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# Cognitive Neuroscience and Robotics: A Mutually Beneficial Joining of Forces

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**Abstract—** This paper describes an ongoing interdisciplinary collaboration between robotics and human cognitive neuroscience research. We argue such research is beneficial to both disciplines and can be viewed a win-win. Not only it is important to understand the human factors in human-robot interaction, collaborations with robotics can also help cognitive scientists answer questions about human brain and behavior, and take steps toward understanding how the human brain enables some of our most important skills such as action understanding, social cognition, empathy, and communication.

*Social robotics, neuroimaging, fMRI, uncanny valley*

## I. INTRODUCTION

From paleolithic statues of goddesses to modern horror stories (e.g., Frankenstein), humans have long been preoccupied with creating other entities in their likeness. Advances in technology now allow us to create increasingly

realistic and interactive humanoid agents. Lifelike humanoid robots are becoming commonplace; and assistive technologies are changing the face of education and healthcare [1,2]. Research on how humans perceive, respond to and interact with these agents is therefore increasingly important. However little is understood about human social cognition in this new, wider context. An interdisciplinary perspective on HRI is especially important, since this field will impact issues of public concern in the near future, for example in domains such as education and healthcare [3-5]

Our research brings together robotics with cognitive neuroscience to explore how humans perceive, respond to, and interact with others, including artificial agents, and specifically, robots. The research program is interdisciplinary, spanning the biomedical and social sciences, technology, science and engineering. Neuroscience and psychology research exploring human robot interaction (HRI) can make valuable contributions to robotics. Conversely, experiments in collaboration with roboticists can help advance neuroscience by allowing us to ask

new questions, or control parameters we cannot manipulate in biological systems.

The goal of this research program is to both improve our understanding of how the human brain enables social cognition, and to help engineers and designers in developing interactive agents that are well-suited to their application domains, as well as to the brains of their creators.

## II. ACTION PERCEPTION AND ROBOTICS

In primates, the perception of body movements is supported by network of lateral superior temporal, inferior parietal and inferior frontal brain areas. Here, we refer to this network as the action perception system, or APS (Fig. 1). Two of the areas within the APS, (PMC and IPL) contain *mirror neurons* in the macaque brain [6]. Mirror neurons respond not only when a monkey executes a particular action, but also when it observes another individual perform the action. For instance a mirror neuron that fires as the monkey cracks a peanut, can also fire as the monkey observes someone else crack a peanut. It is thought that a similar system underlies action perception in the human brain [7-10]. Some researchers have argued that in addition to subserving action processing, the APS helps in linking “self” and “other” in the brain, and thus may constitute a basis for social cognition [6].

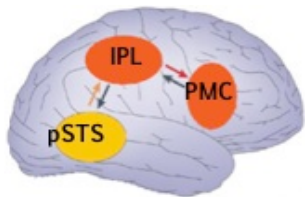


Figure 1: Schematic of the Action Perception System (APS), consisting of posterior Superior Temporal Sulcus (pSTS), Inferior Parietal Lobule (IPL), and Premotor Cortex (PMC). Figure adapted from [10].

The finding that the visual perception of another entity automatically engages the observers’ own motor system has important implications for the field of human-machine interaction. It would be fair to say that in the nervous system, simply seeing another agent automatically engages interaction.

The APS has received intense interest from neuroscientists in the last decade and a half, and we can now use the accumulated knowledge in this field to study how the human brain supports HRI. Conversely robotics can help research on the human brain by allowing us to test functional properties of the APS and other brain areas. For example, we may ask, during interactions with robots, does the brain rely on the same or distinct processes as with interactions with humans?

Due to the presence of mirror neurons, the neural activity in PMC and IPL regions during action perception is often interpreted within the framework of “simulation”: A visually perceived body movement is mapped onto the perceiving agent’s sensorimotor neural representations and “an action is understood when its observation causes the motor system of the observer to ‘resonate’”[11]. But what are the boundary conditions for ‘resonance’? What kinds of agents or actions

lead to the simulation process? Is human-like appearance important? Is human-like motion?

On the one hand, it seems reasonable that the closer the match between the observed action and the observers’ own sensorimotor representations, the more efficient the simulation will be. In support for this, the APS is modulated by whether the observer can in fact perform the seen movement [12]. The appearance of the observed agent may be additionally important [13, 14].

On the other hand, human resemblance is not necessarily always a positive feature in robots. The “uncanny valley” hypothesis has proposed that as a robot is made more human-like, the reaction to it becomes more and more positive, until a point is reached at which the robot becomes oddly repulsive [15]. While this phenomenon is well known to roboticists and computer animators, there is little scientific evidence in favor of or against it [16-21].

Robots can have nonbiological appearance and movement patterns – but at the same time, they can be perceived as carrying out recognizable actions. Is biological appearance or biological movement necessary for engaging the human Action Perception System (APS)? Robots can allow us to ask such questions and to test whether particular brain areas are selective or sensitive to the presence of a human, or an agent with a humanlike form, or respond regardless of the agent performing the action.

There is a small neuroscience literature on the perception of artificial agents, including robots [22-25]. Unfortunately, the results are highly inconsistent. Many studies had used toy robots or very rudimentary industrial robot arms, so the results were not informative regarding state-of-the-art humanoid robots. Furthermore, the roles of humanlike appearance or motion were not explored in previous work. We used neuroimaging (functional Magnetic Resonance Imaging (fMRI)) along with a method called Repetition Suppression (RS) to overcome limitations of previous work [26], and studied this question with well-controlled stimuli developed in by an interdisciplinary team [27].

## III. NEUROIMAGING STUDY: PERCEPTION OF ROBOT ACTIONS

We performed fMRI as participants viewed video clips of human and robotic agents carrying out recognizable actions. fMRI is a powerful method that allows imaging the activity of the live human brain non-invasively and has revolutionized

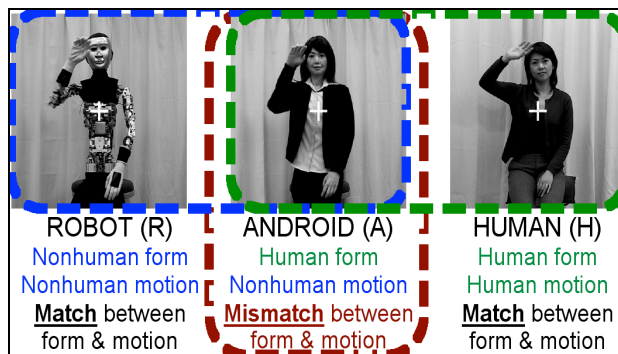


Figure 2: Stills from the videos depicting the three agents (R, A, H) and the experimental conditions (form and motion) they represent.

neuroscience, though as with any method, there are limitations (e.g., no ferromagnetic materials, limited interactivity).

We used Repliee Q2, an android developed at Osaka University in collaboration with Kokoro Ltd [28, 29]. Repliee Q2 has a very human-like appearance (Fig. 2, Android (A)). In order to achieve this, the robot's face was modeled after an adult Japanese female (Fig. 2, Human (H)). Repliee Q2 can make facial expressions, as well as eye, head, upper limb, and torso movements. It has 42 degrees of freedom (d.o.f.) in its movements, with 16 d.o.f. in the head. With very brief exposure times, Repliee Q2 is often mistaken for a human being, but more prolonged exposure and interaction can lead to an uncanny valley experience [29].

Importantly, Repliee Q2 was videotaped both in its original human-like appearance (A) and in a modified, more mechanical appearance (Fig. 2, Robot (R)). In this latter condition, we removed as many of the surface elements as possible in order to reveal the electronics and mechanics underneath. The silicone covering the face and hands could not be removed, so we used a custom mask and gloves to cover these areas. The end result was that the robot's appearance became obviously mechanical and nonhuman. However, since the A and R are in fact the same robot, the motion kinematics are the same for these two conditions.

There were thus three agents: human (H), robot with human form (A), and robot with nonhuman form (R). H and A are very close to each other in form, both with humanlike form, whereas R has nonhuman form. In terms of the movement, H represents truly biological motion and A and R are identical, both with mechanical kinematics. Using fMRI and RS, we explored whether the human brain would display specialization for human form (similar responses for A and H, and different for R) or motion (similar responses for R and A, and differential responses for H). Another possibility was for RS responses not to reflect biological form or motion per se, but instead pattern like the uncanny valley. In this scenario, the RS responses to the H and R would be similar to each other, even though these two agents are divergent from each other in both form and movement.

The articulators of Repliee Q2 were programmed over several weeks at Osaka University. The same movements were videotaped in both appearance conditions (R and A). The human, the same female adult to whom Repliee Q2 was designed to resemble, was asked to perform the same actions as she naturally would. All agents were videotaped in the same room and with the same background. A total of 8 actions per actor were used in the experiment (e.g., drinking water from a cup, waving hand). 20 adults participated in the fMRI experiment. Participants had no experience working with robots. Each was given exactly the same introduction to the study and the same exposure to the videos prior to scanning since prior knowledge can affect attitudes to artificial agents differentially [30]. Before the experiment, subjects were told that they would see short video clips of actions by a person, or by two robots with different appearances and were shown all the movies in the experiment. By the time scanning started, participants were thus not uncertain about the robotic identity of the android.

Scanning was conducted at the Wellcome Trust Centre for Neuroimaging, in London, UK using a 3T Siemens Allegra scanner and a standard T2\* weighted gradient echo pulse sequence. During fMRI, subjects viewed the stimuli projected on a screen in the back of the scanner bore through a mirror placed inside the head coil. There were blocks of 12 videos, each preceded by the same video (Repeat) or a different video (Non-repeat), which allowed us to compute the RS contrast (Non-repeat > Repeat). Every 30-seconds, they were presented with a statement about which they would have to make a True/False judgment (e.g., "I did not see her wiping the table"). Since the statements could refer to any video, subjects had to be attentive throughout the block. Data were analyzed with SPM software (<http://www.fil.ion.ucl.ac.uk/spm>).

RS differed considerably between the agents (Fig. 3). All agents showed RS in temporal cortex near the pSTS. For A, extensive RS was found in additional regions of temporal, parietal and frontal cortex (Fig. 3b).

In the left hemisphere, lateral temporal cortex responded to H and A, but not to R. The specific location of this activation corresponds to extrastriate body area (EBA), a region that responds strongly during the visual perception of the body and body parts [31]. Our data showed that robotic appearance can weaken the RS response in the EBA.

Aside from the left EBA, we did not find evidence for APS coding for human-like form or motion per se. Instead, for the android, whose form is humanlike, but its motion is mechanical, increased responses were found in a network of cortical areas. This was most pronounced (and statistically significant) in the IPL [27], one of the nodes of the APS (Fig. 3b, circled areas).

But why would there be an area of the brain highly selective for androids? This response pattern brings to mind the uncanny valley – except, rather than valleys, we measured “hills” in the neural responses, in the form of increased RS. A framework within which to interpret these data is the predictive

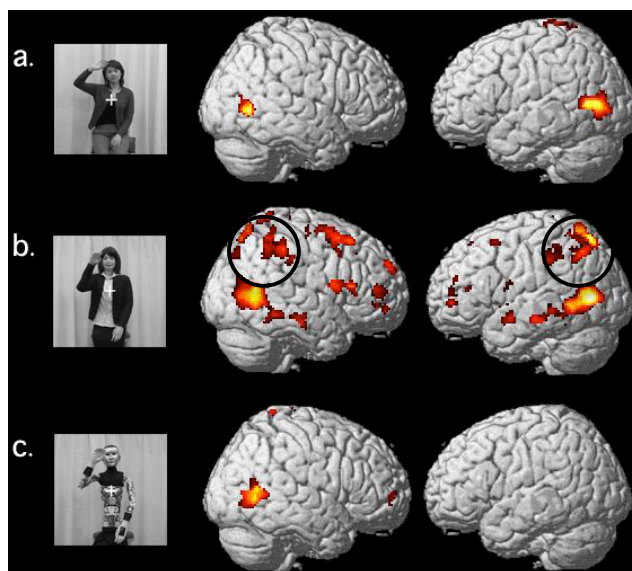


Figure 3. Repetition suppression (RS) results for the Human (a), Android (b), and Robot (c). (Non-repeat > Repeat at  $t \geq 8.86$ ,  $p < 0.05$  with False Discovery Rate (FDR) correction for multiple comparisons, with a cluster size of at least 30 voxels). Figure adapted from [27].

coding account of cortical computation [32-34]. Predictive coding is based on minimizing prediction error among the levels of a cortical hierarchy (e.g. the APS). More specifically, during the perception of H and R, there is no conflict between form and motion of the agent. H appears human and moves like a human. R appears mechanical and moves mechanically. For A on the other hand the agent’s form is humanlike, which may result in a conflict when the brain attempts to process and integrate the movement of the agent with its form. This conflict leads to the generation of a prediction error, which is propagated in the network until the predictions of each node are minimized. During this process, we can measure the prediction error in the fMRI responses. It is not possible from the current data to know the exact neural sources, the directionality, and the time course of error propagation, but it is clear that the cortical network is engaged more strongly during the perception of A compared with the agents that lead to less prediction error (R and H). Furthermore, the effect is largest in parietal cortex, which is the node of the network that links the posterior, visual components of the APS and the frontal, motor components [27, 35].

In summary, in this interdisciplinary study, we found that a robot with highly humanlike form is processed differentially compared with a robot with a mechanical form, or with an actual human. These differences are found in a network of brain areas, most prominently in parietal cortex [27]. We propose these “hills” in the brain activity reflect the prediction error that is propagated in the system. The uncanny valley may thus arise from processing conflicts in the APS, and the resultant error signals, which can in turn be measured using fMRI [34].

#### IV. OTHER EXAMPLES AND FUTURE DIRECTIONS

We have described a neuroimaging study in order to explain how such work can inform both neuroscience and robotics. In another fMRI experiment, we have explored the perception of emotional facial expressions of humans and

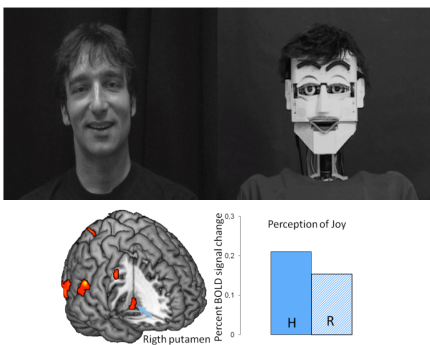


Figure 4. Subjects viewed emotional facial expressions performed by a human and a robot. fMRI analyses revealed that some regions of the brain that are important for processing emotional stimuli showed reduced response to the robot. Figure adapted from [36].

robots [36]. The methods were similar to the study described above, with subjects viewing the stimuli in the MRI scanner. They viewed close-up videos a human and a robot performing emotional facial expressions (e.g., joy, Fig 4). Subjects were asked to perform two tasks: one requiring them to make

judgments about the emotions of the stimuli, the other about the motion characteristics of the stimuli.

In brain areas important for processing emotional stimuli, activity was reduced in response to robot expressions compared with human expressions, suggesting emotional resonance may be reduced towards a clearly nonhuman, mechanical agent. Consistent with this, in the action perception study described above, amygdala (a key brain area for emotion processing) response to the robot was less than that for the android and human conditions (although this effect was just short of statistical significance [27]). In the PMC node of the APS on the other hand, activity depended not only on the agent, but also on the task: higher activation was found during viewing humans when attention was directed towards movement, but higher activity for the robot was found when attention was directed towards the emotional content of the action. Altogether, these results suggest that some emotion processing areas show reduced responses for robots, but that robots can elicit motor resonance, especially when the subjects attend the emotional content of the stimuli.

These studies are only a beginning. In future work, we can utilize animation in order to modulate form and motion parameters more precisely (although this is likely to lead to a decrease in presence [37]). We will also use other neuroimaging and psychological methods in addition to, or in conjunction with fMRI. We are currently using magnetoencephalography (MEG) and electroencephalography (EEG), both of which allow for imaging brain activity with high temporal resolution so that we can study the temporal dynamics of action processing. EEG also allows neuroimaging in more dynamic and interactive settings compared with fMRI [38] and through Brain Computer Interface (BCI) systems,, can be used in the evaluation of new robots [39].

#### V. DISCUSSION

Humanoid robots are increasingly part of our daily lives [1-5]. With application in domains such as healthcare, education, communications, entertainment, and the arts, exploring human factors in the design and development of artificial agents is ever more important. This will require an interdisciplinary approach, to which we have contributed new data from cognitive neuroscience.

Using cognitive neuroscience, we have been able to suggest an interpretation for the classic anecdotal reports of the uncanny valley hypothesis. The uncanny valley has many potential dimensions [15, 16, 40]. While our experiments were not designed in an optimum fashion to “explain” the uncanny valley, the results suggest an intriguing link between the phenomenon, and brain responses in the APS. As shown in Figure 2, the android condition features a mismatch between form and motion. In a predictive coding, the android is not predictable: an agent with that form (human) would typically not move mechanically as Repliee Q2 does. When the nervous system is presented with this unexpected combination, a propagation of prediction error may occur in the APS. We suggest this framework may contribute to an explanation for the uncanny valley and future experiments will test this hypothesis.

Using robotics, we were able to answer questions regarding the neural basis of action and emotion perception. We were able to test functional properties of human action perception system (APS) as well as emotion processing networks in the brain. These findings help shed light on how our brains enable social cognition, an important skill, and part of what it means to be human.

Interdisciplinary collaboration between cognitive neuroscience and robotics can be a win-win for both sides. Joining forces, we can answer questions in both disciplines, and create the HRI of tomorrow.

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