Embodiment, Situatedness, and Morphology for Humanoid Robots Interacting with People

Blanca Miller and David Feil-Seifer

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Abstract

The aim of human-robot interaction (HRI) is that people intuitively understand robots. When integrating humanoid robots into our daily lives, a myriad of factors can influence how a person perceives and interacts with a robot. Particularly, humanoid robots' embodiment, situatedness, and morphology can individually and collectively affect the interactions between a person and robot, including the utilitarian and aesthetic factors of the robot's physical design. It is therefore necessary to investigate how humanoid design choices impact a robots functions in society. In this chapter, we discuss what it means for a robot to be embodied, situated, and to have morphology. Further, we consider relevant HRI research

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B. Miller · D. Feil-Seifer (✉)
Department of Computer Science & Engineering, University of Nevada, Reno, Reno, NV, USA
e-mail: blancamiller@nevada.unr.edu; dave@cse.unr.edu

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alongside research that underscores the need for roboticists to integrate embodied cognition, situatedness, and morphology in robotic design. For example, research findings demonstrate a materially embodied design that accounts for situatedness as a necessary element for eliciting positive perception of a robot agent. Moreover, we expand on the need for the robotics field to extend its empirical research with varying degrees of implementation that disassociate and control for design factors to distinguish which particular elements provoke positive, neutral, or negative effects in HRI. Without a more robust literature base to discern the most effective forms of robotics within commonplace applications, it will be difficult to know if the applied robotic forms achieve the most compelling HRI.

Keywords
Embodiment · Morphology · Human-Robot Interaction · Social Robotics

1 Introduction

Robotics have and will continue to take on an ever more ubiquitous presence in society and across industries including transportation, healthcare, education, manufacturing, and customer service [19]. In each of these sectors, the interactions and successful cooperation between humans and robots depend on each understanding the other's roles and needs. The design choices of roboticists, whether operational or aesthetic, impact the facilitation of interactions between a robot and human [45]. However, the general design of a robot depends on consideration of several factors including its embodiment, presence, morphology, sensing capability, and actuation. Beyond a robot's physical attributes, consideration for the use of the robot, the context of the interaction, and the biases and preconceived notions that individuals and groups have are critical to constructing effective operation. Design factors for the successful integration of robots into everyday human environments also include safety and dependability of a humanoid, as their failures can degrade the quality of an interaction [50] for both present and future exchanges. Knowing that these factors can have drastic effects on the perceptions humans have about robots, it indicates a need for quality robotic design grounded in robust research-based findings to produce adequate interactions between a robot agent and people. Robotic design is a multifaceted problem due to the critical end goal of HRI that robots be intuitively understood by people [37].

The consensus among roboticists is that using humanlike form and functionality in robot design should facilitate human-robot interaction, as people are accustomed to interacting with one another [5, 45]. However, what is meant by form can be broad and highly variable as it includes facial features [5], the physical humanlike silhouette of a robot, or a combination of the two, making form an often loosely defined aspect of a robot. Recent design trends in robotics reinforce this notion and align with the evolutionary argument that, because we evolved to interact with one another, resemblance of robotics to humans should make our interactions with robots easier. But merit of this consensus renders skepticism as current research indicates that the spectrum of design choice is vast, complex, and is not limited to form. Embodiment research of artificial cognitive systems has mainly investigated the external features of robotics, but recent research of embodied cognitive science has evolved to include both the external design and the control system to achieve true cognition [56]. The form of a robot, or lack thereof, can have significant consequences for the degree to which people apprehend it and whether a person is willing to engage with it. As such, embodiment, situatedness, and morphology of a robot need to be considered beyond the mere functionality they provide, but also for the perception of these factors during interactions with a robot. Ultimately, the goal is to identify a theory that delineates the robotic attributes that cause people to perceive robots more favorably [63] and consequently be willing to engage in HRI on a long-term and collaborative level.

2 Embodiment

The field of embodiment addresses the need to understand how robots effectively interact with people and the environment in which they operate. The definition of embodiment and its effects on HRI are elusive. However, insight into robot embodiment can help robot developers be aware of the role physical interaction plays in robot behavior and how perceptions of a robot can be affected by its physical instantiation [43]. Several influential ideas have stemmed from studies discussing how embodiment relates to the development of cognition in human beings and how that might inform roboticists' research. This includes the foundational concept that cognition is dependent upon its relationship with interactions between the mind and body, that is, that the mind is inseparable from its physical experiences [10, 28].

The simplest definition of embodiment is the traditional biological definition of an organism with a bodily or material representation. However, embodiment has more recently evolved into a term that is applicable to computational machines and their place within the world. Pfeifer and Scheier [43] defined it as follows:

> *Embodiment*: A term used to refer to the fact that intelligence cannot merely exist in the form of an abstract algorithm but requires a physical instantiation, a body. In artificial systems, the term refers to the fact that a particular agent is realized as a physical robot or as a simulated agent (p. 649).

Encompassing both physical and virtual agents and connecting the body and mind are key reasons why this definition has become a integral part of the embodiment literature.

This perspective aligns with psychological research which states that human cognition evolved from dense and immediate sensorimotor interactions with the environment, thus understanding the mind requires evaluating its relationship to the physical interaction with the world [61]. Extending this idea, Brooks [8] early on noted that "Intelligence is determined by the dynamics of interaction with the world" (p. 6). Similarly, Riegler [48] stated, "A system is embodied if it has gained competence within the environment in which it has developed" (p. 347). Thus, it is not plainly the physical instantiation that defines embodiment of an artificial system, but what a system gains from interacting with its surroundings. Encompassing what is necessary, but not necessarily sufficient, has also become a major part of the embodiment discussion. Duffy and Joue [15] have offered a more comprehensive interpretation of the term:

> The strong embodiment of an agent into its environment can be perceived as a more cohesive integration with the environment promoting learning and adaptation requiring the agent to have:
>
> – The ability to coordinate its actuator and sensor modalities to interactively explore its environment;
> – Goal-oriented behavior on micro and macro levels;
> – Bi-directional interaction between the agent and its environment;
> – Bi-directional communication between the agent and other agents in the environment; and
> – An understanding of the physics of the environment, e.g. gravitational effect and friction, to reduce internal environment representation loading by inferences (p. 6)

Investigative discourse has led to the determination that there is a spectrum of weak to strong embodiment [15]. Duffy and Joue [15] argued that weak embodiment is operationalized when a robot's body is situated in an environment but remains "a static abstraction of the world and not in the dynamic world itself" (p. 6). Meaning, the agent lacks integration with its environment. Integration is how strong embodiment, on the other hand, is achieved; as stated above, higher-degrees of embodiment promote "learning and adaptation." Additionally, there exists a distinction in perspective of those who view machines whose abilities include intelligence as mechanisms manipulated by their environments versus AI cognition that develops through the interactions with its environment [54]. It is then important not to overlook embodiment descriptions of systems who react and learn from their environments as this added complexity is a nontrivial task of robotic design.

One early driving argument from two prominent sources Maturana and Varela [36] and von Uexküll [58] disputed that machines could ever resemble living organisms. The researchers argued that living entities are made up of components which continuously interact, regenerate, and evolve, while man-made machines do not. Rather, the components comprising a machine are constructed independently of it and those components do not regenerate or evolve as parts of the system. Based on this notion, it seems obtaining robotic embodied cognition is unattainable.

Nevertheless, the field of embodied cognition has flourished. And though the above argument is uncontested, it seems that the level of lifelike characteristics the aforementioned theorists, Maturana and Varela [36] and von Uexküll [58], described is not what most modern development of robotics and experimental research currently seeks to achieve. Instead, a robot's ability to function, interact, and react to their surroundings would currently suffice, as that in itself is an ambitious goal within the community's current understanding of artificial intelligent cognition. Therefore, some degree of embodied cognition is attainable and valid within biological and psychological fields, though not to the degree that living organisms experience.

Theoretical discussions, like the one above, have served to clarify how roboticists now define the field of embodied cognition [12]. More explicit understanding of its implementation has also been identified through experimental research of *functional* differences, such as the form a manipulator should take, which can range between a simple grabber to a more complex form that resembles that of a human hand [6]. Empirical work comparing robots to virtual agents, for example, has indicated social effects. Bartneck et al. [2] concluded that robotic embodiment has no more effect on people's emotions than that of a virtual agent, while animacy was correlated with perceived intelligence. Conversely, other empirical work has found the presence of a physical body has an effect on the interactions between a person and a robot [60]. This indicates the need for varied and more extensive research where social and functional differences between embodied and non-embodied agents are distinguished. Further, it is important to justify the benefits of a robot beyond the likely added cost of employing a robot system over a virtual agent for a given task. This is especially true for robotics with assistive applications [19], where the added cost of a robot platform should be justified by a larger client benefit [20]. Likewise, it has been demonstrated that embodiment has a positive effect on patient motivation [17] and task compliance [1]. Moreover, in-person interactions between a human and a robot have a greater effect on weight loss than using a non-embodied agent [62]. Specifically, a functional exploration of robot embodiment should examine the effect embodiment has on the perceived role of a robot [20], the trust one places in a robot [46], the perceived animacy or emotional capability of a robot [11], and the perceived intelligence of a robot [31]. The above studies indicate a need to discern how embodiment relates to different contexts. In the next section, we will tease apart the *embodiment* of an agent from its *situatedness* to understand how the environment influences HRI (Fig. 1).

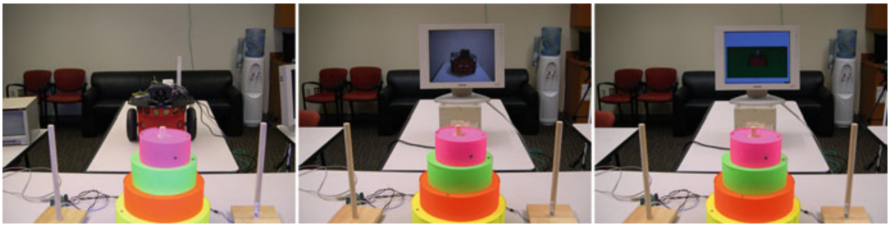

Fig. 1 **Left,** the simulated robot used for the embodiment study; **center**, the embodied non-co-located robot; **right**, the embodied co-located robot. In this study, a robot was interacting with a user autonomously during a game-playing task. The users were asked to rate the robots for intelligence, watchfulness, and likability [60]. The users rated the embodied robot highest on all these ratings, followed by the embodied non-co-located robot, followed by the virtual agent. These results support the use of an embodied agent over a virtual agent on a screen

3 Situatedness

In recent years, the robotics field has seen a surge in research in the area of situatedness, or situated AI, due to the need to understand how robots can be integrated into the variety of everyday human tasks. The concept of situatedness contributes greater complexity to the embodiment field as it is not only the physical space a robot occupies that influences interactions between humans and robots, but the context of those interactions also plays a role. Situatedness describes the context or environment in which a robot operates. Context refers to the location where a robot is placed (a hospital, an automobile manufacturing plant, a person's home) and who the robot interacts with in the environment (a worker, an employee from a different department, a patient, a patient's family). More specifically, how the robot navigates verbal and physical interactions are dependent on its purpose.

Situatedness is a concept derived from the field of human cognition. Lindblom [33] explained the need to examine the context of an AI for the following reason, "while a cognitive process is being carried out, perceptual information continues to come in that affects the environment in task-relevant way" (p. 626) [33]. This statement indicates that it is not sufficient to design AI that operates in isolation from their environment as the location can change, the audience can change, or the nature of the interaction can change and thus alter the intended action of the system. Rickheit and Wachsmuth [47] defined this robot's ability as *robustness*; an attribute that facilitates *integrated* meaning. They explained this notion from the perspective of a human being, where humans are not hindered by incomplete or garbled information due to their inherent robustness. That is, people can counterbalance disorder by relating information from multiple sources to generate integrated meaning, such as sensemaking through language with the use of observational information and vice versa. For robots to then reach at least adequate performance in everyday human spaces, it requires that roboticists account for the situatedness of their robot's design through some degree of robustness that will allow navigation in dynamic settings. A focus on situated interaction could examine the use of relative communication as in gestures [7] or deictic pronouns [25]. The use of deictic pronouns has had an effect on interaction quality [23]. Thus, taking into consideration the variability that exists depending on context, it has become increasingly critical to understand how this variability influences robotic design.

The benefit of developing situated AI is the facilitation of human-machine interactions to resemble those of human-human interactions [34]. This means that the goal of AI design is to enable a robot with the capacity to interact with a human in a manner that is perceived as familiar to a person, as in an interaction with another person. Language is one critical component of these interactions. Within a given environment, the meaning of language and the possible actions that can be carried out is limited because the context of an environment steers the meaning that can be extracted [47]. For instance, the actions a robot would need to carry out in using a "stapler" in a body shop would be very different from those in a hospital as the two "staplers" are significantly different in shape and application. Because robots are not currently able to distinguish between context, Rickheit and Wachsmuth [47] recommend designing robotics that are more specialized in the immediate future. Instead of placing the focus on a "universal" robot, the focus should shift to the deliberate development of a robot's specific intended functions. In this case, the situatedness of a robot would drive its design and also change the meaning of the actions it takes in service of its goals. The dependency that a robot has on its environment is one reason why robot design should be specialized to a particular task [42], but it should do so while maintaining adaptability to the uncertainty of those environments [26].

One strategy proposed for the flourishing of research and design of situated AI is using an interdisciplinary approach. An interdisciplinary approach involves taking on different research perspectives and using research findings as springboards for current gaps in a field's understanding. Turning to a study of organisms, Bechtel [3] states, "Biological mechanisms are always situated and dependent on their environments as well as in a critical sense distinct from them" [3]. This statement indicates that the mind and body need not be disassociated to achieve distinction in an environment. Moreover, despite the study being an analysis of organisms to understand the advantages in segregating component activities for modularity, the author advocates a mechanistic perspective, as roboticists use. Using an interdisciplinary perspective aided the conclusion and underscoring that organismic systems are integrated, not isolated, from their environment and should be understood as such. As the above study shows, an interdisciplinary approach may help steer research in unexpected and innovative directions that promote new research perspectives, for HRI that means new robotic design. In the discussion below, we delve further into the topic of design and describe some of the design considerations that have been suggested and others that have been implemented to engage robots in real-world operations. This will help serve as a basis for future research directions of robotic design.

Similar to interactions between humans, a person forms hypotheses about the capability and actions of a robot during the initial exchanges of an interaction [20]. Pitsch [44] proposes roboticists equip robotic systems to make explicit their abilities for interaction during the early stages of an exchange with a person, thus establishing the necessary conditions to accomplish effective human-robot interactions. Conversely, the mismatch between observed and actual robot capabilities can create interaction challenges [21]. Additionally, a design strategy that depends on human competencies of sensemaking and adaptability would also benefit the system in a highly variable and unpredictable environment [44]. Though humans have the ability to make sense of their surroundings and infer greater understanding about a system's functional capacity, in comparison to a robotic system, this idea may not be viable in contexts with vulnerable population, such as hospitals or work with children. Thus, taking into consideration the common variables in the situated space where a robot will operate is imperative prior to implementing its design.

Suchman [57] proposes a different approach, stating that human-machine interaction is "less a project of simulating human communication than of engineering alternatives to interaction's situated properties" (p. 185). Rather than taking a design perspective of imitating human-to-human interactions with literal substitutions carried out by the robot, robotics design should engage in engineering alternatives to how humans accomplish particular goals, as the system is different and accesses different processes to achieve a goal. For example, based on current expectations of humans in assembly worker positions, Rickheit and Wachsmuth [47] list the following functions as necessary for a robotic system to effectively operate alongside other workers in that environment. They include:

- Perceiving audio, visual, and cognitive processes;
- Speaking; and
- Planning for execution of movement toward objects, e.g., object avoidance.

Researchers note that a robot worker, like a human worker, must be able to carry out the same functions as both individuals and members of a human-robot team. Given these objectives, design features that have been shown to generate effective interaction based on the capacity of the robot should be applied, rather than attempting to design a system that imitates the human worker. Therefore, studying the most effective operation for a robot, given the task goal, is the more appropriate technique in design, as roboticists can then determine what components are necessary for the system and which are superfluous. A person may use their arms to carry a box, for example, but a robot might use a platform in the middle of its body or one attached to its “feet”. This also highlights the need to consider operations and executions that might be available to a robot, but are not for humans, as these operations may enhance the integration of a robot within existing working groups and provide added benefits to human workers.

Rickheit and Wachsmuth [47] also highlight one critical component that necessitates a robot’s high degree of adaptability, being able to work around people and as members of human-robot teams. These tasks include action executions such as grabbing and placing, but they more specifically involve maneuvering those actions around people and working collaboratively and in close proximity with people. This objective prompts an essential question, how can robots integrate into a social environment? Social environments necessitate that a robot be able to communicate with different kinds of people in a manner that accurately conveys to humans what the robot means. This faculty has been previously tested and shown to provoke difficulty of interaction when the robot is not equipped to manage unpredictable behavior. One study found that when a person interacted with a robot who provided information about a museum venue, the person perceived the robot’s pointing gesture as “misplaced” [57]. The misunderstanding with the robot was due to the robot trying to communicate direction when the person had not expected a physical action from the robot in that moment. Other issues exposed during this same study included the robot’s inability to detect confusion by the human following the “misplaced” response, which further depreciated the quality of the interaction between the human and robot [57]. To surmount the challenges of engaging robots in highly variable and unpredictable environments, design methods need further research within diverse settings. Moreover, taking into consideration the need to realize collaborative tasks and robot-specific tasks (tasks that are uncommon to humans), the embodiment and situatedness of a robot should not only be reflected in its design and actuation capabilities. Instead, embodiment and situatedness should be embedded in the sensing and planning capabilities of the robot. In this way, communication can be facilitated to be implicit in nature, using features of the environment and the task to communicate intent and action [9], not explicit, as in communication through an interface which is more computerlike than humanlike and noninteractive in nature [52]. The robotics field now widely agrees that it is necessary to equip robots with the ability to navigate their environment, so that they are able to carry out their intended tasks. Without the capacity to navigate and adapt to the diverse factors that will disturb a robot's path, practical functionality will remain unrealistic for day-to-day applications in real-world or uncontrolled spaces. This engineering, however, is not a small undertaking as it requires that a robot have the capacity to instantaneously account for variations in the environment and readjust its trajectory. Therefore, it is necessary to expand the empirical research that measures and isolates the design elements for navigating particular environments to provoke effective HRI.

4 Morphology

Morphology is a key factor of robotic design as the expectations people have when interacting with a system influences the ease with which the robot carries out tasks [29]. A robot's morphology, or form, in both physical and virtual environments, is generally assigned using biologic inspiration and general guidelines rather than research-based methods that have been shown to improve HRI [13]. Biologic inspiration of shape is generally of two designs, anthropomorphic and zoomorphic. Anthropomorphic forms (humanlike) include humanoids and androids, while zoomorphic forms (animal-like) include quadrupedal and hexapod robots. More narrowly, design considerations include characteristics like facial features, limb(s), height, mass, and abilities like carrying a payload, manipulating objects, and dynamically reconfiguring any of the aforementioned characteristics based on task needs. Decisions about robot morphology have only become more critical in robotic design as the embodiment argument that a machine's intelligence and physical instantiation are necessary and sufficient to co-develop for successful HRI has gained widespread support. However, currently only limited research exploring how and why morphology and intelligence should be co-optimized exists [6].

4.1 Anthropomorphism

The most dominant of the morphological areas is in anthropomorphic design. Anthropomorphism is the study of humanlike characteristics applied to nonhuman objects [63]. The implementation of features that resemble humans in robotic design is due to the anthropomorphic literature's identification of positive effects on HRI [22]. For example, Złotowski et al. [63] study provided evidence that an emotionally expressive robot (using gestures and complementary sounds) is perceived as more anthropomorphic or humanlike than one that is not emotionally expressive. Anthropomorphic features are distinguished from tendencies as features encompass the robot's form, while tendencies are concerned with how the features are perceived by humans [16]. Anthropomorphism may be a meaningful approach of design for effective HRI, but it is difficult to understand its current effect as anthropomorphic properties are often too distinct to allow for valid comparison between studies [22]. Specifically, the complexity and high design variability of anthropomorphic robots do not lend itself well to experimental comparison and challenge the degree to which it can be applied for effective HRI.

Despite the challenge of high design variability in anthropomorphic literature, some recent research has taken place to compare components. Mavrogiannis et al. [37] compared four robotic arms with a fifth normalized human arm to determine the human likeness of design with the assumption that the most similar design to a human arm is ideal. This study was also significant in its development of methodology, which the authors argue can serve future study's comparisons of similarity between their robotic arms and the ideal, or human, robotic arm. However, it is important to consider that this idealization based in biology may not be the best comparison. Instead, the comparison should be made with a system whose goal is comparable to that of the intended objectives of the compared arm. Similarly, Liarokapis et al. [32] proposed an open-source, easily reproducible, hand design with the aim that it has an efficient grasp for various applications. Although these studies and studies like them contribute to the understanding of how roboticists can more effectively construct robotic arms and hands, these studies have not addressed the effectiveness of designs in facilitating HRI.

One important consideration of anthropomorphic robotic design, therefore, is the degree to which a robot should take on humanlike features to accomplish effective HRI. One prevailing reason is that robotic design should involve form dictated by function [16] for the purpose of making evident the robot's capacity for interaction and avoiding misinterpretations of its abilities. Furthermore, Duffy [16] argues that this ongoing approach to research of anthropomorphic design should lead to the identification of an ideal set of features that strike a balance between people's expectations and the machine's capabilities. For example, the aforementioned study of emotionally expressive robots also tested the influence of intelligence (responding correctly to a question in a quiz game), which had no effect on anthropomorphism [63]. The authors suggest that intelligence may not play as a significant factor in anthropomorphism as people might expect robots to possess intelligent qualities. However, the assessment used in this study may have been the limiting factor as the approach to measure humans' perceptions of robot intelligence was based on correct answers rather than an ability to reason and craft judicious responses.

More generally, a need exists for HRI to investigate how the anthropomorphic design choices made by roboticists influence HRI, as the aim of HRI is that robotics be intuitively understood by people [37]. To accomplish a more comprehensive understanding of anthropomorphism, that is, a theory that delineates the robotic attributes that cause people to perceive robots more favorably based on their visual similarity with humans, this need must be addressed [63]. A significant limiting factor for anthropomorphic robot design choices lies in the lack of understanding of people's current perceptions and biases about robotics. This scarcity in research should be addressed in conjunction with the set of ideal attributes to achieve an in-depth understanding and effective implementation of HRI.

4.2 Experimental Study of Computer vs Humanoid

One study conducted by this chapter's authors examined the role that embodiment and morphology might play in a person's attitudes toward that robot [11]. Rather than look at therapeutic interaction or other positive social interaction, we decided to examine negative social interaction. Negative behavior, such as workplace verbal aggression is not an uncommon sight between colleagues in office settings. It can be just as common for machines to receive this same kind of treatment. However, a clear difference exists in how a bystander may perceive similar actions, based on the agent receiving those interactions. A copy machine, for example, might be physically or verbally abused for being too slow, even though it is meeting its performance standard. After a person observes this incident, they might continue on their day without being affected. In the case of the copy machine, such mistreatment might rarely provoke sympathy for it. People are able to continue throughout their day unchanged and unaffected by those interactions. However, if a person were to be mistreated, that would generally be considered unacceptable (Fig. 2).

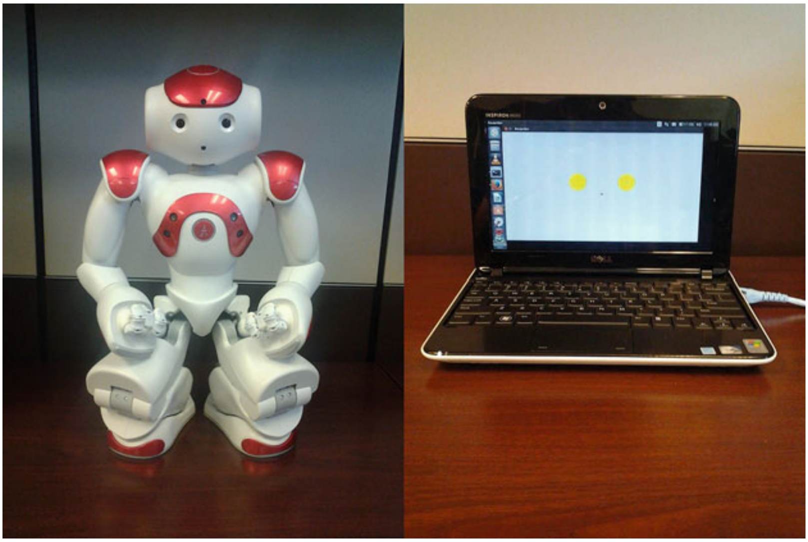

Fig. 2 **Left**: NAO, used for the robot condition. **Right**: the computer agent for the described embodiment study [11]. The results show that the embodiment of an agent has an effect on the perception of mistreatment directed at the robot

Motivation: To examine this in the context of robotics, we asked if the indifference described above would still be the case if the agent being mistreated was a robot. These different embodiments may have significantly different effects on interactions with and perceptions of robots. It is conceivable that a similar reaction to observed mistreatment might occur between humans and robots, since human-robot interaction (HRI) and human-computer interaction (HCI) can emulate human-human interaction (HHI). We wished to quantify that social dividing line for the acceptance of targeted mistreatment toward robots.

Procedure: We recruited participants to work in groups with a robot collaborator. The participants completed the "Lost at Sea" team-building exercise. An experimenter explained the task to the group of participants. The experimenter then left the room. The participants were given a 3-minute time limit to complete the task as a team. At the three-minute mark, the agent prompted the participants, informing them that it was time to start recording their answers. The agent (robot or computer) recorded the answers that the group had agreed upon. This part of the study served as a distractor and was used to set up a scenario where a confederate could be observed interacting with the agent.

One of these participants was an experiment confederate employed to provoke the necessary behavior for the experiment. The confederate would always be the person "randomly" selected to present the answers to the agent. The agent was designed to always incorrectly record the third and fifth answers and respond to the confederate acknowledging its mistake. At this point, the main experiment manipulation occurred. For half of the groups, the confederate would react neutrally toward the agent (control group). For the other half, the confederate would act aggressively toward the agent (experiment group). Neutral behavior by the confederate was neither praising nor mistreating the agent. In our study the confederate consistently answered with simple "yes" or "no" responses to the agents. We defined aggressive as "verbal or physical behavior that is meant to damage, insult, or belittle another." The confederate never directed any physical abuse to the participants or the robot/computer agents. Examples of the confederate's verbal abuse would be the confederate stating "No that isn't the right answer. This isn't hard to understand" or "This robot is stupid, we should have just written our answers down."

Results: We employed a between-participant 2 × 2 factorial design where participants worked in groups averaging 5 in a collaborative task which included an agent (robot or computer) and a confederate that (did or did not) deliberately mistreat the agent. The independent variables included the agent and the confederate's behavior toward the agent. Our dependent variables included the participants' reactions and perceptions of the agent. To understand how mistreatment of a robot can affect the people observing it, we measured 80 participant responses in 9 different categories: nonoperational definition of mistreatment, operational definition of mistreatment, level of emotional capability, reliability, sympathy, faith in confederate, physical appearance, interest and enthusiasm, and familiarity.

The results strongly supported our hypothesis that the accepted levels of mistreatment between a robot and a computer would be different. Ratings for the embodied humanoid robot were higher than the computer for both the level of observed mistreatment and the emotional capability of the agent. However, this only happened when the agents were mistreated. When non-mistreating interaction occurred, the participants did not observe differences between the agent types with regard to emotional capability, reliability, and so on [11, 40].

4.3 Experimental Studies of Robot Morphology

Motivation and Procedure: One potential confound that arose from the study described in the previous section is that the robot (Nao) was small and could be perceived as vulnerable and defenseless [49]. Other robots are much larger and not likely to appear as vulnerable. The size and morphology of a robot have also been shown to be a factor that provokes different perceptions in HRI. To examine this feature of the robot's morphology, we redesigned the study to examine the differences in perception of mistreatment between a larger robot (Baxter) and a smaller robot (Nao). We repeated the "Lost at Sea" task and 2×2 study design with the agent factor having two levels (larger robot, smaller robot). We recruited another 80 participants and gave them an identical evaluation [35].

Results: We hypothesized that a large robot would not be perceived as emotionally capable as a small robot and that the large robot would not be seen as mistreated. Within a group made up of participants, a robot, and a confederate (the planted person who delivered the verbal abuse), the participants perceived verbal abuse differently for behavior that was directed at the two robots in the same way. In fact, when participants provided written description of how the shape of the robot might have influenced their perceptions, the small NAO robot was considered cute and more emotionally capable; the large Baxter was intimidating and not as deserving of sympathy. Indeed, the participants showed no significant perception of mistreatment toward the large robot. Participants also felt the large robot was less emotionally capable. We found that when verbal abuse was directed at a larger robot, participants would not consider such behavior mistreatment, but they would when similar abuse was directed at a child-size robot. When asked, people thought that a larger robot could "take care of itself" and was not as vulnerable [35]. However, given that there were differences between the Nao and the Baxter other than just size, we can only conclude that morphology may play a part in the potential for observing mistreatment. Current work is also examining the role that robot size may play in a person's response to that robot (Fig. 3).

These findings offer design guidelines for robot morphology dependent on the context and task(s) that a robot will perform. In a manufacturing setting, the emotional response attached to a robot during HRI may not be a critical component to consider, but in a hospital or educational setting, this may be a factor that significantly affects how people interact with the machine. Thus it is evident that a vast breadth of research is necessary to identify robotic morphology that co-optimizes, situates, and embodies machines to achieve effective HRI.

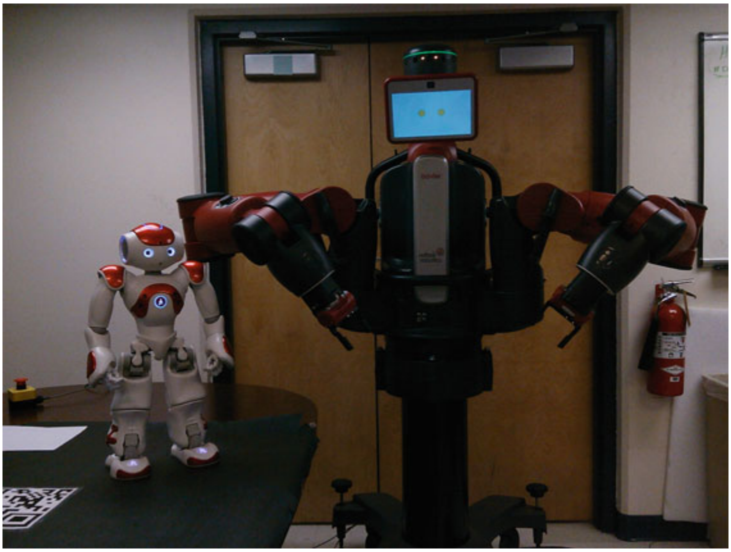

Fig. 3 **Left**: NAO, used for the small robot condition. **Right**: Baxter, used for the large robot condition in a study on humanoid morphology [35]. The results of this study demonstrated that morphology affects perception of behavior directed at the robot

4.4 Variations in Humanoid Design

The various characteristics that make up the morphology of a robot can facilitate or depreciate HRI. Hence, identifying the characteristics that increase effective HRI is a critical part of robotic research. One important attribute of design is facial features. A face may resemble a human or animal in physical shape, or it may be a virtual face on a screen. Both types of implementations have different advantages and drawbacks in design and HRI. DiSalvo et al. [14] investigated 48 static robot head images and determined that noses, eyelids, and mouths significantly affect the perception of humanness of humanoids and that increased numbers of facial features provoked higher perceptions of humanness. Likewise, the study found that participants associated less humanness for a robot with greater head width than height. These findings offer insight for robotic design choices; however, increased humanness of appearance does not mean that a robot would be better at facilitating interaction. As the study notes, context, speech, gestures, and physical vs virtual presence will influence perceptions. This is not an uncommon trend in robotic research. Although roboticists have identified some design guidelines for effective robotic morphology, those findings require research on how they influence HRI (Fig. 3).

Similarly, Bongard [6] found that evolutionary co-optimization, concurrently optimizing the body and intelligence of an artificial system, increases the probability of a robot discovering a successful solution in manipulating a robot. This

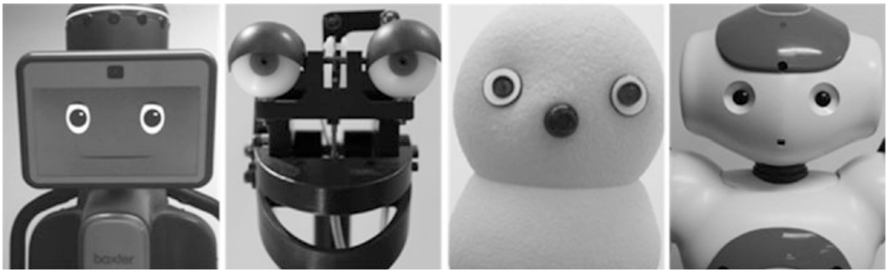

Fig. 4 Some examples of the range of robot faces. While each of these faces has elements similar to human faces (e.g., eyes, nose, mouth), they are each distinctly robotic in nature

work utilized trial-and-error manipulation of a series of objects coupled with a morphology optimization approach which evolved a robotic arm with three, four, five, or six fingers for improved grasping performance. The finger radii, length, and spacing between the fingers (angle change) were used as the dynamic variables for the various number of fingers. The study found that "as the number of evolved morphological aspects increases, the robots become increasingly robust when confronted with objects of previously unseen size" (p. 214). As with the study of robotic heads, the finger morphology findings are significant and important to robotic design, but how they will influence HRI in a situated and embodied robot remains a crucial question to address. A robot whose manipulative components autonomously vary dependent on task performance, as with the finger length and radii of Bongard [6] study, may facilitate or depreciate the interaction with a human.

4.5 Related Work: Virtual Agents

Up to this point, our discussion of robotics has been limited to embodied, situated, and anthropomorphized robots that are concrete and material. However, virtual agents, or digitally represented robots, also make up a critical part of this discussion. Distinctions between robots, which inhabit physical space, and virtual agents are well accepted and evidenced by the two prominent subfields of human-robot interaction vs. human-computer interaction [39]. HCI is currently the more prevalent interaction for the general public given their ease of access through online and gaming platforms [4]. Researchers have found this prevalence to influence human behavior and interactions in both positive and negative ways. It is then critical that roboticists understand how material and virtual agents differ and how they are similar in their influences on humans for the induction of effective interactions.

One study in this space has identified that people consider physically present embodied agents to be more appealing, perceptive, helpful, watchful, and more enjoyable than their virtual counterparts [60]. The study's findings are significant as the collocated material robot comparison was conducted with two kinds of virtual agents, a tele-present robot (remotely located and streamed onto a screen) and a simulated robot (computer generated). A second and larger study made a similar comparison using the previous study's three types of HRI: a robot that was material and collocated, material and tele-present, and immaterial and simulated [30]. But a fourth condition was also tested with the individual and a simulated robot streamed onto a screen. These researchers confirmed their hypothesis that participants would be more engaged and would anthropomorphize the material and collocated robot more than the other three robotic representations. The Kiesler et al. [30] study, however, was unique due to the nature of the interaction. In this study, the participants and various robots discussed their health habits including exercise, diet, mental well-being, and social desirability. Kiesler et al. [30] found that participants were less willing to disclose information related to undesirable behavior and ate fewer of the snacks provided when interaction took place with the material and collocated robot rather than the other three robots. The study concluded that the particular situatedness of this study was a factor that provoked a distinct influence on HRI as the information being discussed was personal and considered confidential by the participant.

The aforementioned studies offer a contrast in empirical research and underscore the need for greater evaluation of these variations in embodiment, situatedness, and morphology across diverse circumstances. Depending on the context, or situatedness, physical presence may subvert a robot's purpose (i.e., to learn as much as possible about an individual's health habits) as the second study indicates. However, if the intent is to coach an individual, as was the case with the robots in the first study, then a material and collocated robot is the best form. Moreover, understanding the implications of virtual agents' embodiment, situatedness, and morphology is also in need of evaluation for effective HRI, as these factors are not limited to physically present robots. That is, a virtual agent is embodied if it has a physical non-abstract form; it is situated in that its interactions with a human being are dependent on context (i.e., location or individual vs group dynamics); and it has morphology if its embodiment is that of a biological form (i.e., human or dog) [18].

A third study may offer greater reasoning as to why these distinctions are essential. In a meta-analysis of 32 studies comparing avatars and agents, researchers found avatars are more influential in social interactions than agents, especially when perceived to be controlled by a human [24]. Additionally, if the interaction took place in an immersive environment, the avatar had greater influence on the individual than if the interaction took place on a desktop computer. It was outside of the scope of the study to compare these simulations with robots, but the comparison is nevertheless necessary to identify the most effective means of interaction for computer and robot applications. From the above study's results, it seems understanding whether a virtual agent embodiment and/or morphology offers improved interactions is highly dependent on its application. A virtual agent that is a person's wake-up call may not be as persuasive in getting a person out of bed if it is not embodied or if it lacks morphology. Similarly, widely-used GPS navigation systems might be more or less effective if they are embodied and/or have morphology. Without a more robust literature base to discern the most effective forms of robotics within commonplace applications, it will be difficult to know if the applied robotic forms achieve the most compelling HRI.

4.6 Experimental Study of Embodiment and Situatedness

Motivation: The field of robotics has identified that a more in-depth understanding of design choices is needed to create ideal robots based on a robot's applications. Research in assistive contexts, for example, has demonstrated that embodied robots can provide greater benefits to humans than non-embodied agents by encouraging user task compliance [59]. This suggests intrinsic benefits for the use of robots in assistive contexts. To explore this concept more deeply, this study was extended with a designed task that did not leverage the physical capabilities of an embodied robot, but instead limited the robot to control for the social/communicative aspects of HRI.

Procedure: Participants were assisted by a robot in a game-playing/puzzle task with one of three robot forms: a co-located physical robot, a physical robot located in a separate room that was streamed on a computer screen, and a less-realistic simulation of the robot displayed on a screen. Participants would interact with one of these agents for 10–15 m and then evaluate the agent.

Results: Participants rated the embodied co-located robot as more watchful, helpful, and likable than the non-co-located realistic robot, which was in turn rated higher than the simulated (nonrealistic) agent. These findings suggested that there are several aspects that differ between a robot and a virtual agent and highlighted how these differences in embodiment and situatedness for the three kinds of agents influence HRI. The three conditions explored in this study (a physical robot body, a physical robot located elsewhere through a video link, and a simulation of a robot) were an attempt to control variables to isolate the effects of embodiment from realism and co-locatedness [60]. This is one direction of research that should be further explored to identify what kinds of embodiment are needed in different kinds of contexts.

4.7 Uncanny Valley and Humanoid Robotics

The theory of uncanny valley explains an increased relationship between an object's degree of humanlikeness and the affinity a person has toward the object [38]. However, a person's disposition toward a robot experiences a valley effect, or dip, as its resemblance to a human increases. This affinity valley is provoked by an object's appearance. When an object's appearance is neither sufficiently distinct to be inanimate, nor similar enough to be human, it causes the object to be perceived as eerie. Although an often cited consideration, few studies have examined the theory's validity [53]. One exception is a study that compared nineteen people's functional magnetic resonance machine imaging (fMRI) scans, taken when watching actions carried out by a robot, android, or human [51]. The study was not able to make conclusive statements regarding the specific uncanny valley effect, but its findings do indicate greater brain activity for an object that is not well explained by a person, namely, the Android.

Recent interest and criticism of the uncanny valley theory have increased as research of robotic design for effective HRI has flourished. Discussions surrounding the necessary design parameters that provoke a person to trust and be willing to interact with a robot have made this notion more prevalent. This is especially true for consideration of robots' embodiment, situatedness, and morphology [11, 20, 27, 35, 60]. Additionally, researchers have noted that as the ubiquity of robotics increases in society, the uncanny valley may be of less consideration since people will be accustomed to interact with machines that resemble their biology but don't move or behave quite like them [51]. Until then, it behooves the HRI community to understand the design attributes that will contribute to positive interactions between humans and robots.

5 Conclusion

Throughout this chapter, we have discussed the purpose of and the research that supports the need to integrate embodiment, situatedness, and morphology, especially anthropomorphism, in robotic design. Specifically, we understand that within the embodiment field, there exists a need to discern the degree to which embodied cognition is attainable, the degree to which social and functional differences between embodied and non-embodied agents are distinguished, and how embodiment influences HRI in different contexts. We also identified the widely accepted idea that the dynamic nature of everyday interactions means it is necessary to equip intelligent systems with the ability to adapt and revise action based on the variability within an environment, namely, that an intelligent system accounts for its situatedness. Without this capacity, navigating and adapting to unexpected and diverse factors that disturb a robot's path will limit its practical functionality and make the robot an unrealistic tool for day-to-day applications. To facilitate HRI, robotic systems should make explicit their abilities for interaction during the early stages of an exchange with a person; using this approach can help establish the necessary conditions to accomplish a more effective HRI [44]. This is especially necessary as prior research has found that human perceptions of what a robot's capabilities are can be mismatched when simply informed by observation, thus creating challenges between the human and robot that compromise the goal of the interaction [57]. More specifically, it is recommended that communication be achieved through facilitation factors considered to be implicit in nature and utilize features of the environment and the task to communicate intent and action [9]. Lastly, anthropomorphic robotic design has been identified as a more effective approach to facilitating HRI [63]. But, as is the case for both embodiment and situatedness, the specific anthropomorphic properties that provoke increased effectiveness of HRI have not been identified due to the high degree of variability that exists for robot design [22]. Without a more robust literature base to discern the most effective forms of robotics within commonplace applications, it will be difficult to know if the applied robotic forms achieve the most compelling HRI.

6 Future Directions and Open Problems

Based on the above findings, it is evident that a comprehensive understanding of the distinctive design features that optimize HRI remains a pronounced need in the field of robotics. Because robots are inherently situated, in that they “occupy particular and specific real-world contexts” [41], making those design determinations is nontrivial. Robotic cognition is dependent upon material instantiation and on social and environmental interactions [41]. A comprehensive understanding then requires extensive investigation where varying degrees of embodiment, situatedness, and morphology are implemented. Moreover, this research should involve the investigation of both the disassociation and the interaction of embodied, situated, and morphological attributes. More broadly, there exists a need to expand empirical research that measures and isolates the design elements for navigation of particular environments.

The robotic research community also notes the need for future studies to involve highly controlled factors, such as comparing the same robot in several different environments and for different kinds of interactions. As more explicitly comparable investigations are conducted, roboticists will gain an understanding of the design elements that should be present based on the specific contexts in which their robot will operate and for the various tasks the robot will perform. Further, to steer the robotics field in a direction that helps determine the effects of embodiment and situatedness on robotic cognition, Spivey et al. [55] proposes future research involves the construction of “computational models that implement sensorimotor grounding as intrinsic to cognitive processes” (p. 1). The authors argue that a theory that isolates the various influences of the different kinds of embodiment will bring clarity to the work of roboticists. Lastly, future studies should involve the testing of robots in environments that reflect realistic use in order to simulate experiences with uncontrolled variables as they reflect the kinds of challenges the robot will encounter in real-world HRI.

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