it to get to them. However, the robot got closest to the subjects when it approached using speed profile v_5.

The analysis also shows that the subject's body position significantly ($F(2.58) = 13.665$, $p < 0.001$, ${\eta_p}^2 = 0.320$) affects the distance they will accept between themselves and the approaching robot. Thus, we can reject null hypothesis H_{03} and adopt the alternative hypothesis H_3. In the post hoc tests with a Bonferroni correction, the mean distances between standing and sitting, and between sitting and lying differed significantly. No significant difference existed between standing and lying. Figure 7 shows the mean distances as a function of the two significant effects.

The analysis also included the between-subject factor of age group. The different age groups were found to have no significant ($F(2.27) = 0.700$, $p = 0.505$) influence on the distance accepted. This means that we cannot reject null hypothesis H_{04}.

5.2 Preliminary and Concluding Interviews

All 30 subjects had already heard, read or seen something about robots. Most of them mentioned robots that have appeared in films (e.g. *R2D2* and *Transformers*), industrial robots (e.g. those used in automotive factories) and domestic robots (e.g. for vacuum cleaning). Two of the subjects had personal experience of robots through contact to the field of industrial robotics. None of the subjects had ever heard of the Care-O-bot® 3. Thus, in terms of acceptance of the Care-O-bot® 3, all 30 subjects were in the awareness and first-contact stages at the beginning of the empirical study.

The study recorded the subjects' affinity for technology in terms of a personality trait [21] before and after the test. The subjects were asked to rate 19 statements using a five-point Likert scale, ranging from 1 (strongly agree) to 5 (strongly disagree). The subjects' affinity for technology in the preliminary interview ($\bar{x} = 2.56,\ \text{SD} = 0.39$) hardly differed from the results recorded in the concluding interview ($\bar{x} = 2.54,\ \text{SD} = 0.41$).

In the concluding interview, the same Likert scale was used to rate the subjects' statements as had been used for the initial assessment of their affinity for technology. The responses produced the following results:

- The statement "I had a positive impression of the appearance of the Care-O-bot® 3" had an average rating of $\bar{x} = 2.30$ and a standard deviation of $\text{SD} = 1.02$.
- The statement "The Care-O-bot® 3 did not look dangerous" had an average rating of $\bar{x} = 1.73$ and a standard deviation of $\text{SD} = 0.83$.
- The statement "I think it is important that a robot has different sides for different functions, and that these sides do not look the same" had an average rating of $\bar{x} = 3.01$ and a standard deviation of $\text{SD} = 1.41$.

The subjects were divided on how they felt about the appearance of the Care-O-bot® 3, though the results do show a slight positive tendency. It was very clear that the Care-O-bot® 3 did not look dangerous to the subjects, as on average they gave it a rating of at least 2 (agree). Subjects were divided on whether or not they felt that distinct-looking sides for different functions were important. It is therefore not possible to draw a conclusion on this point.

In the concluding interview, subjects were asked to say which of the speeds and speed profiles they preferred. Of the 30 subjects, 86.7 % said they preferred the speed profiles v_4 and v_5 (where the robot slowed down as it approached) to the three constant speeds v_1, v_2 and v_3. The results on which profile the subjects preferred were quite evenly split: 53.3 % voted for speed profile v_4 (smooth deceleration), and 46.7 % voted for speed profile v_5 (graduated deceleration). Results for the constant speeds v_1, v_2 and v_3 showed that 77.7 % preferred v_2, 13.3 % preferred v_1, and 10 % preferred v_3.

6 Summary and Outlook

The results of the empirical study on the robot can provide guidance for designing robot behaviour (H_2) and appearance (H_1) with respect to the minimum distance that humans will accept between themselves and a robot. The different body positions that the subjects adopted during the test (H_3) covered the different contexts in which a person would use the robot. These results also provide guidance for robot design.

The study found that the constant speed level significantly influenced the distance that the subject would accept between themselves and an approaching robot. The results show that the slower the robot travelled, the closer the subjects allowed it to come. Therefore, if a service robot can only (e.g. for technical reasons) move at constant speeds, it should travel as slowly as possible when around people. But in situations where the robot is working at a reasonable distance from humans, it can move faster to increase its efficiency.

It is possible to reduce the distance that people will accept between themselves and the robot, without slowing the average speed, by using speed profiles where the robot decelerates as it approaches. The study showed that the smooth deceleration profile (v_4) was associated with a significantly shorter distance than the constant speed v_2, even though the average speed was the same in both cases. The graduated deceleration profile (v_5) reduced the distance even further than the smooth deceleration profile (v_4). It therefore makes sense to use a graduated profile in cases where the robot has to get very close to the user. The subjective rating of the two speed profiles in the concluding interview shows no clear preference among the subjects for one profile over the other. Therefore, the design guidance only takes the objective measurements into account.

The study found that the robot's appearance had no significant influence on the accepted distance. Going to great lengths to change the appearance of a non-humanoid service robot so that things like technical components and manipulators are no longer visible will therefore do nothing to encourage users to let the robot come closer.

The subjects' body position significantly influenced the distance they were willing to accept. The results suggest that, contrary to what might be expected, the influence is not linked to the time needed to potentially move out of the robot's path. If it was, then the robot would have got closest when the subjects were standing, with sitting and lying coming in second and third respectively. It is more likely that the influence is related to the size of the image formed on the retina. The size of the retinal image of a real object changes depending on the viewing angle and distance. The results indicate that this affects the accepted distance. Subjects allowed the robot to come closest when they were seated, which is the position where the image on the retina is smallest. The image is slightly bigger when a person is standing, and subjects kept the robot further away here than when sitting. The furthest distances were recorded for lying down, when the image is at its largest. Subsequent studies should therefore investigate a possible correlation between the image formed on the retina and the distance people will accept between themselves and the robot in order to understand why body position is an influencing factor.

The study found that age did not affect distance. It therefore appears unnecessary to develop separate robot behaviours or appearances for different age groups. However, it should be noted that the test subjects were highly homogenous in terms of their experience of robots and their affinity for technology. The study was unable to establish what effect their prior knowledge and associated mental models had on the outcomes. It is therefore inadvisable to generalise the results beyond the sample tested.

With regard to the methodology used, the study achieved a high degree of validity and objectivity thanks to the consistent study design and the permutation of the factor levels. The distances shown in this study are, unlike the findings of other studies, the actual distances that the subjects accepted. This is because we recorded individual reaction times, measured how far the robot travelled in that time and then subtracted that value from the distances measured. By taking account of age—and gender-related reaction times like this, we ensured that the results were not skewed by the way aging affects the speed at which the subjects pressed the button. The fact that the test used a fully functional robot, and was thus not a Wizard-of-Oz experiment, further enhances the generalisability of the data and makes the study stand out from many experiments conducted in the past.

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References

1. Mori, M.: The Uncanny Valley. In: Energy, 7(4), pp. 33–35, Translated by Karl F. MacDorman and Takashi Minato (1970)
2. Mizoguchi, H., Sato, T., Takagi, K., Nakao, M., Hatamura, Y.: Realization of expressive mobile robot. Robotics and Automation, Proceedings, 1997 IEEE International Conference, pp. 581–586 (1997)
3. Duffy, B. R.: Anthropomorphism and Robotics. The Society for the Study of Artificial Intelligence and the Simulation of Behaviour, 20
4. Oestricher, L.: Cognitive, social, sociable or just socially acceptable robots? In: 16th IEEE International Conference on Robot and Human Interactive Communication, pp. 558–563 (2007)
5. Goetz, J., Kiesler, S., Powers, A.: Matching robot appearance and behavior to tasks to improve human-robot cooperation. In: Robot and Human Interactive Communication: Proceedings of the 2003 IEEE International Workshop, pp. 55–60 (2003)
6. Walters, M.L., Dautenhahn, K., te Boekhorst R., Koay, K.L., Woods, S.N.: Exploring the design of robot appearance and behavior in an attention-seeking "Living Room" scenario for a robot companion. In: IEEE: Proceedings of the 2007 IEEE Symposium on Artificial Life, pp. 341–347 (2007)
7. Walters, M.L., Dautenhahn, K., Koay, K.L., Kaouri, C., Boekhorst, R., Nehaniv, C., Werry, I., Lee, D.: Close encounters: spatial distances between people and a robot of mechanistic appearance. In: Humanoid Robots, 5th IEEE-RAS International Conference, pp. 450–455 (2005)
8. Walters, M.L., Dautenhahn, K., te Boekhorst, R., Kheng Lee Koay, Kaouri, C., Woods, S., Nehaniv, C., Lee, D., Werry, I.: The influence of subjects' personality traits on personal spatial zones in a human-robot interaction experiment. In: Robot and Human Interactive Communication, ROMAN, IEEE International Workshop, pp. 347–352 (2005)
9. MacDorman, K.F.: Subjective ratings of robot video clips for human likeness, familiarity, and eeriness: An exploration of the uncanny valley. In: ICCS/CogSci-2006 long symposium: toward social mechanisms of android science, Vancouver (2006)
10. Bischof, N.: Struktur und Bedeutung. Hans Huber, Eine Einführung in die Systemtheorie für Psychologen. Bern (1995)
11. Ikuta, K., Ishii, H., Nokata, M.: Safety evaluation method of design and control for human-care robots. The Int. J. Robot. Res. **22**(5), 281–297 (2003)

12. Traver, V.J., del Pobil, A.P., Perez-Francisco, M.: Making service robots human-safe. In: IEEE/RSJ international conference on intelligent robots and systems (IROS 2000). Proceedings, Vol. 1, 2000, pp. 696–701
13. Yamada, Y., Yamamoto, T., Morizono, T., Umetani, Y.: FTAbased issues on securing human safety in a human/robot coexistence system. In: IEEE international conference on systems, man, and cybernetics. IEEE SMC'99 conference proceedings, Vol. 2, pp. 1058–1063 (1999)
14. Bartneck, C., Kulić, D., Croft, E., Zoghbi, S.: Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots. In: Int. J. Soc. Robot. Vol. 1, No. 1, pp. 71–81 (2009)
15. Jochems, N.: Altersdifferenzierte Gestaltung der Mensch-Rechner-Interaktion am Beispiel von Projektmanagementaufgaben. In: Schlick, C. (ed.) Industrial Engineering and Ergonomics. Shaker Verlag, Aachen (2010)
16. Mertens, A., Reiser, U., Brenken, B., Lüdtke, M., Hägele, M., Verl, A., Brandl, C., Schlick, C.: Assistive robots in eldercare and daily living: automation of individual services for senior citizens. In: Jeschke, S., Liu, H., Schilberg, D. (eds.) Intelligent Robotics and Applications—Fourth International Conference, ICIRA 2011, pp. 542–552. Springer Verlag, Berlin (2011)
17. Marquie, J.C., Jourdan-Boddaert, L., Huet, N.: Do older adults underestimate their actual computer knowledge? Behav. Inf. Technol. **21**(4), 273–280 (2002)
18. Reed, K., Doty, H.D., May, D.R.: The impact of aging on self-effcacy and computer skill acquisition. J. Manag. Issues **17**(2), 212–228 (2005)
19. Karrer, K., Glaser, C., Clemens, C., Bruder, C.: Technikaffinität erfassen—der Fragebogen TA-EG. In: Lichtenstein, A., Stößel, C., Clemens, C. (Hrsg.) Der Mensch im Mittelpunkt technischer Systeme, 8. Berliner Werkstatt Mensch-Maschine-Systeme (ZMMS Spektrum, Vol. 22, No. 29). Düsseldorf: VDI Verlag GmbH, pp. 196–201 (2009)
20. Luczak, H.: Untersuchungen informatorischer Belastung und Beanspruchung des Menschen. Fortschrittberichte der VDI-Zeitschrift, Vol. 10, No. 2, Düsseldorf: VDI-Verlag (1975)
21. Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H.: Konstruktionslehre. Springer Verlag, Berlin (2007)
22. Brandl, C., Mertens, A., Bröhl, C., Mayer, M., Schlick, C.: Akzeptanzorientierte Gestaltung von Innovationen bei technikunterstützten personenbezogenen Dienstleistungen, In: Gesellschaft für Arbeitswissenschaft e.V. (Hrsg.) Gestaltung nachhaltiger Arbeitssysteme - Wege zur gesunden, effizienten und sicheren Arbeit, Dortmund: GfA-Press, pp. 483–486 (2012)
23. Davis, F.D.: User acceptance of information technology: system characteristics, user perceptions and behavioral impacts. Int. J. Man Mach. Stud. **38**(3), 475–487 (1993)
24. Venkatesh, V., Bala, H.: Technology acceptance model 3 and a research agenda on intervention. Dec. Sci. **39**(2), 273–315 (2008)
25. Kollmann, T.: Akzeptanz innovativer Nutzungsgüter und –systeme. Gabler, Wiesbaden (1998)
26. Hoch, A., Simons, F., Haag, M., Parlitz, C., Reiser, U., Hägele, M.: Care-O-bot® 3—Mobiler Serviceroboter mit ausgeprägter Manipulationsfähigkeit. In: Kompetenznetzwerk Mechatronik BW: Intelligente mechatronische Systeme: Internationales Forum Mechatronik, begleitend zur MOTEK, Stuttgart. Göppingen, pp. 360–371 (2008)
27. Schlick, C., Bruder, R., Luczak, H.: Arbeitswissenschaft. Springer Verlag, Berlin (2010)
28. Haas, H.-J.: Sport im Alter—Leistungsphysiologie. In: van den Berg, F., Wulf, D. (eds.) Angewandte Physiologie. Georg Thieme Verlag, Stuttgart (2008)
29. Bortz, J.: Statistik für Human- und Sozialwissenschaftler. Springer Medizin Verlag, Heidelberg (2005)