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Or Yizhar
Amber Maimon
maimon.amber@gmail.com
Zohar Tal
Iddo Yehoshua Wald
Hadas Erel
Doron Friedman
Oren Zuckerman
Amir Amedi

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Neural Correlates of Perceiving Animacy in Robotic Objects

Or Yizhar[1,2†], Amber Maimon[1,3*†], Zohar Tal[5†], Iddo Yehoshua Wald[1,4], Hadas Erel[6], Doron Friedman[7], Oren Zuckerman[6], Amir Amedi[1]

[1*]The Baruch Ivcher Institute for Brain, Cognition, and Technology, Baruch Ivcher School of Psychology, Reichman University, Herzliya, Israel.
[2]Max Planck Institute for Human Development, Research Group Adaptive Memory and Decision Making, Germany, Berlin, Germany.
[3]Computational Psychiatry and Neurotechnology Lab, Department of Brain and Cognitive Sciences, Ben Gurion University, Be'er Sheva, Israel.
[4]Digital Media Lab, Department of Mathematics and Computer Science, University of Bremen, Bremen, Germany.
[5]Proaction Laboratory, Faculty of Psychology and Educational Sciences, University of Coimbra, Coimbra, Portugal.
[6]Media Innovation Lab, Sammy Ofer School of Communications, Reichman University, Herzliya, Israel.
[7]Advanced Reality Lab, Sammy Ofer School of Communications, Reichman University, Herzliya, Israel.

*Corresponding author(s). E-mail(s): maimon.amber@gmail.com;
Contributing authors: or.yizhar@gmail.com; zoharit@gmail.com; wald@uni-bremen.de; hadas.erel@runi.ac.il; doronf@runi.ac.il; oren.zuckerman@runi.ac.il; amir.amedi@runi.ac.il;
†These authors contributed equally to this work.

Abstract

The prevalence of robots in modern society calls for gaining a fundamental understanding of the underlying principles of human-robot interaction. In particular, we need to understand how people perceive robots and how different physical and social characteristics affect this perception. Here, we examined the neural correlates of observing simple gestures performed by a non-humanoid social robot, focusing on the role of the Ventral Occipitotemporal (VOT) cortex in processing perceived animacy. Our results reveal that a broad bilateral cortical network is activated, comprising areas related to action observation, the social brain, and the visual cortex, including the VOT. We also found a correlation between the level of neural responses in the VOT, especially in the left hemisphere, and individual animacy ratings of the robotic object. This correlation provides a physical basis for such subjective ratings. These results suggest a complex representation of perceived animacy across the lateral-medial axis of the VOT, explained by spatial cortical location and the amplitude of neural responses. Furthermore, we discuss the implications of these findings for understanding how people perceive robots, their behaviors and intentions, which are crucial for developing social robots that can interact with humans more naturally.

Keywords: HRI, human-robot interaction, animacy, MRI, non-humanoid robots, neural correlates

1 Introduction

Today robots are prevalent in many industries and sectors. From medicine, where robots are involved in disease diagnosis and even surgical procedures [1] to education, where robots take part in delivering learned material, among other roles [2] and even to our domestic household lives, lending a hand in cleaning [3], cooking [4], and pet care [5] among other household tasks. Robots are involved in an ever-growing variety of crucial human activities and behaviors, they can operate remotely in faraway environments or conduct factory work, and even be involved in entertainment or similar domains in which they interact socially with humans. It is not unlikely that we will see an increasing number of physical robots in everyday life in the near future, with various types of Human Robot Interaction (HRI) 'relationships' emerging. Such new and diverse relationships raise important questions on the human perception of robot behavior, which are addressed by a growing literature of HRI research [6–8]. Robots are already becoming part of our everyday lives, and many robots today are designed to address more than functional needs. In the current study, we focus on the social aspects of HRI rather than the practical ones that are more commonly explored.

1.1 Robotic duality and animacy

Robots present special cases of machines that exhibit human-like behavior and participate in or supplement human tasks. The duality is particularly pertinent since there is ever increasing autonomy in the capacity of robots to perform numerous tasks, from robots that autonomously collaborate to play soccer [9], to robotic personal assistants [10], all the way to autonomous robot surgeons [11]. This results in a paradoxical duality of immediate social interpretation during interaction with robots, alongside conscious awareness of the robot's identity as a machine. In fact, previous work indicates that interactions with autonomous machines trigger social and emotional interpretations. According to the Computers Are Social Actors (CASA) framework [12], humans treat or relate to machines, among them robots, as they treat and relate to other people. People have been shown to apply social rules to their interactions with computers/machines, indicating that the interaction is inherently social [12]. This is particularly interesting with non-humanoid robots that may have a mechanical appearance, but are still perceived as social entities [13, 14].

Many theories commonly emphasize the "sameness" between humans and robots with reference to social robots, be it with respect to their gestures, their voices, and other characteristics designed to interact similarly to human interaction [15]. The "otherness" approach differs phenomenologically and experientially and adopts a contrasting viewpoint. Recently, there has been a growing appreciation for the notion of "otherness", an aesthetic categorization that values the differences between social robotic objects and humans [16–19].

This growing appreciation for robotic "otherness" is in line with the understanding that today's robots do not necessarily need to be human-like, with the over-resemblance to humans even being correlated with the eerieness and unease of interaction exhibited by the uncanny valley effect [20]. It can be claimed that non-humanoid robots are likely to be much more pervasive, as they can be designed directly for their intended functions without limitations related to human appearance. In addition, they are inexpensive, easy to use, and readily available. Although non-humanoid robots do not directly mimic human behavior or appearance, their interaction with humans typically leads to consistent social experiences [13, 14, 21], making them a unique and interesting case to study in behavior and neuroimaging.

1.2 Responses to non-humanoid vs. humanoid robots

A key question in the field of HRI is how different robotic properties facilitate human interaction [22]. A feature considered important in this respect in the design of robotic agents is their level of animacy, which is relevant to both perception and meaningful interactions [23]. We interpret an

object's animacy as related to its 'liveliness', in the sense that it has a mental state that can induce self-propelled behavior [24, 25]. There are three main cues by which we categorize an object as animate: human-like surface features such as faces or limbs [23], movement patterns that resemble biological motion [23], and purposeful movements that are directed toward a goal or express some form of communicative intention [22, 26]. This definition is not limited to humanoid robots that have human appearance and directly mimic human behavior. Previous studies indicated that robotic objects designed as familiar or abstract objects are also perceived as entities [21, 27]. The autonomous movements of even very simple robotic objects are commonly perceived as consistent social cues that can greatly facilitate interaction with them [14, 21, 27].

In recent years, there has been growing interest in understanding the underlying processes that guide human social interactions with robots [28]. While most of these studies focus on behavioral measures, meaningful insights can also be derived by identifying the neural mechanisms underlying social HRI using EEG [29] and neuroimaging [30]. Neuroimaging studies have previously been conducted to explore some of the neural correlates involved in HRI. For example, comparing neural responses to humanoid robotic agents in perceptual or mentalizing tasks and neural responses to humans [31–34]. It has been shown that visual perception of humanoid robots can induce activity in cortical networks typically associated with social cognition (see Wiese et al. [22] for a review). This raises the question of whether it is the human-like appearance and features of humanoid robots that account for such similarities in brain activity or perhaps it is their autonomous behavior?

An fMRI study by Gazzola et al. [35] compared neural activations induced by the observation of actions performed by a human or a non-humanoid robot. They presented videos of simple and complex movements performed by a human actor or an industrial robot. Importantly, the kinematics of the robot were characterized by only one degree-of-freedom motion and constant velocity, thus clearly nonbiological. However, the authors found the same neural activation elicited by observing both human and robotic actions. Tai et al. [36] studied mirror neuron system activation following the presentation of robotic human-like arm actions characterized by non-biological kinematics. Their findings suggest that such actions activate the human mirror neuron system, even though their kinematics do not exactly match human motor programs, but only under the condition that the action goal is understood.

1.3 Animacy in the brain

Parallel to these studies focused on HRI, neuroimaging studies have been conducted exploring perceived animacy, more generally construed. These studies have associated animal processing with the occipital and temporal cortical areas, including the posterior superior temporal sulcus (pSTS) and the ventral occipitotemporal cortex (VOT), which is known for its involvement in high-level processing and categorization of visual stimuli [37–40]. Recent studies suggest that animacy is one of the driving factors of VOT functional organization, so that inanimate objects are represented in medial areas, while animate categories are represented in lateral areas in a continuous gradient [39, 41–43]. For example, a work by Sha and colleagues investigated the functional representation of animacy characteristics in the VOT and found that neural responses to visual images of animals with low animacy (such as insects) were similar to those of nonliving objects rather than to other living animals with higher animacy [39]. Anatomically, the fusiform gyrus, which is part of the VOT, is divided by the mid-fusiform sulcus (MFS) into medial and lateral areas. The MFS also serves to delineate the border between different cytoarchitectonic areas (areas that differ in their cellular composition). Based on cytoarchitectonic mapping, the fusiform gyrus is divided into four regions of different patterns of neuronal organization and density within the fusiform gyrus (FG1-4) [44]. The MSF has also been suggested to mark a transition zone between functional domains within the VOT, such as the separation between face-selective areas and place-selective areas (see Figure 1) [45–49].

1.4 The robotic object used in the study

This study employs an animated and expressive non-humanoid social robotic object [27]. It was designed as a small desktop robot, reminiscent of

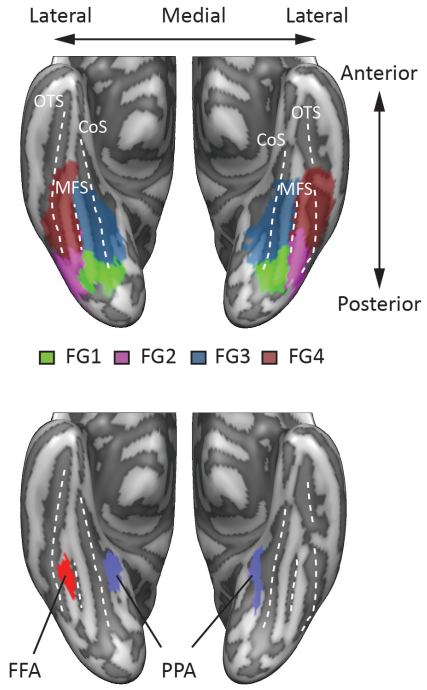

Fig. 1 Anatomical and functional characteristics of the VOT: Macroscale anatomical markers that characterize the VOT - Occipitotemporal Sulcus (OTS); Mid Fusiform Sulcus (MFS); Collateral Sulcus (CoS). Top image: FG1-4 cytoarchitectonic division of the fusiform gyrus as specified in previous literature. Bottom image: Peak activation for houses and faces stimuli in relation to the macroscale anatomical markers as indicated by the visual localizer scan - Fusiform Face Area (FFA); Parahippocampal Place Area (PPA).

a desk lamp, that can perform a set of carefully defined physical movements that are combined to create various gestures (see Figure 2). The robotic object was such designed with the aim of eliciting affective responses from humans in its surroundings and has been employed in numerous HRI studies. The motivation for using this particular robotic object centered around its being explicitly designed and utilized in research as an "empathy object", defined as "interactive robotic devices that reflect aspects of the human-human interaction around them, in real-time, through subtle physical gestures" [50]. Our belief is that in contrast to the robotic object's inanimate form, its abilities in displaying "empathy" using gestures, relate to elements of perceived animacy such as having a mental state that propels behavior, biological motion, purposeful movement, and expression of communicative intent. In the past, this robotic object was used in studies where it served as a key factor in promoting calmness in interpersonal conversations [50], supplementing the quality of emotional support [51], conveying humor as a means to reduce social awkwardness [52, 53] and improving people's sense of security [54]. Some research has also indicated that the robot's gestures can be interpreted as indicating interest and care [54]. The robot's movements were the result of an extensive animation study that developed in detail the robot's appearance with respect to its movement. This is in line with the approach of designing robots specifically with movement in mind [55]. The aim of the animation study was to provide the robotic object with organic movement patterns that resemble those of living creatures such as fish or invertebrates (see Hoffman et al. [55], for more information).

1.5 The present study

The possibility of an animacy continuum in the VOT raises questions about the cortical representation of different robotic agents along this axis. For example, how are non-humanoid robots represented along this continuum? Although humanoid robots have been shown to activate the lateral areas of the VOT (like the fusiform face area FFA during robotic facial expression) [31], that is, high on the 'animate' continuum, it is not yet clear whether this would also be the case for non-humanoid robots. Would their lack of biological features register these as inanimate objects, represented on the medial parts of the VOT? To explore and answer these questions, in this study, we employed a video study methodology in which we presented robotic gestures to participants.

As described above, the mere physical attributes of the robotic object used in the current study, are those of an ordinary desk lamp (an inanimate object). However, its autonomous responsive movements which have been shown to be associated with an emotional interpretation, are reminiscent of those of a living creature. In the present study, this ambiguity between the robotic object's physical appearance and its movement lends to different animacy perceptions of the robotic object, corresponding to a high degree of intersubject variation, meaning that the same visual stimuli of the robotic object resulted in

different subjective animacy ratings. This inability raised the question as to forecasting how the perception of the robotic object will be mapped on the functional medial-lateral dimension of the VOT. Thus, our model enables us to study the interaction between the perceived animacy of a robot and its representation in the brain. Will the perception of this robotic object be mapped to areas correlated with inanimate objects due to its appearance? Or areas correlated with living creatures due to its autonomous responsive movements? To answer these questions, we conducted an fMRI experiment with repeated sessions of various robotic gestures, as well as a session of known visual localizers and a behavioral questionnaire (described in detail in the Materials and methods section). We implemented cortex-based alignment analysis to localize neural activation along the medial-to-lateral organization of the VOT and compared the results with anatomical and functional markers within this area.

2 Materials and methods

2.1 Subjects

In the current study, a total of 13 healthy right-handed subjects (9 women, 4 men), aged 24-40 (mean age 29.9 SD 6.56), with no neurological deficits were scanned. The Ethics Committee of the Hadassah Medical Center approved the experimental procedure and written informed consent was obtained from each subject prior to the scanning procedure. The subjects received compensation of 150NIS for their participation.

2.2 Experiment and stimuli

In this experiment, we examined the neural response to visual gestures of the non-humanoid robotic object. Visual stimuli were presented using a PC through an LCD projector (NeuroNordicLabs) on a translucent screen. Subjects viewed the grayscale stimuli through a tilted (45°) mirror positioned above the forehead. Participants were presented with a set of 12 prerecorded videos with a range of gestures performed by the robotic object, and mirrored versions of the same videos for a total of 24 stimuli. There were two repetitions of each of the videos, such that a run consisted of 48 stimuli, with a total of two runs performed in each session. The starting frame of each video showed a non-moving object on the far side of the screen (a stationary plant) with the robotic object in the center of the screen (Figure 2).

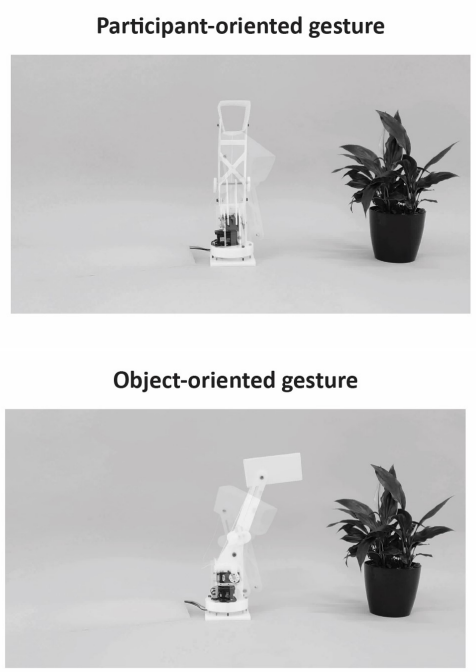

Fig. 2 Experimental setup: Representative snapshots of the robotic gesture videos presented. In the top image, the robotic object moves toward the participant, and in the bottom one, toward the plant.

Each video consisted of a single robotic object gesture characterized by its movement towards the object to the side of the screen, towards the participant to the center of the screen, or a gesture that ends between the participant and the object. The robot remained in the same location in all videos. In order to draw more general conclusions about viewing the gestures of the non-humanoid robotic object, it was paramount to ensure that the results were not biased toward a particular movement or viewing angle. This prevents, for example, circumstances in which a gesture towards the participant would elicit a unique or different response than a gesture directed towards an object. By presenting a range of different gestures that were subsequently analyzed together, our objective was to control for the possible effects of viewing angle or communicative intention biases. Each gesture

lasted 4.5s (3 TRs), and the videos were grayscaled to further reduce visual biases. To control for fatigue, participants were asked to perform a 1-back task, in which they were required to respond within 1.5s post-stimulus whether the last two stimuli were identical or different. The experimental setup followed a slow event-related design, with a pseudo-randomized order of stimuli presentation, and a period of rest (7.5s) after each stimulus.

As a visual localizer, we used a block design to localize five areas of functional visual categories in the extrastriate cortex: objects, body parts, faces, houses, and textures. Nine images from the same visual category were presented in each epoch; each image was presented for 800ms, followed by a 200ms blank screen. Each epoch lasted 9s followed by a 6s blank screen. A central red fixation point was present throughout the experiment. Each experimental condition was repeated 7 times, in pseudorandom order. During the experiment, one or two consecutive repetitions of the same image occurred in each epoch. The participants' task was to covertly report whether the presented stimulus was identical to the previous stimulus or not.

To measure behavioral attitudes towards the robotic object, we used the Godspeed questionnaires proposed by Bartneck et al. to assess human-robot interaction [56]. The standardized questionnaire quantifies the participants' perception of the interaction on five different subscales, of which we chose three that were determined to be most suited for our experiment and the characteristics of the robotic object: likeability (5 items), anthropomorphism (5 items) and animacy (6 items). Each item in each category is scaled semantically between two opposites on discrete points from one to five (e.g. animacy - artificial opposite to lifelike). Participants had no prior interaction with the robot and were naïve regarding its appearance, motivation, intent, and ways of communication. Participants were not explicitly informed that they were viewing a "robot", rather the robotic object was referred to simply as an "object" by experimenters.

2.3 Functional and anatomical MRI acquisition

High resolution three-dimensional anatomical volumes were collected using an MP-RAGE sequence. Typical parameters were: Field of View (FOV) - 23cm (RL) x 23cm (VD) x 17cm (AP); Foldover axis: RL, data matrix: 160 x 160 x 144 zero filled to 256 in all directions (approximate 1mm isovoxel native data), TR/TE=9ms/6ms, flip angle = 8°. BOLD fMRI measurements were obtained in a whole-body, 3–T Magnetom Skyra scanner (Siemens, Germany). The scanning session included anatomical and functional imaging. The functional protocols were based on multi-slice gradient echoplanar imaging (EPI) using Siemens's 20-channel head matrix coil. Functional data were collected under the following timing parameters: TR = 1.5s, TE = 30ms, FA = 70°, image matrix = 76 x 76, FOV = 192 with an in-plane resolution of 2.52mm. 51 axial slices with a thickness of 2.5mm and a 0mm gap were acquired for full coverage of the cortex. The first ten images were excluded from the analysis because of non-steady-state magnetization.

2.4 Preprocessing of fMRI data

Data analysis was performed using the BrainVoyager 20.6 software package (Brain Innovation, Maastricht, The Netherlands). Functional magnetic resonance data were corrected for slice timing and head motion. No functional data showed translational or rotational motion exceeding 2mm in any given axis or had spike-like motion of over 1mm in any axis. Pre-processing also included high-pass filtering the time course of each voxel. The low-frequency cutoff was set to two cycles per run that are regressed out to create a filtered time course. Cortical reconstruction included white matter segmentation using a grow region function embedded in BrainVoyager software package. The remaining cortical surface was then inflated. For group analysis, the functional data was spatially smoothed (spatial Gaussian smoothing, FWHM = 6mm) to overcome inter-subject anatomical variability. The functional and anatomical data sets for each subject were normalized to a standardized MNI space. Group results were aligned with a 3D cortical reconstruction of an MNI normalized brain (FreeSurfer's FsAverage brain).

2.5 Cortex-based alignment

To register activation maps with known anatomical markers along the VOT we used a cortex-based alignment algorithm (CBA) implemented in BrainVoyager [57, 58]. The brain of each subject was aligned to an Fs-average brain surface. Briefly, the reconstructed folded cortical representations of each of our 13 subjects were morphed into a spherical representation that resulted in a curvature map with various degrees of smoothness. The essential step of alignment is an iterative procedure that follows a coarse-to-fine matching strategy, gradually decreasing the smoothness of the surface. Then all functional data sets were aligned to a cortical surface that allowed the use of anatomical labels along the VOT.

2.6 Neuroimaging data analysis

General Linear Model (GLM) analysis: To compute statistical parametric maps, we applied GLM with hemodynamic response function (HRF) convolved predictors. Second-level statistical parametric maps were calculated with hierarchical random-effects model analysis. A statistical threshold criterion of $P < 0.01$ was set for all results unless otherwise reported. We employed multiple comparisons using a cluster-size threshold estimator, based on a Monte Carlo simulation approach extended to 3D datasets, implemented in the "Cluster Threshold Estimator" plugin of the BrainVoyager 20.6 software. This correction method is based on Monte Carlo simulations that calculate the probability of obtaining different cluster sizes [59]. In combination with relaxed single-voxel thresholds, calculated cluster extent thresholds are applied to the statistical map, ensuring that a global error probability of $p < 0.05$ is met.

For the visual localizer session, each functional area was defined by contrasting one visual category with all other categories and choosing the peak cluster (with minimal cluster threshold surface of 40 mm^2). Region-of-interest (ROI) analysis: To place neural activations along the medial-to-lateral organization of the VOT, we used a predefined map of four anatomical ROIs in the right and left hemispheres [44]. These include the following. FG1, FG2, FG3, FG4. Statistical parametric maps of overall activation in response to robotic gestures were calculated for each subject separately and used to calculate the correlation with the ratings of the behavioral questionnaire.

2.7 Behavioral data analysis

Participants' responses were averaged to a single score for Animacy, Likeability, and Anthropomorphism. Each category score was tested against a theoretical chance level (c = 3) using a one-sample T-test. The differences between each pair of category scores were then examined with a paired T test (Table 2). These analyses were performed using MATLAB software (MathWorks), statistical tests were double-sided and corrected for multiple comparisons using False Discovery Rate ($\alpha = 0.05$). In cases where the correction deemed the score insignificant, a corrected p-value was added.

3 Results

In this fMRI experiment, short video clips were presented in which a robotic object performed varying gestures. The movements of the robotic object were directed in three different orientations: facing the participant, facing an object, or facing an intermediate angle (neutral); see Figure 2. To test whether individual behavioral ratings correlate with neural responses, we initially performed a standard GLM analysis, in which all gestures were contrasted to baseline. Then we calculated the correlation between behavioral ratings in different categories and individual activation levels for all robotic gestures in the VOT.

3.1 Perception of robotic gestures

First, we examined the responses of the whole brain to robotic gestures. Figure 3 presents the statistical parametric map of a whole brain GLM analysis in response to different robotic gestures ($t(12) = 3.5$, $p < 0.01$ random-effects analysis for the whole group, corrected for multiple comparisons). Responses to visual stimuli extensively activated bilateral visual cortices, parietal and frontal cortices, anterior insula, and posterior areas in the temporal lobe. To observe the spatial organization of the responses to robotic gestures, we focused our analysis on the VOT. Figure 3 presents the activation for robotic gestures, and the group functional CBA maps of the peak activation results.

To define functional areas in the visual ventral cortex, we used a visual localizer that consisted of presenting stimuli from various visual categories (Figure 1). In the medial to lateral axis, the VOT extends from the Parahippocampal Gyrus (PHG) through the Fusiform Gyrus (FG) and to the Occipitotemporal Sulcus (OTS). The FG is longitudinally divided by the midfusiform sulcus (MFS), a shallow but anatomically consistent sulcus [60–63]. With the representation of functional visual domains showing a medial-to-lateral organization, affirming the relationship between our cytoarchitecture anatomical maps and functional recruitments for our participants: selective activation for houses and scenes is localized medial to the MFS, in the Parahippocampal Place Area (PPA). Faces were represented in the lateral VOT corresponding to the Fusiform Face Area (FFA).

Using CBA, we could further register our functional maps relative to the cytoarchitectonic areas that parcellate the fusiform gyrus. Figure 3 presents the maximum probability maps of the cytoarchitectonic areas, projected on the FreeSurfer average cortical surface and the overlap between these ROIs and the peak activation for robotic gestures. The results show that the peak response in the visual cortex is located in the posterior VOT, in area FG2 in the right hemisphere and area FG1 in the left hemisphere.

3.2 Correlation between patterns of VOT activations and ratings in the behavioral questionnaire

In addition, participants completed a behavioral questionnaire designed to assess human-robot interaction. The different items in the behavioral questionnaire were grouped into three categories (animacy, anthropomorphism, and likeability) and averaged across all participants (Figure 4, and Table 1). To test whether there is a correspondence between participants' judgments on the behavioral questionnaire and their neural responses, we correlated individual rating scores of the three categories with the level of neural activity (as manifested by the GLM t-statistic values). Although the correlation with anthropomorphism and likeability ratings did not reach significance level (Table 2), animacy was found to be highly correlated with VOT activations across the group

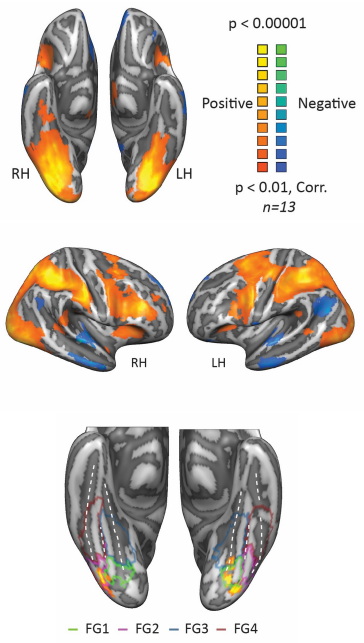

Fig. 3 All robotic gestures versus baseline: Statistical parametric map of all robotic gestures compared to rest baseline, presented on the inflated cortical surface of FreeSurfer average brain. The bottom image shows only the peak activation alongside the outline of the four cytoarchitectonic areas of the fusiform gyrus

(Figure 4 and Table 3). Animacy ratings were correlated with a wide area in the left hemisphere that spreads along both lateral and medial VOT subareas.

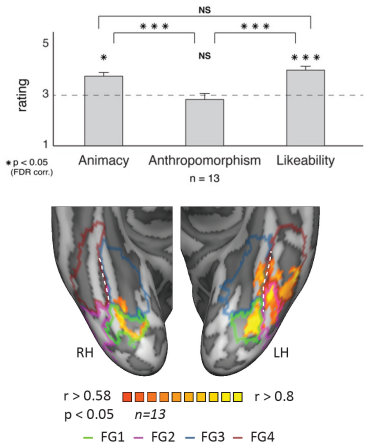

Fig. 4 Rating results and correlations. Top: Average ratings of the behavioural questionnaire. Bottom: ROI Correlation analysis of behavioral ratings to evoked neural responses: Statistical parametric map of the correlation between animacy rating and the neuronal responses within the VOT.

Table 1 Group (n = 13) HRI ratings

	Rating	SE	t	p
Animacy	3.44	0.17	2.61	0.012
Likeability	3.74	0.19	3.94	<0.001
Anthropomorphism	2.29	0.29	-0.73	0.016

Table 2 Group (n = 13) HRI rating differences

Comparison	Difference	t	p
Animacy vs. Likeability	-0.3	-1.86	0.087
Animacy vs. Anthropomorphism	1.15	5.55	<0.001
Likeability vs. Anthropomorphism	1.45	6.43	<0.001

Table 3 Correlation between HRI ratings and neural responses in the Ventral Occipitotemporal Cortex (n = 13)

VOTC Area	Animacy		Anthropo-morphism		Likeability	
	r	p	r	p	r	p
FG1 LH	0.72	0.005	0.37	0.208	0.25	0.413
FG1 RH	0.71	0.007	0.55	0.053	0.20	0.518
FG2 LH	0.64	0.018	0.45	0.122	0.11	0.723
FG2 RH	0.20	0.507	0.20	0.507	-0.19	0.535
FG3 LH	0.12	0.69	-0.05	0.863	-0.09	0.777

To better characterize the spatial pattern of this correlation, we analyzed the animacy correlation separately for each cytoarchitectonic area of the VOT in both hemispheres. The results show that the left lateral VOT (FG2 and FG4) and the bilateral posterior medial areas (FG1) are correlated with the animacy ratings ($p < 0.05$, corrected for multiple comparisons). In other words, subjects who rated the robotic object higher in the animacy dimension showed a higher activation response in the left lateral VOT compared to the right hemisphere (Table 3).

4 Discussion

In this study, we provide contributions to both the fields of neuroscience and HRI by employing a robot for basic scientific research. In terms of neuroscience, our findings reveal a correlation between the perceived level of animacy and neural activity within specific cortical areas. In addition, our findings contribute to the field of human-robot interaction by providing physical evidence supporting animacy ratings. Our research helps to refine the definition of animacy and gain a deeper understanding of the essential features that contribute to it. We "deconstruct animacy" and its meaningful role in HRI, such as in gaining a better understanding of theory of mind.

4.1 Implications for neuroscience

In the present study, we explored the neural correlates of simple gestures performed by a non-humanoid robot, with a specific interest in the VOT, that plays an important role in processing visual categories [61, 64–66]. Our main result shows a high correlation between the individual animacy ratings of the robotic agent and the level of neural responses in the VOT, especially in the left hemisphere. This is interesting in light of previous research that indicates the cortical representations of the perceived levels of animacy might follow a continuous spatial pattern within the VOT such that animate objects activate the lateral parts of the VOT and inanimate objects activate the more medial parts.

Here we find that viewing gestures performed by a non-humanoid robot recruit a wide bilateral cortical network that includes areas of the action-observation network (premotor and parietal cortices), the social brain network (inferior frontal gyrus, insula, pSTS, and FFA) and the visual cortex, including the VOT (Figure 3). Other features that evaluate HRI, such as resemblance to humans or likeability, were not correlated with neural responses in the VOT. To keep subjects naïve to the experimental goals, we refrained from describing the robotic object as a robot and collected behavioral reports only after the neuroimaging session. Thus, although subjects were not asked to categorize or judge the animacy levels during the fMRI sessions, VOT activations were correlated with animacy ratings. The representation of animacy within the VOT has been described primarily in relation to different anatomical locations. An animate-to-inanimate functional axis is superimposed on a medial-to-lateral anatomical axis centered on the mid-fusiform sulcus.

Although previously it was unclear where the robotic object would be placed along this axis, our group results show peak activations on both

sides of the MFS and both hemispheres, correlating with individual differences in the perception of the robot's animacy. Several works have shown that the lateral VOT is activated for objects that are not associated with living organisms but show high levels of animacy [6, 24, 67, 68], such as animated geometric shapes or industrial machines. One way to explain this might be that the VOT is highly responsive to images of moving objects compared to still objects, regardless of the basic nature of the object. However, our results indicate that movement itself is likely less relevant than its contribution to the perceived animacy.

4.2 Implications for HRI

The past decade has seen an increased interest in the development of robots that interact with humans in profound ways, turning human perception of robots into an important research and design question [22, 69]. Recent studies report two characteristics that are strongly associated with the acceptance of robots as social agents: human-like surface appearance and human-like movement [26]. Consequently, most neuroimaging studies focused on the similarity in neural responses evoked between humanoid robots and humans during perceptual or mentalizing tasks [31–33, 70, 71]. These works show that human-like robots can activate brain areas related to action observation and social interaction in a similar way as human agents.

A study by Cross et al. showed that beliefs concerning an agent's possession of human-like animacy modulate social networks in the brain more than the agent's human-like appearance or movement [72]. These findings demonstrate that the perceived animacy is not only grounded in physical features, but is also shaped by prior knowledge. Many robots in our environment are not human-like, and knowledge of their neuronal representation is still very limited. Here, we show that non-humanoid robot gestures also activate the action observation network including the fusiform gyrus. The gestures of the robotic object were designed as simple gestures without any physical interaction with other objects so that the activations would not be attributed to goal-directed movement. Furthermore, we did not find a correlation between the activation levels around the fusiform gyrus and the perceived human likeness of our robot. Instead, our results reinforce the notion of animacy as a basic principle that is represented in the VOT, which might offer an added explanation for the neural responses evoked by robotic agents beyond the similarity to humans and goal-directed movements.

This study can have numerous implications for HRI. Little is known about the mechanisms underlying the interpretation of social cues in HRI. While we can partially assume that humanoid robots would activate mechanisms similar to human interactions, it is less clear how non-humanoid robots would be perceived, as they represent on the one hand a machine, and on the other a social entity. Understanding correlations, as presented in this paper, can inform the HRI community on how to address the design of social cues even with simple, visually machine-like robots. By identifying underlying neurological mechanisms, we can identify the similarities and differences between these forms of HRI to human-human interactions and adjust the robots' design and behavior accordingly. Previous research has indicated that even when devoid of specific emotional metaphors in their design, abstract robotic objects can evoke positive or negative affect when interacting with humans [21]. Moreoever, movement has been shown to be particularly effective in conveying emotional content. [73]

Yet it is not fully clear what underlies these affective interactions and to what level of abstraction this can be taken. For example, the affective grounding approach sees emotion as a collaborative dynamic resulting from interaction and proposes studying emotion in HRI as an interaction paradigm "by focusing less on abilities to correctly identify expressions but to understand how people read emotional meaning into the behavior of robots" [74]. The present study takes this one step further, to investigate not only how, but also what physically underlies the emotional meaning, providing insight into the link between the neural underpinnings and subjective responses. We believe that even beyond the element of design, gaining a better understanding of the neural correlates of how animacy is perceived could have implications for understanding affective responses to robotic objects and guide future development with respect to interaction more generally construed.

4.3 Relevance to theory of mind

This study provides insight into the debate on the problem of other minds. Specifically with respect to robots and theory of mind, and the neural correlates thereof. This study found animacy to be correlated with VOT activation, particularly in the left hemisphere. This is interesting in light of previous research that has indicated that subjects who scored high on factors related to theory of mind in a behavioral study had greater functional connectivity specifically in the left hemisphere when tested in the MRI [75].

Theory of mind is believed to be key for human interaction in general, possibly also for human-robot interaction moving forward into the future [76]. A major approach towards addressing the question of how we know other entities have minds is through their actions or physical appearance. One perspective suggests that if they act or look as we do, we are more likely to conclude that the entities have minds as we do [77]. Descartes, who had a particular fascination with automata, equated all beings, including humans, to machines of different levels of complexity [78]. According to him, the animacy of robots, to the extent of even attributing minds to them, would depend upon their level of ability to simulate animate beings (such as humans). On the other hand, Alan Turing had a different perspective. According to Turing, there is no need for physical similarity between machines and man, stating that "we should feel that there is little point in trying to make a 'thinking machine' more human by dressing it up in such artificial flesh." [79]

4.4 Limitations and future directions

The current study is not free from limitations. First of all, this study employs a robotic object that is not viewed in real life but rather we employed a video study methodology. While presentation of robot gestures on video has drawbacks [80], this methodology is commonly used in HRI research and has been shown to be effective in exploring people's perceptions of robotic technologies [81, 82]. In the present study, it was necessary to use this methodology due to the restrictions imposed by the MRI itself, which would not allow direct interaction firsthand with the robotic object. Additionally, it may not be representative of all types of non-humanoid robotic agents, and its generalizability may be limited. Furthermore, due to the desire to keep participants naive with respect to the objectives of the study, we did not record the animacy ratings of the participants during the experiment, but only after the experiment ended, which narrowed down some of the possibilities for correlation analysis.

While our study suggests insights into the neural mechanisms underlying HRI, we limited the scope of our investigation to animacy, and more research is needed to capture the complexity of social HRI sufficiently. Finally, while due to the specific objectives of the present study, all gestures were analyzed together, future studies could be designed taking into account precisely the differences between the gestures, specifically the variation in level of interaction with the viewer, and how this affects the neural correlates underlying the interaction and the affective response. It could be of interest to see how the different gesture types affect the perception of the robot, including the questions of the behavioral questionnaire omitted in the current study (e.g. perceived safety).

In this study, apart from a spatial pattern, we find a very significant correlation between activation levels and individual animacy ratings in both the lateral and medial areas of the VOT. First, this provides a physical foundation for subjective animacy ratings. Furthermore, our findings suggest that animacy might be represented in the VOT not only spatially but quantitatively, a claim that needs to be substantiated by future direct studies. If this is indeed the case, it may be possible from this finding to formulate a gauge of the level to which humans attribute animacy or construct a theory of mind towards robots they interact with based on such a quantitative measure. If this is indeed the case, it could allow for employing machine learning methods to predict one's behavioral ratings from the MRI data of the individual. This would be a step toward truly understanding the neural correlates of HRI. Although it is beyond the scope of the present study, our findings hint at this possibility and encourage future exploration of this intriguing direction.

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Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

Ethics approval and consent to participate The Ethics Committee of the Hadassah Medical Center approved the experimental procedure and written informed consent was obtained from each subject prior to the scanning procedure.

Data availability Data will be made available on reasonable request.

References

[1] D'Ettorre, C., Mariani, A., Stilli, A., Baena, F.R., Valdastri, P., Deguet, A., Kazanzides, P., Taylor, R.H., Fischer, G.S., DiMaio, S.P., *et al.*: Accelerating surgical robotics research: A review of 10 years with the da vinci research kit. IEEE Robotics & Automation Magazine **28**(4), 56–78 (2021). Publisher: IEEE

[2] Belpaeme, T., Kennedy, J., Ramachandran, A., Scassellati, B., Tanaka, F.: Social robots for education: A review. Science robotics **3**(21), 5954 (2018). Publisher: American Association for the Advancement of Science

[3] Kim, J., Mishra, A.K., Limosani, R., Scafuro, M., Cauli, N., Santos-Victor, J., Mazzolai, B., Cavallo, F.: Control strategies for cleaning robots in domestic applications: A comprehensive review. International Journal of Advanced Robotic Systems **16**(4), 1729881419857432 (2019). Publisher: SAGE Publications Sage UK: London, England

[4] Bollini, M., Tellex, S., Thompson, T., Roy, N., Rus, D.: Interpreting and executing recipes with a cooking robot. In: Experimental Robotics: The 13th International Symposium on Experimental Robotics, pp. 481–495 (2013)

[5] Suresh, A., Laha, D., Gaba, D., Bhambri, S.: Design and Development of Innovative Pet Feeding Robot. In: Robot Intelligence Technology and Applications 5: Results from the 5th International Conference on Robot Intelligence Technology and Applications 5, pp. 221–237 (2019)

[6] Castelli, F., Happé, F., Frith, U., Frith, C.: Movement and mind: a functional imaging study of perception and interpretation of complex intentional movement patterns. Neuroimage **12**(3), 314–325 (2000). Publisher: Elsevier

[7] Dautenhahn, K.: Socially intelligent robots: dimensions of human–robot interaction. Philosophical transactions of the royal society B: Biological sciences **362**(1480), 679–704 (2007). Publisher: The Royal Society London

[8] Scholtz, J.: Theory and evaluation of human robot interactions. In: 36th Annual Hawaii International Conference on System Sciences, 2003. Proceedings of the, p. 10 (2003)

[9] Schwab, D., Zhu, Y., Veloso, M.: Zero shot transfer learning for robot soccer. In: Proceedings of the 17th International Conference on Autonomous Agents and MultiAgent Systems, pp. 2070–2072 (2018)

[10] Martinez-Martin, E., Pobil, A.P.: Personal robot assistants for elderly care: an overview. Personal assistants: Emerging computational technologies, 77–91 (2018). Publisher: Springer

[11] Bonfe, M., Boriero, F., Dodi, R., Fiorini, P., Morandi, A., Muradore, R., Pasquale, L., Sanna, A., Secchi, C.: Towards automated surgical robotics: A requirements engineering approach. In: 2012 4th IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics (BioRob), pp. 56–61 (2012)

[12] Nass, C., Steuer, J., Tauber, E.R.: Computers are social actors. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, pp. 72–78 (1994)

[13] Erel, H., Hoffman, G., Zuckerman, O.: Interpreting non-anthropomorphic robots' social gestures. In: Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction, Chicago, Illinois. ACM (2018)

[14] Erel, H., Shem Tov, T., Kessler, Y., Zuckerman, O.: Robots are always social: Robotic movements are automatically interpreted as social cues. In: Extended Abstracts of the 2019 CHI Conference on Human Factors in Computing Systems, pp. 1–6 (2019)

[15] Fink, J.: Anthropomorphism and human likeness in the design of robots and human-robot interaction. In: Social Robotics: 4th International Conference, ICSR 2012, Chengdu, China, October 29-31, 2012. Proceedings 4, pp. 199–208 (2012). Springer

[16] Bewley, H., Boer, L.: Designing Blo-nut: design principles, choreography and otherness in an expressive social robot. In: Proceedings of the 2018 Designing Interactive Systems Conference, pp. 1069–1080 (2018)

[17] Boer, L., Bewley, H.: Reconfiguring the appearance and expression of social robots by acknowledging their otherness. In: Proceedings of the 2018 Designing Interactive Systems Conference: DIS'18, pp. 667–677 (2018)

[18] Sandry, E.: The potential of otherness in robotic art. Robots and Art: Exploring an Unlikely Symbiosis, 177–189 (2016). Publisher: Springer

[19] Zhou, R., Schwemler, Z., Baweja, A., Sareen, H., Hunt, C.L., Leithinger, D.: TactorBots: A Haptic Design Toolkit for Out-of-lab Exploration of Emotional Robotic Touch. In: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, pp. 1–19 (2023)

[20] Mori, M., MacDorman, K.F., Kageki, N.: The uncanny valley [from the field]. IEEE Robotics & automation magazine **19**(2), 98–100 (2012). Publisher: IEEE

[21] Anderson-Bashan, L., Megidish, B., Erel, H., Wald, I., Hoffman, G., Zuckerman, O., Grishko, A.: The greeting machine: an abstract robotic object for opening encounters. In: 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), pp. 595–602 (2018)

[22] Wiese, E., Metta, G., Wykowska, A.: Robots as intentional agents: using neuroscientific methods to make robots appear more social. Frontiers in psychology **8**, 1663 (2017). Publisher: Frontiers Media SA

[23] CastroGonzalez, Admoni, H., Scassellati, B.: Effects of form and motion on judgments of social robots animacy, likability, trustworthiness and unpleasantness. International Journal of Human-Computer Studies **90**, 27–38 (2016) https://doi.org/10.1016/j.ijhcs.2016.02.004

[24] Santos, N.S., Kuzmanovic, B., David, N., Rotarska-Jagiela, A., Eickhoff, S.B., Shah, J.N., Fink, G.R., Bente, G., Vogeley, K.: Animated brain: A functional neuroimaging study on animacy experience. NeuroImage **53**(1), 291–302 (2010). Publisher: Elsevier

[25] Tremoulet, P.D., Feldman, J.: The influence of spatial context and the role of intentionality in the interpretation of animacy from motion. Perception & psychophysics **68**, 1047–1058 (2006). Publisher: Springer

[26] Wykowska, A., Chaminade, T., Cheng, G.: Embodied artificial agents for understanding human social cognition. Philosophical Transactions of the Royal Society B: Biological Sciences **371**(1693), 20150375 (2016). Publisher: The Royal Society

[27] Hoffman, G., Zuckerman, O., Hirschberger, G., Luria, M., Shani Sherman, T.: Design and evaluation of a peripheral robotic conversation companion. In: Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-robot Interaction, pp. 3–10 (2015)

[28] Hari, R., Henriksson, L., Malinen, S., Parkkonen, L.: Centrality of social interaction in human brain function. Neuron **88**(1), 181–193 (2015). Publisher: Elsevier

[29] Bossi, F., Willemse, C., Cavazza, J., Marchesi, S., Murino, V., Wykowska, A.: The human brain reveals resting state activity patterns that are predictive of biases in attitudes toward robots. Science Robotics **5**(46), 6652 (2020) https://doi.org/10.1126/scirobotics.abb6652 . Publisher: American Association for the Advancement of Science. Accessed 2023-06-16

[30] Sciutti, A., Bisio, A., Nori, F., Metta, G., Fadiga, L., Pozzo, T., Sandini, G.: Measuring human-robot interaction through motor resonance. International Journal of Social Robotics **4**, 223–234 (2012). Publisher: Springer

[31] Chaminade, T., Zecca, M., Blakemore, S.-J., Takanishi, A., Frith, C.D., Micera, S., Dario, P., Rizzolatti, G., Gallese, V., Umiltà, M.A.: Brain response to a humanoid robot in areas implicated in the perception of human emotional gestures. PLoS one **5**(7), 11577 (2010). Publisher: Public Library of Science San Francisco, USA

[32] Krach, S., Hegel, F., Wrede, B., Sagerer, G., Binkofski, F., Kircher, T.: Can machines think? Interaction and perspective taking with robots investigated via fMRI. PloS one **3**(7), 2597 (2008). Publisher: Public Library of Science San Francisco, USA

[33] Takahashi, H., Terada, K., Morita, T., Suzuki, S., Haji, T., Kozima, H., Yoshikawa, M., Matsumoto, Y., Omori, T., Asada, M., *et al.*: Different impressions of other agents obtained through social interaction uniquely modulate dorsal and ventral pathway activities in the social human brain. cortex **58**, 289–300 (2014). Publisher: Elsevier

[34] Wang, Y., Quadflieg, S.: In our own image? Emotional and neural processing differences when observing human–human vs human–robot interactions. Social cognitive and affective neuroscience **10**(11), 1515–1524 (2015). Publisher: Oxford University Press

[35] Gazzola, V., Rizzolatti, G., Wicker, B., Keysers, C.: The anthropomorphic brain: the mirror neuron system responds to human and robotic actions. Neuroimage **35**(4), 1674–1684 (2007). Publisher: Elsevier

[36] Tai, Y.F., Scherfler, C., Brooks, D.J., Sawamoto, N., Castiello, U.: The human premotor cortex is' mirror'only for biological actions. Current biology **14**(2), 117–120 (2004). Publisher: Elsevier

[37] Bell, A.H., Hadj-Bouziane, F., Frihauf, J.B., Tootell, R.B.H., Ungerleider, L.G.: Object representations in the temporal cortex of monkeys and humans as revealed by functional magnetic resonance imaging. Journal of neurophysiology **101**(2), 688–700 (2009). Publisher: American Physiological Society

[38] Kriegeskorte, N., Mur, M., Ruff, D.A., Kiani, R., Bodurka, J., Esteky, H., Tanaka, K., Bandettini, P.A.: Matching categorical object representations in inferior temporal cortex of man and monkey. Neuron **60**(6), 1126–1141 (2008). Publisher: Elsevier

[39] Sha, L., Haxby, J.V., Abdi, H., Guntupalli, J.S., Oosterhof, N.N., Halchenko, Y.O., Connolly, A.C.: The animacy continuum in the human ventral vision pathway. Journal of cognitive neuroscience **27**(4), 665–678 (2015). Publisher: MIT Press One Rogers Street, Cambridge, MA 02142-1209, USA journals-info˜. . .

[40] Wiggett, A.J., Pritchard, I.C., Downing, P.E.: Animate and inanimate objects in human visual cortex: Evidence for task-independent category effects. Neuropsychologia **47**(14), 3111–3117 (2009). Publisher: Elsevier

[41] Chao, L.L., Weisberg, J., Martin, A.: Experience-dependent modulation of category-related cortical activity. Cerebral Cortex **12**(5), 545–551 (2002). Publisher: Oxford University Press

[42] Martin, A.: The representation of object concepts in the brain. Annu. Rev. Psychol. **58**, 25–45 (2007). Publisher: Annual Reviews

[43] Proklova, D., Kaiser, D., Peelen, M.V.: Disentangling representations of object shape and object category in human visual cortex: The animate–inanimate distinction. Journal of cognitive neuroscience **28**(5), 680–692 (2016). Publisher: MIT Press One Rogers Street, Cambridge, MA 02142-1209, USA journals-info˜...

[44] Rosenke, M., Weiner, K.S., Barnett, M.A., Zilles, K., Amunts, K., Goebel, R., Grill-Spector, K.: A cross-validated cytoarchitectonic atlas of the human ventral visual stream. Neuroimage (2017)

[45] Grill-Spector, K., Weiner, K.S.: The functional architecture of the ventral temporal cortex and its role in categorization. Nature Reviews Neuroscience **15**(8), 536–548 (2014). Publisher: Nature Publishing Group UK London

[46] Nasr, S., Liu, N., Devaney, K.J., Yue, X., Rajimehr, R., Ungerleider, L.G., Tootell, R.B.H.: Scene-selective cortical regions in human and nonhuman primates. Journal of Neuroscience **31**(39), 13771–13785 (2011). Publisher: Soc Neuroscience

[47] Nobre, A.C., Allison, T., McCarthy, G.: Modulation of human extrastriate visual processing by selective attention to colours and words. Brain: a journal of neurology **121**(7), 1357–1368 (1998)

[48] Puce, A., Allison, T., Asgari, M., Gore, J.C., McCarthy, G.: Differential sensitivity of human visual cortex to faces, letterstrings, and textures: a functional magnetic resonance imaging study. Journal of neuroscience **16**(16), 5205–5215 (1996). Publisher: Soc Neuroscience

[49] Weiner, K.S., Grill-Spector, K.: Sparsely-distributed organization of face and limb activations in human ventral temporal cortex. Neuroimage **52**(4), 1559–1573 (2010). Publisher: Elsevier

[50] Zuckerman, O., Hoffman, G.: Empathy objects: Robotic devices as conversation companions. In: Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction, pp. 593–598 (2015)

[51] Erel, H., Trayman, D., Levy, C., Manor, A., Mikulincer, M., Zuckerman, O.: Enhancing emotional support: The effect of a robotic object on human–human support quality. International Journal of Social Robotics **14**(1), 257–276 (2022)

[52] Press, V.S., Erel, H.: Designing non-verbal humorous gestures for a non-humanoid robot. In: Extended Abstracts of the 2022 CHI Conference on Human Factors in Computing Systems. CHI EA '22. Association for Computing Machinery, New York, NY, USA (2022). https://doi.org/10.1145/3491101.3519924 . https://doi.org/10.1145/3491101.3519924

[53] Press, V.S., Erel, H.: Humorous robotic behavior as a new approach to mitigating social awkwardness. In: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems. CHI '23. Association for Computing Machinery, New York, NY, USA (2023). https://doi.org/10.1145/3544548.3580821 . https://doi.org/10.1145/3544548.3580821

[54] Manor, A., Megidish, B., Todress, E., Mikulincer, M., Erel, H.: A non-humanoid robotic object for providing a sense of security. In: 2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), pp. 1520–1527 (2022). https://doi.org/10.1109/RO-MAN53752.2022.9900747

[55] Hoffman, G., Ju, W.: Designing robots with movement in mind. Journal of Human-Robot Interaction **3**(1), 91–122 (2014)

[56] Bartneck, C., Kulić, D., Croft, E., Zoghbi, S.: Measurement instruments for the anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety of robots. International journal of social robotics **1**,

71–81 (2009). Publisher: Springer

[57] Frost, M.A., Goebel, R.: Measuring structural–functional correspondence: spatial variability of specialised brain regions after macro-anatomical alignment. Neuroimage **59**(2), 1369–1381 (2012). Publisher: Elsevier

[58] Goebel, R., Esposito, F., Formisano, E.: Analysis of functional image analysis contest (FIAC) data with brainvoyager QX: From single-subject to cortically aligned group general linear model analysis and self-organizing group independent component analysis. Human brain mapping **27**(5), 392–401 (2006). Publisher: Wiley Online Library

[59] Forman, S.D., Cohen, J.D., Fitzgerald, M., Eddy, W.F., Mintun, M.A., Noll, D.C.: Improved Assessment of Significant Activation in Functional Magnetic Resonance Imaging (fMRI): Use of a Cluster-Size Threshold. Magn. Reson. Med. **33**, 636–647 (1995)

[60] Caspers, J., Zilles, K., Eickhoff, S.B., Schleicher, A., Mohlberg, H., Amunts, K.: Cytoarchitectonical analysis and probabilistic mapping of two extrastriate areas of the human posterior fusiform gyrus. Brain Structure and Function **218**, 511–526 (2013). Publisher: Springer

[61] Kanwisher, N., McDermott, J., Chun, M.M.: The fusiform face area: a module in human extrastriate cortex specialized for face perception. Journal of neuroscience **17**(11), 4302–4311 (1997). Publisher: Soc Neuroscience

[62] Lorenz, S., Weiner, K.S., Caspers, J., Mohlberg, H., Schleicher, A., Bludau, S., Eickhoff, S.B., Grill-Spector, K., Zilles, K., Amunts, K.: Two new cytoarchitectonic areas on the human mid-fusiform gyrus. Cerebral Cortex **27**(1), 373–385 (2017). Publisher: Oxford University Press

[63] Weiner, K.S., Barnett, M.A., Lorenz, S., Caspers, J., Stigliani, A., Amunts, K., Zilles, K., Fischl, B., Grill-Spector, K.: The cytoarchitecture of domain-specific regions in human high-level visual cortex. Cerebral cortex **27**(1), 146–161 (2017). Publisher: Oxford University Press

[64] Epstein, R., Kanwisher, N.: A cortical representation of the local visual environment. Nature **392**(6676), 598–601 (1998). Publisher: Nature Publishing Group UK London

[65] Peelen, M.V., Downing, P.E.: Is the extrastriate body area involved in motor actions? Nature neuroscience **8**(2), 125 (2005). Publisher: Nature Publishing Group US New York

[66] Striem-Amit, E., Cohen, L., Dehaene, S., Amedi, A.: Reading with sounds: sensory substitution selectively activates the visual word form area in the blind. Neuron **76**(3), 640–652 (2012). Publisher: Elsevier

[67] Gobbini, M.I., Koralek, A.C., Bryan, R.E., Montgomery, K.J., Haxby, J.V.: Two takes on the social brain: a comparison of theory of mind tasks. Journal of cognitive neuroscience **19**(11), 1803–1814 (2007). Publisher: MIT Press

[68] Schultz, R.T., Grelotti, D.J., Klin, A., Kleinman, J., Gaag, C., Marois, R., Skudlarski, P.: The role of the fusiform face area in social cognition: implications for the pathobiology of autism. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences **358**(1430), 415–427 (2003). Publisher: The Royal Society

[69] Breazeal, C., Dautenhahn, K., Kanda, T.: Social robotics. Springer handbook of robotics, 1935–1972 (2016). Publisher: Springer

[70] Chaminade, T., Rosset, D., Da Fonseca, D., Nazarian, B., Lutcher, E., Cheng, G., Deruelle, C.: How do we think machines think? An fMRI study of alleged competition with an artificial intelligence. Frontiers in human neuroscience **6**, 103 (2012). Publisher: Frontiers Media SA

[71] Cross, E.S., Liepelt, R., C. Hamilton, A.F., Parkinson, J., Ramsey, R., Stadler, W., Prinz,

W.: Robotic movement preferentially engages the action observation network. Human brain mapping **33**(9), 2238–2254 (2012). Publisher: Wiley Online Library

[72] Cross, E.S., Ramsey, R., Liepelt, R., Prinz, W., Hamilton, A.F.d.C.: The shaping of social perception by stimulus and knowledge cues to human animacy. Philosophical Transactions of the Royal Society B: Biological Sciences **371**(1686), 20150075 (2016). Publisher: The Royal Society

[73] Löffler, D., Schmidt, N., Tscharn, R.: Multimodal expression of artificial emotion in social robots using color, motion and sound. In: Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction, pp. 334–343 (2018)

[74] Jung, M.F.: Affective Grounding in Human-Robot Interaction. In: Proceedings of the 2017 ACM/IEEE International Conference on Human-Robot Interaction, pp. 263–273. ACM, Vienna Austria (2017). https://doi.org/10.1145/2909824.3020224 . https://dl.acm.org/doi/10.1145/2909824.3020224 Accessed 2023-10-29

[75] Marchetti, A., Baglio, F., Costantini, I., Dipasquale, O., Savazzi, F., Nemni, R., Sangiuliano Intra, F., Tagliabue, S., Valle, A., Massaro, D., *et al.*: Theory of mind and the whole brain functional connectivity: Behavioral and neural evidences with the Amsterdam Resting State Questionnaire. Frontiers in psychology **6**, 1855 (2015). Publisher: Frontiers Media SA

[76] Krämer, N.C., Pütten, A., Eimler, S.: Human-agent and human-robot interaction theory: Similarities to and differences from human-human interaction. Human-computer interaction: The agency perspective, 215–240 (2012). Publisher: Springer

[77] Epley, N., Waytz, A., Cacioppo, J.T.: On seeing human: a three-factor theory of anthropomorphism. Psychological review **114**(4), 864 (2007). Publisher: American Psychological Association

[78] Descartes, R.: A Discourse on Method. Aladdin Book Company, ??? (1901)

[79] Turing, A.M.: Mind. Mind **59**(236), 433–460 (1950)

[80] Schilbach, L., Timmermans, B., Reddy, V., Costall, A., Bente, G., Schlicht, T., Vogeley, K.: Toward a second-person neuroscience1. Behavioral and brain sciences **36**(4), 393–414 (2013). Publisher: Cambridge University Press

[81] Lehmann, H., Saez-Pons, J., Syrdal, D.S., Dautenhahn, K.: In good company? Perception of movement synchrony of a non-anthropomorphic robot. PloS one **10**(5), 0127747 (2015). Publisher: Public Library of Science San Francisco, CA USA

[82] Woods, S.N., Walters, M.L., Koay, K.L., Dautenhahn, K.: Methodological issues in HRI: A comparison of live and video-based methods in robot to human approach direction trials. In: ROMAN 2006-the 15th IEEE International Symposium on Robot and Human Interactive Communication, pp. 51–58 (2006)