Designing Social Cues for Collaborative Robots: The Role of Gaze and Breathing in Human-Robot Collaboration

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ABSTRACT

In this paper, we investigate how collaborative robots, or *cobots*, typically composed of a robotic arm and a gripper carrying out manipulation tasks alongside human coworkers, can be enhanced with HRI capabilities by applying ideas and principles from character animation. To this end, we modified the appearance and behaviors of a cobot, with minimal impact on its functionality and performance, and studied the extent to which these modifications improved its communication with and perceptions by human collaborators. Specifically, we aimed to improve the *Appeal* of the robot by manipulating its physical appearance, posture, and gaze, creating an animal-like character with a *head-on-neck* morphology; to utilize *Arcs* by generating smooth trajectories for the robot arm; and to increase the lifelikeness of the robot through *Secondary Action* by adding breathing motions to the robot. In two user studies, we investigated the effects of these cues on collaborator perceptions of the robot. Findings from our first study showed *breathing* to have a positive effect on most measures of robot perception and reveal nuanced interactions among the other factors. Data from our second study showed that, using *gaze* cues alone, a robot arm can improve metrics such as likeability and perceived sociability.

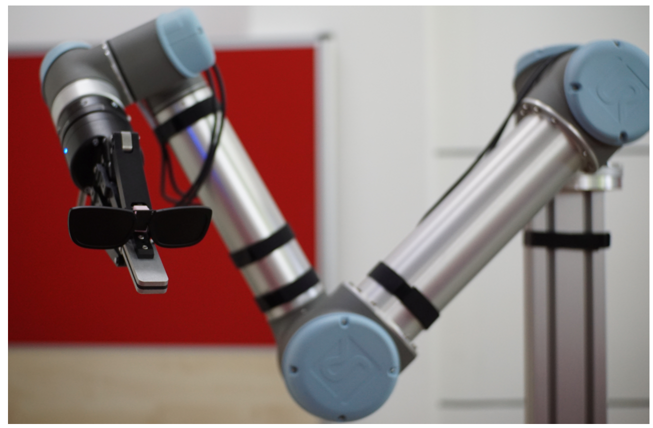

Figure 1: In this paper, we explore how principles from character animation, particularly *Appeal, Arcing,* and *Secondary Action,* can guide the design of social cues, such as *gazing, posture, breathing, appearance as a character,* and *arcing of trajectories,* for collaborative robots and study the extent to which these cues improve human-robot collaboration.

CCS CONCEPTS

• **Human-centered computing → Interaction design**; • **Computer systems organization → Robotics**.

KEYWORDS

Collaborative robots; human-robot collaboration; robot motion; social cues; animation principles; character design

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1 INTRODUCTION

Collaborative robotic manipulators, or *cobots*, are designed to carry out manipulation tasks alongside or in direct interaction with humans in a shared workspace [7, 16]. Envisioned as work-mates, cobots are rapidly being deployed on factory floors to increase efficiency and decrease physical/cognitive load of human workers [17]. This vision promotes cobots as *social* entities on the factory floor that collaborate with human workers [21] and hence requires cobots to establish and maintain both short- and long-term interactions with their human co-workers through the use of social cues. Despite this promising vision, nearly all commercial cobots are designed simply as robotic manipulators with inherent safety features and no standard support for human-robot interaction.

In this paper, we argue that cobots designed with no support for human-robot interaction can still be enhanced with social capabilities by applying ideas and principles borrowed from character animation [27]. To this end, the main contribution of our work is the exploratory application of social cues, with the guidance of principles from character animation, on a cobot platform to improve user experience with and perceptions of the robot. We aim to provide a basis for future work that may investigate a more comprehensive set of social cues, systematically compare the use of social cues against other forms of signaling, and apply findings from this body of work to real-world cobot applications.

Our exploratory study focused on the set of principles from character animation that are feasible to apply to existing cobot platforms and that have been considered by prior work in the human-computer interaction (HCI) and human-robot interaction

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(HRI) and thus can serve as a conceptual baseline. We chose to focus on the principles *Appeal*, *Arcs*, and *Secondary Action* [27] to extend the robot's ability to signal its task intent and internal states and explored ways of implementing associated behaviors on a popular cobot platform with minimal impact on its functionality and performance. Specifically, we aimed to improve the *Appeal* of the robot by manipulating its physical appearance, posture, and gaze, creating an animal-like character with a *head-on-neck* morphology as shown in Figure 1; to utilize *Arcing* by generating smooth trajectories for the robot arm; and to increase the lifelikeness of the robot through *Secondary Action* by adding breathing motions to the robot. In two user studies, we evaluated how these modifications might affect the experience and robot perceptions of human collaborators. In summary, our work makes the following contributions:

(1) The conceptualization and preliminary exploration of a *new design space* for social cues in cobots;
(2) An *empirical understanding* of how social cues might affect user experience with non-social industrial robots;
(3) The initial development of *design guidelines* for the creation of efficient and HRI-capable future cobot systems.

2 PRIOR WORK

2.1 Principles of Animation in Robotics

In their book titled "The Illusion of Life: Disney Animation," Thomas and Johnston [27] presented 12 basic principles that were developed at Disney Studios for traditional cartoon animation (see [15] for their use in 3D computer animation at Pixar), namely; (1) *Squash and Stretch*, (2) *Anticipation*, (3) *Staging*, (4) *Straight Ahead Action and Pose-to-Pose*, (5) *Follow Through and Overlapping Action*, (6) *Slow In and Slow Out*, (7) *Arcs* (or *Arcing*), (8) *Secondary Action*, (9) *Timing*, (10) *Exaggeration*, (11) *Solid Drawing*, and (12) *Appeal*.[1]

Many of these principles have also been used to create human-like behaviors for robots. For example, Van Breemen [28, 29] followed the *Anticipation* and *Secondary Action* principles to create life-like behaviors such as "sleeping" and "turning to other side" on the iCat robot, a cat-like head designed to display facial expressions. Gielniak et al. [12] proposed three different methods to generate *Secondary Action* cues for a humanoid robot for behaviors where a subset of the robot's DOFs are un-actuated or under-actuated.

Takayama et al. [26] applied the principles *Anticipation* and *Follow Through and Overlapping Action* to develop behaviors on an animated PR2 mobile robot and have shown that the application of the principles demonstrated forethought and allowed people to better "read the robot's behaviors." Szafir et al. [24] applied *Arcing*, *Anticipation*, and *Slow In and Slow Out* principles to improve a quadrotor's ability to communicate its motion intent to users and showed that the use of these principles improve the perceived usability, safety, and naturalness of the robot's motions.

Simmons et al. [23] explored how social robots might be designed as coherent, believable characters, building on the principle of *Appeal*, in a way that integrates a rich backstory, evolving story line, verbal and non-verbal social cues, and cultural expressions.

[1]A detailed description of all animation principles is beyond the scope of the paper. Instead, we only present principles that are considered in this paper in Section 3.

2.2 Improving HRI with Collaborative Robots

Prior research on improving the non-verbal human interaction capabilities of collaborative robots falls under three categories:

Facial Animation: On their Baxter and Sawyer cobot platforms, Rethink Robotics (Massachusetts, USA) used a screen with an animated face to effectively communicate the robot's direction of attention through its eyes to its users on the factory floor [21]. Whitney et al. [30] explored how the Baxter robot might utilize facial expressions to signal understanding of or confusion about human commands in ambiguous communication scenarios.

Arm/hand Gestures: Ende et al. [11] identified arm gestures used by humans in collaborative tasks, transferred them on a cobot, and evaluated them in a human-robot collaboration task. In a similar study, Sheikholeslami et al. [22] explored how a robotic gripper might use hand gestures, such as a "thumbs-up" gesture to indicate approval or to provide instructional feedback in an industrial task, and evaluated the ability of human collaborators to recognize the semantics of these gestures.

Arm Motion: Dragan et al. [10] proposed a formalism to create "legible" arm motions that enable observers to infer the robot's goal in ambiguous reach scenarios and applied this formalism to better convey robot intent during pointing [14] and human-robot collaboration scenarios [9]. Bodden et al. [5, 6] extended this approach to address ambiguities in continuous environments and across different robot arm platforms.

At a high level, prior work has primarily considered the robot's geometry to resemble an "arm" structure. Drawing inspiration from human morphology and human arm behaviors, this approach augmented the robot's interaction capabilities with a face animated on a screen or used arm gestures and motions to communicate the robot's internal states or intent. In contrast, we build on the animation principle of creating character *Appeal* and explore the geometry of the robot to assume a *head-on-neck* morphology, taking inspiration from families of animals, such as Anatidae (e.g., ducks) and Canidae (e.g., dogs), that use their heads for both manipulation and communication. We argue that approaching the design problem at the level of redefining the cobot as a character—human-like, animal-like, or another alternative—and designing behaviors to establish character *Appeal* widens the range of possible HRI capabilities and opens up a new space for designing communicative cues.

3 INTERACTION DESIGN OF COBOT

Drawing on the character animation principles *Appeal*, *Arcing*, and *Secondary Action*, we designed a set of social cues for a commercially popular cobot platform, a UR5 robot arm (Universal Robots, Odense, Denmark) equipped with a 2F-140 two-finger gripper (Robotiq, Lévis, Canada) (see Figure 1) that included giving it a *head-on-neck* look by augmenting its appearance and implementing gaze and posture cues (*Appeal*), generating smooth motion trajectories for the arm (*Arcing*), and introducing breathing motions to the robot during its idle operation (*Secondary Action*). The paragraphs below describe these cues and related animation principles.

3.1 Appeal

The animation principle *Appeal* underlines the need to create a coherent, believable character that elicits interest and engagement

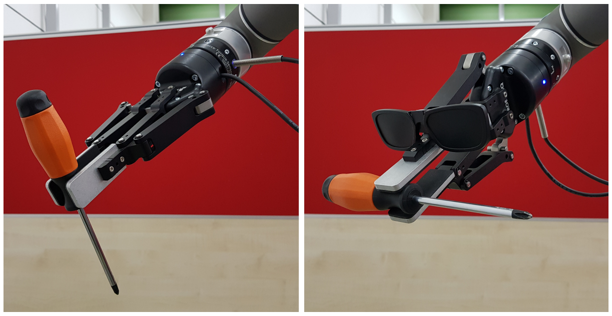

Figure 2: The cobot without (left) and with (right) the *appearance* manipulation, which involved orienting the gripper vertically and mounting a pair of sunglasses on the gripper to create an animal-like character.

[27] through its appearance and behavior, as also explored by Simmons et al. [23]. Following this principle, we aimed to construct a coherent character for the cobot without hindering its manipulation capabilities and adopted the morphology of animals, such as members of the Anatidae family, including ducks, swans, and geese, that use their heads for both manipulation and social interaction. Our design integrated manipulations in the robot's *appearance*, *posture*, and *gaze*, as described below.

3.1.1 Appearance. To suggest an animal-like appearance, we transformed the cobot's gripper into a "head." Specifically, we set the default orientation of the gripper such that the gripper fingers are aligned vertically, resembling a beak/mouth of an animal, and fixated a pair of black-tinted sunglasses on the gripper to create "eyes," as seen in Figure 1. We note, however, that sunglasses represent one of many ways in which the impression of eyes can be created. These modifications created a "face" for the character, enabling it also to display gaze cues for interaction. Figure 2 shows the cobot with and without the *appearance* modification.

3.1.2 Posture. We explored two different robot *posture* configurations: *elbow-up* and *elbow-down*. The elbow-down configuration, as shown in Figure 4, resembles the animal-like neck and complements the *appearance* manipulation to establish the overall head-on-neck appearance of the cobot. The elbow-up configuration is the typical posture for cobots where the elbow joint is positioned above the robot's base. This configuration is preferred in industrial settings, as it reduces the risk of collision with surrounding structures, such as workbenches, and can be used as a baseline for comparison.

3.1.3 Gazing. Gaze is an important cue in social interaction, and the human brain is considered to have dedicated pathways for its interpretation [1]. We implemented *gaze* cues for the cobot by directing the gripper toward a point of interest in space using the last three joints of the arm. These cues further enhanced the robot's ability to express a coherent, believable, and charismatic character through semantic behaviors that are consistent with the cobot's character. Specifically, we designed four gaze cues for the robot:

(1) *Toward the task*: The cobot gazes toward the current/expected location of the task to be conducted by its collaborator.
(2) *Toward the collaborator*: The cobot gazes toward its collaborator's face to acknowledge the completion of a task.
(3) *Toward the target*: Before reaching out toward a point in space, the cobot first gazes toward that target location.
(4) *Idle*: While idling, either before the work has started or after it ended, the cobot gazes toward random points in its vicinity.

3.2 Arcing

The principle of *Arcing* suggests the use of arcs, as opposed to straight lines, as motion trajectories for animated characters [27]. A large body of work in HRI [2, 3, 5, 6, 10, 24] has shown the potential benefits of smooth trajectories in the end-effector or joint space for human-robot collaboration. Yet, most cobot systems are designed to follow trajectories generated by linear interpolations on the end-effector frame between a set of keyframes that are recorded using a teach pendant. Such motions generate straight lines and sharp corners (and thus abrupt pauses) in the trajectory, resulting in a mechanical and "robot-like" motion characteristic. To increase the life-likeness of the motion, as suggested by the *Arcing* principle, we incorporated cubic spline interpolation on our predefined set of keyframes in the joint space and generated smooth trajectories.

3.3 Secondary Action

The principle of *Secondary Action* in animation involves incorporating behaviors such as blinking or shifting body weight from one foot to another into the behaviors of the animated character. Although these actions do not serve an apparent purpose, they contribute to the life-likeness of the character [18]. Our design implemented a behavior for the cobot that resembled *breathing* and was activated during idle periods, such as while waiting for the robot's collaborator to finish a task or to get ready for the next task. The breathing behavior moved the robot's joints such that, while the general direction of the end-effector was kept fixed, the overall volume that the robot's body spans expanded and shrank repeatedly. The small motions of the arm also resulted in small motions in the robot's face, which served as an idle gaze cue. These motions were created using predefined keyframes in terms of six-DOF configuration waypoints. After adding a small amount of random noise on each repeated keyframe, the motions were connected to each other in the robot's configuration space using cubic spline interpolation to create the breathing animation. Cobots in industrial settings remain completely still during idle operation, making it impossible for their users to distinguish between "error" and "wait" states. The *breathing* behavior addresses this ambiguity by explicitly signaling that the robot is in operation and waiting.

4 USER STUDIES

To evaluate the effects of our designed cues on cobot perceptions and user experience, we conducted two user studies.[2] The first user study assessed the effects of the modifications implemented following the *Appeal*, *Arcing*, and *Secondary Action* principles. In this study, only the *appearance* modification was manipulated in the cues designed following the *Appeal* principle, and the *gaze* and *posture* cues were always present. The second user study focused on the other modifications that followed the *Appeal* principle and investigated the effects of *gaze* and *posture* by manipulating them

[2]The studies were carried out with the approval of Middle East Technical University Applied Ethics Research Center under the protocol number 2017-FEN-008.

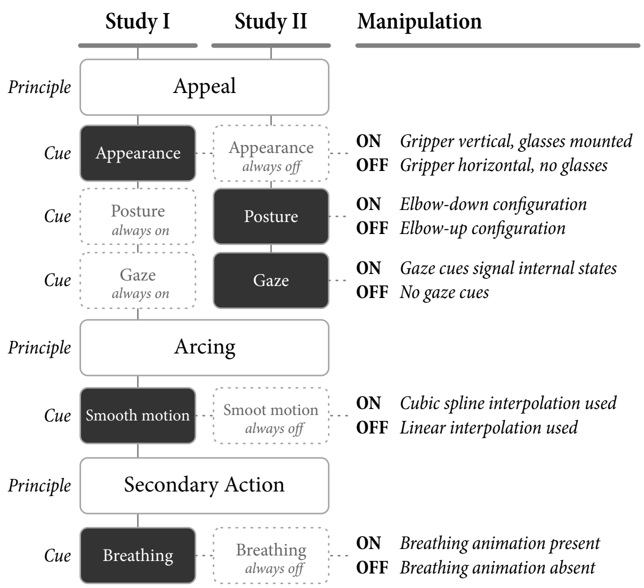

Figure 3: The principles and cues considered in the two studies. Study I manipulated *Appeal*, *Arcing*, and *Secondary Action* principles, including the *appearance*, *smooth motion*, and *breathing* cues. Study II focused on *Appeal*, manipulating *posture* and *gaze* cues.

without the use of the *appearance* modification. Figure 3 provides an overview of the principles and cues considered in the two studies. §5.1 provides further discussion on our study design choices.

4.1 Study I: Appeal, Arcing, Secondary Action

In the first user study, we evaluated the effects of the cues designed following the three animation principles, *Appeal*, *Arcing*, and *Secondary Action*, on user experience with and perceptions of the cobot. The study followed a mixed-model design, manipulating *Arcing* and *Secondary Action* within participants and *Appeal* between participants to prevent confusion that might have been caused by seeing the robot in different physical appearances. Each of the three independent variables had two levels: *ON* and *OFF*. In this study, *Appeal* was manipulated only by including or excluding the *appearance* modification, and the *gaze* cues and elbow-down *posture* were included across all conditions, as shown in Figure 3.

In the study, participants completed four trials of an assembly task in collaboration with the cobot, corresponding to all possible combinations of the *Arcing* and *Secondary Action* conditions, in a counterbalanced order, and filled out two questionnaires after each trial. The questionnaires evaluated user experience with and cobot perceptions using a set of previously validated measures, as described in §4.1.4. The study was audio- and video-recorded with the consent of the participants. To minimize ordering effects, the conditions were counterbalanced using a Latin Square, resulting in 48 unique orderings of the conditions and requiring a minimum of 48 participants for each ordering to be experienced.

4.1.1 Study Task & Setup. In each study trial, the participant screwed four bolts into four of the eight nuts embedded on a wooden plank that was placed on the table in between the cobot and the participant, as shown in Figure 4. During the experiment, the cobot fetched a bolt from a tray and handed it out to the participant. After the bolt was taken, the cobot directed its gripper toward a randomly chosen empty nut on the plank. The participant was then expected to follow this cue and screw the bolt in the correct nut, after which the robot fetched the next bolt. Following the Wizard-of-Oz technique [8, 19], the cobot's consecutive actions were controlled by an experimenter who could observe the study space through a camera stream while staying out of the sight of the participant. The behaviors and the sequence of actions of the cobot were scripted, and the experimenter observed the completion of the screwing task and triggered the cobot to execute the next action in the script.

4.1.2 Generating Motion Trajectories. All the motions of the cobot were based on two sets of keyframes defined as six-DOF robot configuration waypoints. These sets differed in the configuration of the spherical wrist joints based on the condition of the *appearance* manipulation to either keep the gripper in the vertical or the horizontal orientation. To generate complete motion trajectories, the corresponding successive keyframes were connected to each other either using linear interpolation for the conditions where the *smooth motion* manipulation was OFF or cubic spline interpolation for the conditions where the *smooth motion* manipulation was ON.

4.1.3 Study Procedure. The experiment began with the cobot in an idle state. If the *breathing* manipulation was OFF, the cobot stood still. Otherwise, it displayed the breathing behavior described in §3.3. Once the participant sat in the chair and looked toward the cobot, it stopped idling and gazed toward the participant before moving to a working posture closer to the participant. The cobot then gazed toward the bolt tray, fetched a bolt, handed it out to the participant, and returned to the working posture. At this point, it turned its gaze toward a randomly chosen empty nut and continued on with idling while the participant was working. Once the participant completed screwing the bolt, the cobot moved its gaze from the nut toward the participant and then toward the bolt tray once more before fetching the next bolt. When all four bolts were screwed in, the cobot returned to its initial posture and executed its idle behavior until the participant left the work area.

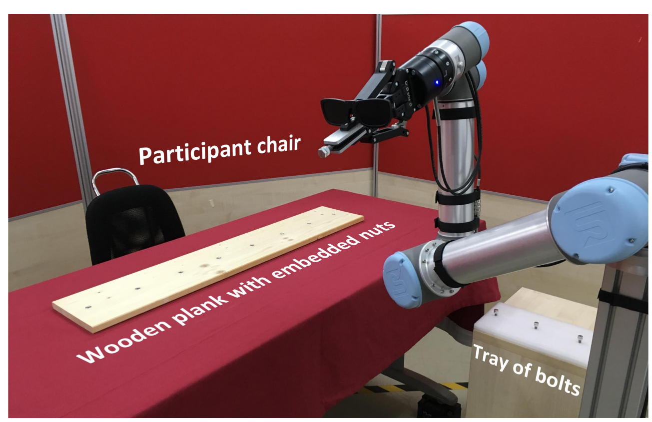

Figure 4: Study setup from the experimenter's perspective.

4.1.4 Measures. Our measures included two previously validated questionnaires from the HRI literature that were administered after each trial. We randomized the order in which items were presented and carried out item reliability analysis for all scales and removed items that did not highly correlate with the other items. First, we used the Godspeed questionnaire developed by Bartneck et al. [4] to measure user perceptions of robots. This questionnaire included the five scales *Anthropomorphism* (Cronbach's $\alpha = .8829$), *Animacy* (Cronbach's $\alpha = .8896$), *Likeability* (Cronbach's $\alpha = .9299$), *Perceived Intelligence* (Cronbach's $\alpha = .8834$), and *Perceived Safety* (Cronbach's $\alpha = .8512$, item 3 removed). The items were rated using seven-point rating scales with numerical and Likert-like labels.

In addition to the questionnaires, the participants were asked to comment on their experience with the cobot in a semi-structured interview, and their responses were audio-recorded.

Our second questionnaire included nine scales developed by Heerink et al. [13] to measure user experience with assistive robots. The scales included *Anxiety* (Cronbach's $\alpha = .8064$), *Attitude* (Cronbach's $\alpha = .7983$), *Intention to Use* (Cronbach's $\alpha = .8383$), *Perceived Adaptability* (Cronbach's $\alpha = .0.6736$, item 2 removed), *Perceived Enjoyment* (Cronbach's $\alpha = .9082$, item 5 removed), *Perceived Sociability* (Cronbach's $\alpha = .8182$), *Perceived Usefulness* (Cronbach's $\alpha = .8375$), *Social Presence* (Cronbach's $\alpha = .7747$, item 4 removed), and *Trust* (Cronbach's $\alpha = .8023$). The wording in some of the items in the scales were adapted to match the specific context of our study. For example, we modified the item "I consider the robot a pleasant conversational partner" to "I consider the robot a pleasant working partner." Participants rated the items on a five-point rating scale.

4.1.5 Participants. We recruited 53 volunteers (11 female, 42 male) from Middle East Technical University campus. Participant ages ranged from 19 to 30 ($M = 21.32$, $SD = 1.51$). The participants included 43 computer Engineering majors, 1 computer engineering graduate student, 4 electrical and electronics engineering major, 1 psychology major, 2 architecture majors, and 2 mechanical engineering majors. Each experiment session took approximately 45 minutes. We excluded data from five participants due to technical and procedural errors and retained data from 48 participants that observed each unique ordering of the conditions.

4.2 Study I Results

We analyzed the data from the two questionnaires using a three-way mixed-model analysis of co-variance (ANCOVA) that used *Appeal* as a between-participants variable, *Arcing* and *Secondary Action* as within-participants variables, and the order in which participants observed the different conditions as a co-variate. We used α levels of .05 and .10 to establish significant and marginal effects, respectively. In the paragraphs below, we first provide the main effects of the design elements and then report on interaction

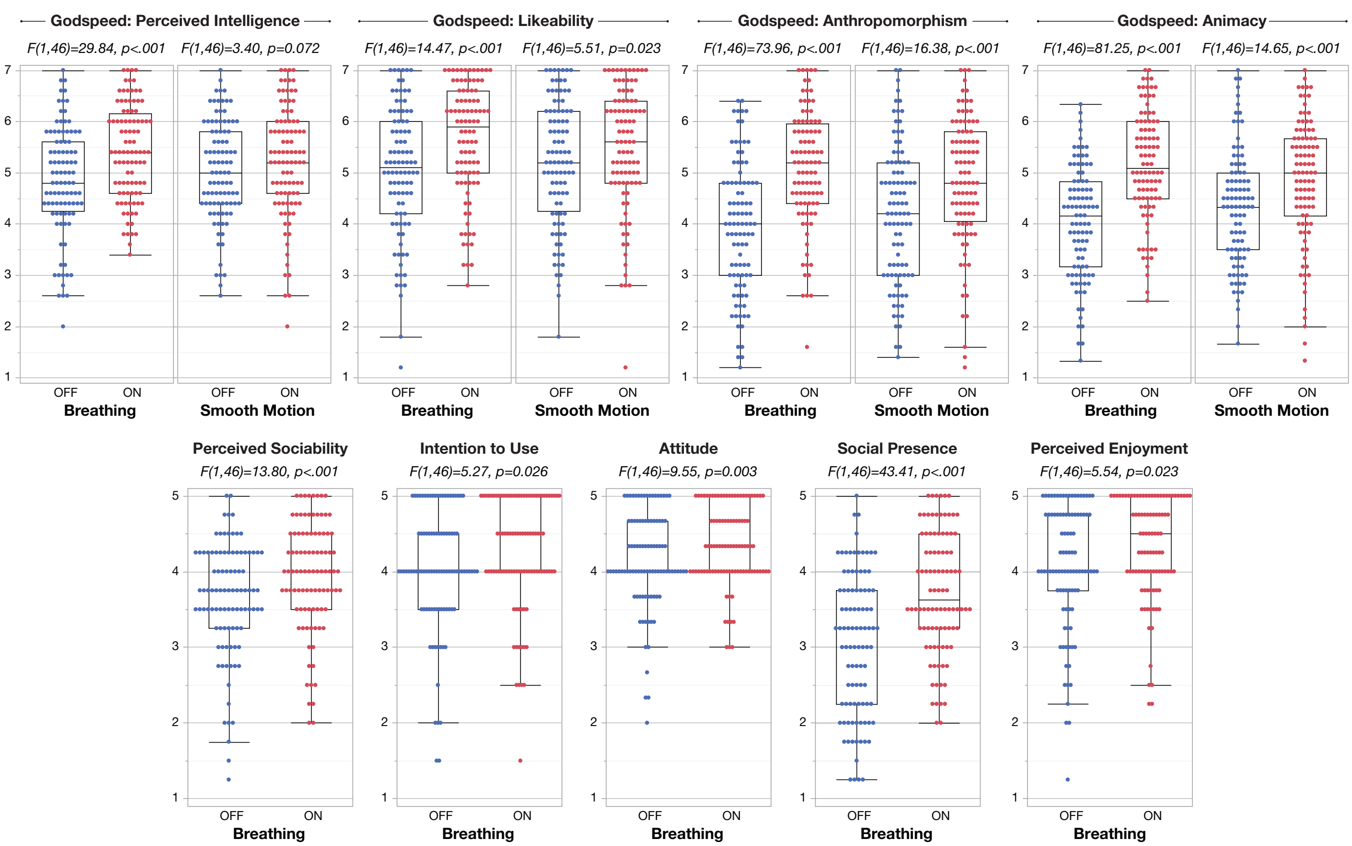

Figure 5: Main effects of the *appearance*, *smooth motion*, and *breathing* cues on measures of cobot perception [4] and user experience [13]. Only the significant and marginal effects are included. Statistical test details are included above each graph.

effects. Figures 5 and 6 show significant and marginal effects. Test results are included in the figures to improve readability, and full test details are provided in the Appendix (§A).

4.2.1 Main Effects. Our analysis showed no effects of the *Appeal* factor on any of our measures, although we report on interaction effects in the next subsection. Although this result was initially surprising, we believe that the *gaze* and *posture* cues, which the robot displayed in both the ON and OFF conditions of the *appearance* manipulation, may have been sufficient for the participants to perceive the robot as a coherent, plausible character without the need for the physical *appearance* modifications. We found *breathing* to have a significant positive effect consistently on most of our measures, including perceived intelligence, likeability, social presence, perceived sociability, intention to use, anxiety, attitude, perceived adaptability, perceived enjoyment, anthropomorphism, and animacy. These effects indicate that incorporating *Secondary Action* to cobots, even during periods when the robot is idle, can greatly enhance the perception of the cobots. Finally, our analysis showed a significant positive effect of *Arcing* on measures of likeability, anthropomorphism, and animacy.

4.2.2 Interaction Effects. We have found a number of interaction effects, including an interaction between *Appeal* and *Secondary Action* on perceived intelligence; we found *Appeal* to further enhance the effect of *Secondary Action*. This result indicates that some design factors, such as *Appeal*, may further enhance the HRI capability of the cobots only when used with other factors, such as *Secondary Action*. This finding provides support for the idea that these cues work together to create the perception of a coherent, plausible character. Our analysis showed a significant three-way interaction between *Appeal*, *Arcing*, and *Secondary Action* on perceived enjoyment. Specifically, when the *breathing* cue was absent but the *appearance* factor was present, *smooth motion* reduced participants' perceived enjoyment of the interaction. Finally, we found an interaction effect between *Arcing* and *Appeal* on perceived enjoyment; *smooth motion* had a marginal positive effect on this measure when the *appearance* cue was absent and no effect when it was present.

4.3 Study II: Posture, Gaze

The findings of Study I, particularly findings associated with the *Appeal* principle, suggest that posture and gaze cues alone may help create a coherent character with *Appeal*. Driven by this observation, Study II aimed to understand the possible effects of *gaze* and *posture* cues in isolation on cobot perceptions. We hypothesized that *gaze* and *posture* cues both improve interaction outcomes with a cobot. The study followed a factorial design, manipulating both factors within-participants, where each independent variable had *ON* and *OFF* levels as shown in Figure 3. Similar to Study I, each participant completed the screwing task in four trials for all possible combinations of our independent variables in a counterbalanced order and filled out the two questionnaires after each trial. This design required a minimum of 24 experiments for one complete set of data and 24 participants for each ordering to be experienced.

Study II followed a similar design and procedure to the first study, utilizing a Wizard-of-Oz approach for robot control, a fixed set of keyframes to generate cobot motions, and the same set of measures. The condition of Study II where *gaze* and *posture* cues were both ON is identical to the condition of Study I where *Appeal*, *Arcing*, and *Secondary Action* were all OFF in terms of the cobot's behaviors and appearance. This overlap allows conceptual comparisons between the two studies. The following paragraphs describe aspects of Study II that differed from Study I.

4.3.1 Study Task & Setup. Participants completed the same bolt assembly task with the cobot as in Study I, where the cobot fetched the bolts one by one as the participant screwed them onto the nuts. However this time, since the *gaze* cue was only present in two of the four trials, instead of relying solely on the cues given by the cobot gaze, the participants were expected to match the bolts with the nuts based on stickers with Greek letters that were attached on both the bolts and the nuts. The assignment of the letters were randomized in each trial.

4.3.2 Generating Motion Trajectories. The cobot motions for this study were generated using two sets of keyframes, recorded as six-DOF end-effector poses, for the two levels of the *posture* manipulation. The complete motion trajectories were computed using linear interpolation between these waypoint poses in the task space.

4.3.3 Study Procedure. The experiment began with the cobot idling, standing completely still. Once the participant sat on the experiment chair and looked toward the robot, it moved to a configuration that is closer to the participant. For the trials where the *gaze* cues were ON, the cobot directed its gripper towards the participant's face, as described in §3.1.3, then gazes at the bolt tray, fetched a bolt, and handed it out to the participant. Then, it gazed toward

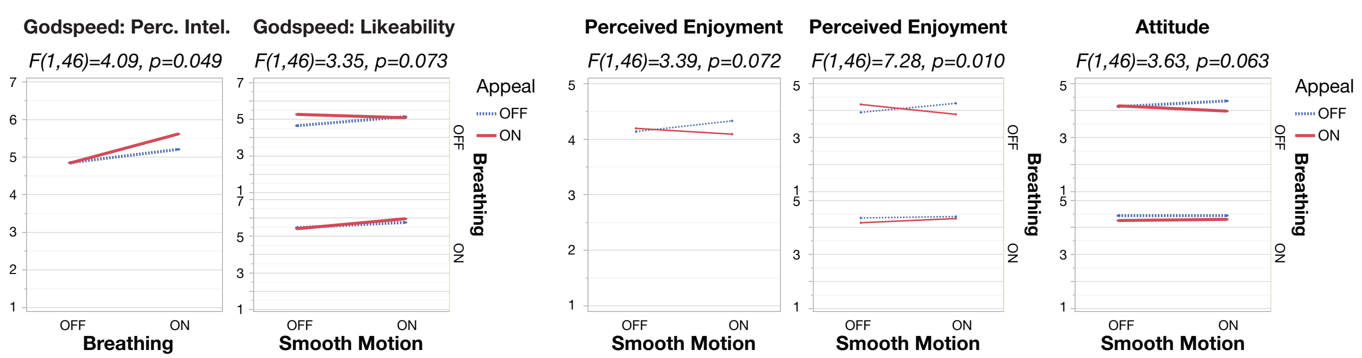

Figure 6: The significant and marginal interaction effects observed in our data from Study I.

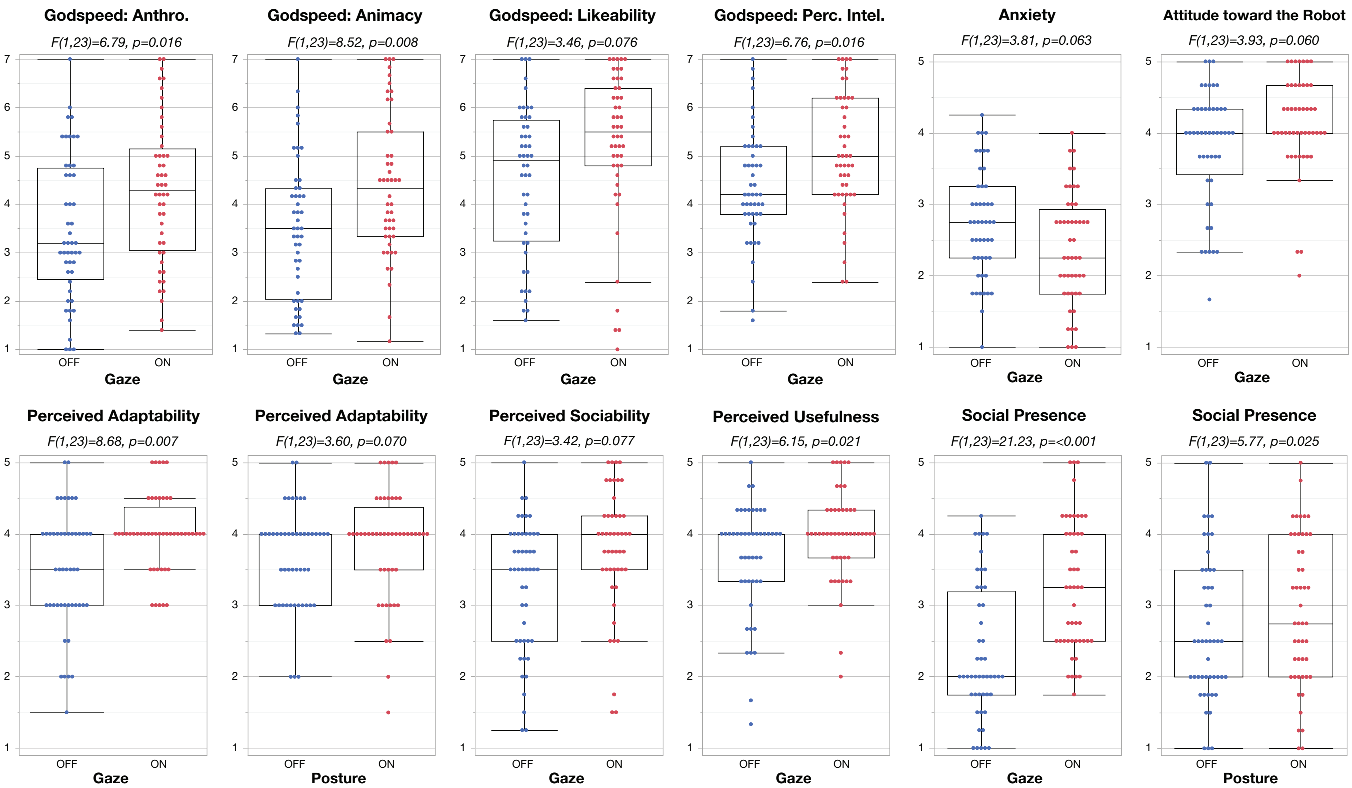

Figure 7: Main effects of the *gaze* and *posture* cues on measures of cobot perception [4] and user experience [13] in Study II. Only the significant and marginal effects are included. Test details are included above each graph.

the nut that matched the current bolt even though this information was also available on the stickers. Once the participant completed the screwing task, the cobot gazed toward the participant and then toward the bolt tray before fetching the next bolt. After all four bolts were screwed in place, the cobot returned to and remained in its initial pose. In the trials where the *gaze* cues were OFF, the robot's gripper was directed toward the ground.

4.3.4 Measures. This study used the same set of measures that were used in Study II, including *Anthropomorphism* (Cronbach's α = .8785), *Animacy* (Cronbach's α = .9161), *Likeability* (Cronbach's α = .9534), *Perceived Intelligence* (Cronbach's α = .9001), and *Perceived Safety* (Cronbach's α = .9149, item 3 removed) to measure robot perceptions and *Anxiety* (Cronbach's α = .6467), *Attitude* (Cronbach's α = .8476), *Intention to Use* (Cronbach's α = .8099), *Perceived Adaptability* (Cronbach's α = .6275, item 2 removed), *Perceived Enjoyment* (Cronbach's α = .8679, item 5 removed), *Perceived Sociability* (Cronbach's α = .8469), *Perceived Usefulness* (Cronbach's α = .8164), *Social Presence* (Cronbach's α = .8492, item 4 removed), and *Trust* (Cronbach's α = .8232) to measure user experience.

4.3.5 Participants. We recruited 24 volunteers (10 female, 14 male) from Middle East Technical University campus. Participant aged between 20 and 24 (M = 21.29, SD = 1.28) majored in computer engineering (15), electrical and electronics engineering (5), metallurgical and materials engineering (2), and architecture (2). As in Study I, each trial lasted approximately 45 minutes.

4.4 Study II Results

We analyzed the data from this study using a two-way repeated measures analysis of variance (ANOVA), including *gaze* and *posture* as within-participants variables. We used the same α levels of .05 and .10 as in Study I to establish significant and marginal effects, respectively. Figure 7 focuses on significant and marginal effects and includes the test details for improved readability. The Appendix (§B) provides complete descriptive and inferential statistics.

Our analyses showed that *posture* had a significant effect on social presence and a marginal effect on perceived adaptability, while *gaze* had a significant positive effect on the majority of our measures, including animacy, anthropomorphism, likeability, perceived adaptability, perceived enjoyment, perceived intelligence, perceived usefulness, and social presence. We did not find any interactions between the factors or any ordering effects.

These findings are consistent with our hypothesis for Study II for gaze, pointing out that gaze cues alone, without any physical modifications on the cobot, strongly contribute to improving character Appeal and cobot perceptions. However, posture affected these outcomes only minimally.

5 DISCUSSION

In this paper, we argued that cobots that are designed with no support for human-robot interaction can still be enhanced with social capabilities by applying ideas and principles from character animation. To this end, building on the animation principles Appeal, Arcing, and Secondary Action, we augmented a commercial cobot's physical *appearance*, implemented *gaze* and *posture* cues, modified its trajectories to display *smooth motion*, and introduced *breathing* cues toward establishing the cobot as an animal-like character. We evaluated the effects of these modifications on human perceptions of and experience with cobots across two studies.

Study I manipulated *Appeal*, *Arcing*, and *Secondary Action*, including only *appearance* but not *gaze* or *posture*. The results showed that *Secondary Action*, particularly *breathing*, has a significant positive effect consistently on most measured interaction outcomes, including perceived intelligence, likeability, social presence, perceived sociability, intention to use, anxiety, attitude, perceived adaptability, perceived enjoyment, anthropomorphism, and animacy. Moreover, the interaction effects indicated that *Appeal* further enhances the effects of *Secondary Action*, suggesting that these cues work together to create the illusion of a lifelike character.

Study II further studied the effects of *Appeal*, focusing on *gaze* and *posture* cues in isolation. The results showed that *gaze* had a significant positive effect on the majority of our measures, including animacy, anthropomorphism, likeability, perceived adaptability, perceived enjoyment, perceived intelligence, perceived usefulness, and social presence. Posture only had a significant effect on social presence and a marginal effect on perceived adaptability.

The results from these two studies clearly illustrate that even the simple act of pointing the gripper of a cobot toward the user or toward an object is perceived as a strong *gaze* cue and that gaze cues presented by a cobot improve robot perceptions and user experience. Moreover, *breathing* as a form of *Secondary Action* improved the life-likeness and user perceptions of the cobot.

5.1 Limitations

Our study has a number of limitations that serve as fruitful avenues for future research. First, in choosing what animation principles to focus on and how to implement these principles, we have made a number of design decisions that shaped our findings. We believe that social cues present a rich and open space for design research into collaborative robots, and more extensive explorations of this space and investigations of a broader set of cues would deepen our understanding of how social cues might be designed for cobots. For example, we chose to achieve physical *Appeal* by simply changing the gripper orientation of the robot and adding a pair of sunglasses, but there are many alternative ways to establish the robot as a coherent, plausible character. Second, our studies followed an unusual design, manipulating different *Appeal* cues across different studies, which was due to a number of factors, including the infeasibility of manipulating all cues in a single study, the difficulty of isolating complementary design elements, and the organic nature of our process in which Study II was motivated by the findings of Study I. Our study design choices makes our findings harder to interpret, although we believe that our findings still provide valuable insight into the use of social cues in human-robot collaboration and inform future research and design. Third, we utilized a Wizard-of-Oz approach to carry out our studies, and the cobot followed a scripted interaction. Implementing such capabilities into cobots for autonomous operation involves a number of technical challenges that we have not considered. For example, displaying some of these communicative cues, such as breathing, might affect the precision of the cobot's operation, and new methods that consider task constraints while planning the use of communicative cues must be developed. Finally, how these cues might affect collaborator perceptions and experience over a long period of time and in the context of a real-world manipulation task (e.g., assembly, stocking, machining) is still unknown. Field studies that deploy cobots with HRI capabilities and studies worker perceptions and experience over time would inform us on the real-world effects of the design elements we have studied.

5.2 Design Implications

Two key design implications result from our findings. First, as highlighted by prior work [21], cobots, despite their task-oriented designs, are seen as social agents, and social cues displayed by these agents improve human perceptions and experience. Our findings, particularly the consistently positive effects we see in most measures of user perceptions and experience, indicate that the design of *social* cues for cobots is a fertile area of design and exploration. We argue that the interactive capabilities of existing cobots can be improved using social cues and that future cobots can be designed to further accommodate the use of social cues, such as the addition of an abstract face or set of eyes as a locus of attention.

A second design implication of our study is that cues with biological and ethological bases, such as *gaze* cues and *breathing* motions, are extremely salient in communicating internal states and intent. Our findings on gaze are consistent with prior work on designing gaze cues for social robots [1, 20] as well as non-social robots [25]. In light of our findings, we suggest that such behaviors serve as salient communication cues in a broad range of HRI contexts from conversational to collaborative interactions with robots.

6 CONCLUSION

We investigated how cobots, designed for manipulation tasks with no intrinsic capabilities for human interaction, can be enhanced with such capabilities by applying ideas and principles from character animation. We modified the appearance and behaviors of a Universal Robots UR5 cobot in order to improve the quality of interaction with humans. Informed by the character animation principles *Appeal*, *Arcing*, and *Secondary Action*, we augmented its physical *appearance*, *posture*, and *gaze*, creating an animal-like character with a *head-on-neck* morphology, generated *smooth motions* for its arm trajectories, and implemented *breathing* motions to improve its life-likeness. In two user studies, we investigated the effects of these cues on human collaborators' perceptions of the cobot. Data from Study I showed that *breathing* improved most measures of cobot perception, and data from Study II showed that gazing behavior alone can be a salient cue for a cobot arm to improve most measured interaction outcomes. These findings have strong implications for the design of interactive behaviors for collaborative robots and the future design of cobot platforms.

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A STUDY I COMPLETE RESULTS

Table 1: ANOVA test results for data from measures of cobot perception [4] in Study I. "*" and "†" denote significant and marginal results, respectively.

Anthropomorphism

Source of Variation	*df*	*F*	*p*
Appearance	1	0.691	0.410
Breathing	1	73.857	<.001*
Smooth Motion	1	16.376	<.001*
Appearance × Breathing	1	0.403	0.529
Appearance × Smooth Motion	1	1.483	0.230
Breathing × Smooth Motion	1	0.242	0.625
Appearance× Breathing × Smooth Motion	1	0.365	0.549
OrderID	1	1.412	0.241
Error	45		

Animacy

Source of Variation	*df*	*F*	*p*
Appearance	1	1.002	0.322
Breathing	1	81.247	<.001*
Smooth Motion	1	14.653	<.001*
Appearance × Breathing	1	0.688	0.411
Appearance × Smooth Motion	1	2.065	0.158
Breathing × Smooth Motion	1	0.564	0.456
Appearance× Breathing × Smooth Motion	1	0.226	0.637
OrderID	1	0.572	0.453
Error	45		

Likeability

Source of Variation	*df*	*F*	*p*
Appearance	1	0.496	0.485
Breathing	1	14.474	<.001*
Smooth Motion	1	5.511	0.023*
Appearance × Breathing	1	0.424	0.518
Appearance × Smooth Motion	1	0.745	0.393
Breathing × Smooth Motion	1	1.027	0.316
Appearance× Breathing × Smooth Motion	1	3.350	0.074
OrderID	1	0.028	0.869
Error	45		

Perceived Intelligence

Source of Variation	*df*	*F*	*p*
Appearance	1	0.816	0.371
Breathing	1	29.844	<.001*
Smooth Motion	1	3.399	0.072†
Appearance × Breathing	1	4.094	0.049*
Appearance × Smooth Motion	1	0.890	0.351
Breathing × Smooth Motion	1	0.001	0.970
Appearance× Breathing × Smooth Motion	1	1.637	0.207
OrderID	1	2.443	0.125
Error	45		

Perceived Safety

Source of Variation	*df*	*F*	*p*
Appearance	1	0.289	0.593
Breathing	1	0.209	0.650
Smooth Motion	1	0.079	0.780
Appearance × Breathing	1	0.093	0.762
Appearance × Smooth Motion	1	1.115	0.297
Breathing × Smooth Motion	1	1.182	0.283
Appearance× Breathing × Smooth Motion	1	0.409	0.526
OrderID	1	0.034	0.854
Error	45		

Table 2: ANOVA test results for data from measures of user experience [13] in Study I. "*" and "†" denote significant and marginal results, respectively.

Anxiety

Source of Variation	*df*	*F*	*p*
Appearance	1	1.904	0.174
Breathing	1	26.100	<.001*
Smooth Motion	1	2.398	0.128
Appearance × Breathing	1	0.408	0.526
Appearance × Smooth Motion	1	0.000	1.000
Breathing × Smooth Motion	1	1.605	0.212
Appearance× Breathing × Smooth Motion	1	1.349	0.252
OrderID	1	0.116	0.736
Error	45		

Perceived Sociability

Source of Variation	*df*	*F*	*p*
Appearance	1	0.000	0.988
Breathing	1	13.804	<.001*
Smooth Motion	1	0.863	0.358
Appearance × Breathing	1	0.340	0.563
Appearance × Smooth Motion	1	1.161	0.287
Breathing × Smooth Motion	1	0.273	0.604
Appearance× Breathing × Smooth Motion	1	2.456	0.124
OrderID	1	0.033	0.857
Error	45		

Attitude

Source of Variation	*df*	*F*	*p*
Appearance	1	1.489	0.229
Breathing	1	9.553	0.003*
Smooth Motion	1	0.060	0.808
Appearance × Breathing	1	0.012	0.913
Appearance × Smooth Motion	1	2.515	0.120
Breathing × Smooth Motion	1	0.014	0.906
Appearance× Breathing × Smooth Motion	1	3.627	0.063†
OrderID	1	0.034	0.855
Error	45		

Perceived Usefulness

Source of Variation	*df*	*F*	*p*
Appearance	1	0.373	0.544
Breathing	1	0.677	0.415
Smooth Motion	1	0.090	0.765
Appearance × Breathing	1	0.003	0.957
Appearance × Smooth Motion	1	0.090	0.765
Breathing × Smooth Motion	1	1.058	0.309
Appearance× Breathing × Smooth Motion	1	2.669	0.109
OrderID	1	0.918	0.343
Error	45		

Intention to Use

Source of Variation	*df*	*F*	*p*
Appearance	1	0.167	0.685
Breathing	1	5.267	0.026*
Smooth Motion	1	1.885	0.176
Appearance × Breathing	1	0.823	0.369
Appearance × Smooth Motion	1	0.175	0.678
Breathing × Smooth Motion	1	0.004	0.952
Appearance× Breathing × Smooth Motion	1	1.303	0.260
OrderID	1	0.011	0.916
Error	45		

Social Presence

Source of Variation	*df*	*F*	*p*
Appearance	1	0.109	0.743
Breathing	1	43.408	<.001*
Smooth Motion	1	2.948	0.093†
Appearance × Breathing	1	0.886	0.352
Appearance × Smooth Motion	1	0.024	0.877
Breathing × Smooth Motion	1	0.008	0.929
Appearance× Breathing × Smooth Motion	1	1.217	0.276
OrderID	1	1.025	0.317
Error	45		

Perceived Adaptability

Source of Variation	*df*	*F*	*p*
Appearance	1	0.160	0.691
Breathing	1	4.998	0.030*
Smooth Motion	1	0.512	0.478
Appearance × Breathing	1	0.408	0.526
Appearance × Smooth Motion	1	1.659	0.204
Breathing × Smooth Motion	1	0.023	0.881
Appearance× Breathing × Smooth Motion	1	0.564	0.456
OrderID	1	0.392	0.535
Error	45		

Trust

Source of Variation	*df*	*F*	*p*
Appearance	1	0.080	0.778
Breathing	1	0.025	0.876
Smooth Motion	1	2.817	0.100
Appearance × Breathing	1	0.222	0.640
Appearance × Smooth Motion	1	0.005	0.942
Breathing × Smooth Motion	1	0.004	0.949
Appearance× Breathing × Smooth Motion	1	0.201	0.656
OrderID	1	0.384	0.539
Error	45		

Perceived Enjoyment

Source of Variation	*df*	*F*	*p*
Appearance	1	0.321	0.574
Breathing	1	5.543	0.023*
Smooth Motion	1	0.302	0.585
Appearance × Breathing	1	0.108	0.744
Appearance × Smooth Motion	1	3.394	0.072†
Breathing × Smooth Motion	1	0.650	0.424
Appearance× Breathing × Smooth Motion	1	7.280	0.010*
OrderID	1	0.598	0.444
Error	45		

Table 3: Mean and standard deviation values for all questionnaire scales used in Study I.

	Appearance OFF					Appearance ON				
	Arcing OFF		Arcing ON			Arcing OFF		Arcing ON		
Breathing	*Mean*	*SD*	*Mean*	*SD*	**Cobot Perceptions**	*Mean*	*SD*	*Mean*	*SD*	*Breathing*
OFF	3.375	1.219	4.375	1.276	Godspeed: Anthropomorphism	3.758	1.268	4.192	1.212	OFF
ON	4.608	1.150	5.283	1.174		4.983	1.166	5.450	0.918	ON
OFF	3.625	1.019	4.313	1.138	Godspeed: Animacy	3.986	0.940	4.174	1.201	OFF
ON	4.604	1.021	5.354	0.959		5.063	1.103	5.528	0.986	ON
OFF	4.642	1.328	5.133	1.112	Godspeed: Likeability	5.258	1.224	5.075	1.364	OFF
ON	5.458	0.995	5.742	0.911		5.400	1.227	5.942	1.239	ON
OFF	4.642	0.976	5.050	0.935	Godspeed: Perceived Intelligence	4.867	1.016	4.808	1.342	OFF
ON	5.133	0.904	5.267	0.939		5.492	0.879	5.725	0.910	ON
OFF	5.333	1.167	5.250	1.180	Godspeed: Perceived Safety	5.188	1.325	5.000	1.482	OFF
ON	5.083	1.239	5.563	1.254		5.271	1.668	5.229	1.429	ON
					User Experience					
OFF	2.531	0.812	2.604	0.831	Anxiety	2.646	0.918	2.833	1.026	OFF
ON	2.510	0.785	2.490	0.858		2.750	0.804	2.698	1.043	ON
OFF	4.139	0.538	4.347	0.399	Attitude	4.167	0.645	3.972	0.884	OFF
ON	4.431	0.515	4.431	0.399		4.250	0.550	4.292	0.632	ON
OFF	3.979	0.634	4.229	0.551	Intention to Use	3.958	0.846	3.938	1.106	OFF
ON	4.208	0.833	4.271	0.722		4.167	0.761	4.354	0.714	ON
OFF	3.896	0.691	4.104	0.571	Perceived Adaptability	3.938	0.712	3.854	0.972	OFF
ON	4.063	0.665	4.146	0.429		4.083	0.504	4.083	0.747	ON
OFF	3.927	0.735	4.260	0.690	Perceived Enjoyment	4.219	0.677	3.854	1.223	OFF
ON	4.344	0.655	4.396	0.608		4.167	0.754	4.323	0.728	ON
OFF	3.542	0.698	3.760	0.610	Perceived Sociability	3.688	0.591	3.521	1.045	OFF
ON	3.885	0.784	3.948	0.638		3.896	0.821	4.042	0.670	ON
OFF	4.042	0.600	4.111	0.535	Perceived Usefulness	4.042	0.794	3.889	0.971	OFF
ON	4.125	0.588	4.125	0.448		3.944	0.693	4.097	0.865	ON
OFF	2.948	0.961	3.167	0.911	Social Presence	3.000	0.909	3.052	1.003	OFF
ON	3.615	0.818	3.656	0.787		3.667	0.820	3.927	0.782	ON
OFF	3.688	0.778	3.604	0.625	Trust	3.833	0.940	3.667	0.905	OFF
ON	3.750	0.834	3.604	0.794		3.729	0.967	3.646	0.994	ON

B STUDY II COMPLETE RESULTS

Table 4: ANOVA test results for data from measures of cobot perception [4] in Study II. "*" and "†" denote significant and marginal results, respectively.

Anthropomorphism

Source of Variation	*df*	*F*	*p*
Gaze	1	6.788	0.016*
Posture	1	1.875	0.184
Gaze × Posture	1	0.085	0.774
Error	23		

Perceived Intelligence

Source of Variation	*df*	*F*	*p*
Gaze	1	6.760	0.016*
Posture	1	0.024	0.879
Gaze × Posture	1	0.172	0.682
Error	23		

Animacy

Source of Variation	*df*	*F*	*p*
Gaze	1	8.522	0.008*
Posture	1	0.293	0.593
Gaze × Posture	1	0.069	0.796
Error	23		

Perceived Safety

Source of Variation	*df*	*F*	*p*
Gaze	1	0.137	0.714
Posture	1	0.074	0.788
Gaze × Posture	1	1.061	0.314
Error	23		

Likeability

Source of Variation	*df*	*F*	*p*
Gaze	1	3.459	0.076†
Posture	1	1.209	0.283
Gaze × Posture	1	0.287	0.598
Error	23		

Table 5: ANOVA test results for data from measures of user experience [13] in Study II. "*" and "†" denote significant and marginal results, respectively.

Anxiety

Source of Variation	*df*	*F*	*p*
Gaze	1	3.807	0.063†
Posture	1	0.010	0.920
Gaze × Posture	1	0.025	0.876
Error	23		

Perceived Sociability

Source of Variation	*df*	*F*	*p*
Gaze	1	3.417	0.077†
Posture	1	1.228	0.279
Gaze × Posture	1	0.039	0.845
Error	23		

Attitude

Source of Variation	*df*	*F*	*p*
Gaze	1	3.928	0.060†
Posture	1	2.704	0.114
Gaze × Posture	1	0.164	0.689
Error	23		

Perceived Usefulness

Source of Variation	*df*	*F*	*p*
Gaze	1	6.148	0.021*
Posture	1	2.188	0.153
Gaze × Posture	1	0.013	0.911
Error	23		

Intention to Use

Source of Variation	*df*	*F*	*p*
Gaze	1	1.525	0.229
Posture	1	0.052	0.822
Gaze × Posture	1	0.020	0.888
Error	23		

Social Presence

Source of Variation	*df*	*F*	*p*
Gaze	1	21.231	<.001*
Posture	1	5.767	0.025*
Gaze × Posture	1	0.506	0.484
Error	23		

Perceived Adaptability

Source of Variation	*df*	*F*	*p*
Gaze	1	8.684	0.007*
Posture	1	3.599	0.070†
Gaze × Posture	1	0.008	0.931
Error	23		

Trust

Source of Variation	*df*	*F*	*p*
Gaze	1	0.148	0.704
Posture	1	0.033	0.858
Gaze × Posture	1	0.676	0.420
Error	23		

Perceived Enjoyment

Source of Variation	*df*	*F*	*p*
Gaze	1	4.285	0.050†
Posture	1	0.034	0.855
Gaze × Posture	1	0.037	0.850
Error	23		

Table 6: Mean and standard deviation values for all questionnaire scales used in Study II.

		Posture OFF		Posture ON	
Cobot Perceptions	*Gaze*	*Mean*	*SD*	*Mean*	*SD*
Godspeed: Anthropomorphism	OFF	3.308	1.565	3.633	1.439
	ON	4.167	1.634	4.383	1.350
Godspeed: Animacy	OFF	3.424	1.608	3.569	1.296
	ON	4.368	1.634	4.424	1.308
Godspeed: Likeability	OFF	4.433	1.536	4.617	1.547
	ON	5.075	1.632	5.425	1.474
Godspeed: Perceived Intelligence	OFF	4.358	1.128	4.417	1.226
	ON	5.142	1.241	5.042	1.220
Godspeed: Perceived Safety	OFF	5.188	1.594	5.083	1.679
	ON	5.125	1.610	5.354	1.652
User Experience					
Anxiety	OFF	2.708	0.803	2.729	0.730
	ON	2.375	0.837	2.375	0.734
Attitude	OFF	3.889	0.797	3.722	0.832
	ON	4.181	0.606	4.083	0.737
Intention to Use	OFF	3.729	0.872	3.729	0.834
	ON	4.000	0.897	3.958	0.871
Perceived Adaptability	OFF	3.417	0.761	3.583	0.893
	ON	3.917	0.545	4.104	0.510
Perceived Enjoyment	OFF	3.521	0.831	3.521	0.844
	ON	3.938	0.681	3.979	0.872
Perceived Sociability	OFF	3.219	0.928	3.354	0.915
	ON	3.729	0.900	3.823	0.845
Perceived Usefulness	OFF	3.611	0.772	3.722	0.784
	ON	3.944	0.686	4.028	0.564
Social Presence	OFF	2.240	0.940	2.396	0.947
	ON	3.094	0.932	3.448	0.875
Trust	OFF	3.438	0.936	3.521	0.994
	ON	3.625	0.947	3.500	1.011