Embodiment and Human-Inspired Socio-Cognitive Mechanisms in Artificial Agents: A Systematic Scoping Review

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Abstract

In the future, autonomous social robots are expected to seamlessly integrate into our society. To be perceived as interactive partners rather than mere tools, these robots must be embodied and capable of navigating complex, dynamic environments. This study explores the critical role of embodiment and examines the application of human-inspired socio-cognitive mechanisms in embodied agents. We conducted a systematic scoping review of 36 publications sourced from Scopus, IEEE Xplore, Web of Science, and PubMed. Our findings reveal a diverse array of human-inspired implementations in embodied agents, including curiosity-driven learning, categorical thinking, and predictive learning. Notably, human-like eye-gaze plays a crucial role in enhancing the anthropomorphism of these agents. By drawing inspiration from human interactions, we can transition from pre-programmed robots to fully autonomous agents that exhibit emergent behaviours and adapt to ever-changing conditions. Embodiment allows agents to communicate their intentions and desires through various modes, facilitating richer interactions. Additionally, multiple studies underscore the importance of using embodied agents to study human behaviours. Furthermore, the choice of embodiment type must depend on the task at hand; for some tasks, virtual embodiment is more effective, while for others, physical embodiment is preferable. This review provides a comprehensive starting point for future researchers interested in developing human-inspired embodied agents.

1 Introduction

As technology advances, artificial agents are set to become widespread, helping humans in support, entertainment, and information sharing. Consequently, humans will inevitably integrate these agents into their social milieu. However, for artificial agents to seamlessly blend into our social environments, they must exhibit social behaviours similar to those of humans. If we are to take robots as teammates, and not mere tools, then we have to ensure that they are socially interactive [1]. Bolotta and Dumas [2] argue that for seamless interaction between naturally intelligent agents and artificially intelligent agents, it is essential to develop agents that are both embodied and biologically inspired.

There is no agreed-upon definition for embodiment, as stated by Ziemke [3]. While a comprehensive analysis of all notions of embodiment is beyond the scope of this review (for more detail, see Deng et al. [4]), we adopt a definition of social embodiment that is particularly relevant to the development of social robots. Barsalou et al. [5] describes social embodiment as the states such as postures, arm movements, facial expressions and other states that arise during social interactions. This can be manifested either virtually or physically (see, Figure 1). An agent is thus considered embodied if it can display these states through its body. Moreover, we also consider agents that have a human-bodily form (i.e., humanoid). This is because, for agents to interact seamlessly with humans, they need to have a similar shared understanding of the environment. This is only possible if their embodiment is similar [6]. The benefit of embodiment is that it equips the agent with expressive ways to convey social information. Embodiment of an agent also improves people's perception of the agent and task performance [4].

An agent is said to be biologically inspired if their architecture takes inspiration from the fields of social neuroscience or social psychology as described by Bolotta and Dumas [2]. By taking inspiration from human social cognition and psychology, we can move away

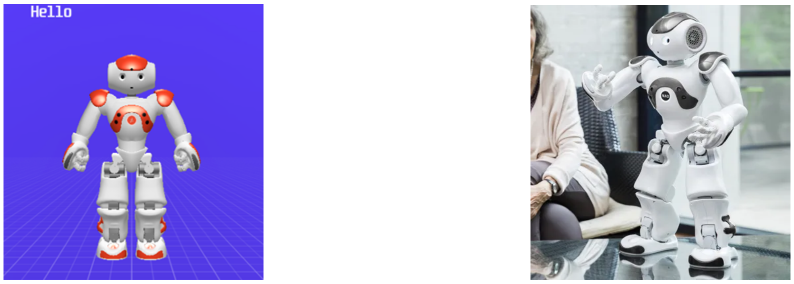

Figure 1: An example of a virtually embodied robot (**left**) and a physically embodied robot (**right**).

from pre-programmed robotic systems, towards fully autonomous social agents that display emergent social behaviours that can adapt in a dynamic environment [7]. This is a crucial step if we want to facilitate natural human-robot interactions, in a complex and dynamic environment. Moreover, when artificial agents exhibit human-like behaviours, humans tend to employ cognitive strategies commonly used in human-human interactions. Notably, they ascribe mental states to these agents when their behaviours are reminiscent of those exhibited by humans [8].

Motivated by the need to explore and systematically map the diverse ways in which human-inspired social cognition has been integrated into embodied agents, and to understand the benefits of these integrations, we conducted a systematic scoping review of the existing literature. Our study aims to address the following research questions:

1. **RQ1:** How have embodied agents taken inspiration from human social cognition, and what benefits do these mechanisms provide?
2. **RQ2:** How has embodiment been manifested in artificial agents, what benefits does it provide, and what design principles can maximise these benefits?
3. **RQ3:** How can research in embodied agents and social cognition work together to synergise their effort?

This review aims to provide a comprehensive starting point for future research by summarising and systematically mapping the existing body of literature and offering directions for future investigations by identifying research gaps.

The structure of the paper is as follows: First, section 2 details the methodology used for the literature survey. In section 3, we summarise and synthesise the data extracted from the papers. section 4 synthesise the observations from the analyses studies and highlight the limitation of the current study, giving a good starting point for future researchers to extend this work. Finally, a concise conclusion will be given in section 5.

2 Methodology

To address the research question, we conducted a systematic scoping review, guided by PRISMA (Preferred Reporting Items for Systematic Review and Meta-analyses) extension for Scoping Reviews [9]. In this section, we detail the systematic scoping review process. subsection 2.1 outlines the information sources and justifies the search query. subsection 2.2 describes the criteria for selecting and filtering references. Finally, subsection 2.3 explains the data extraction and synthesis process.

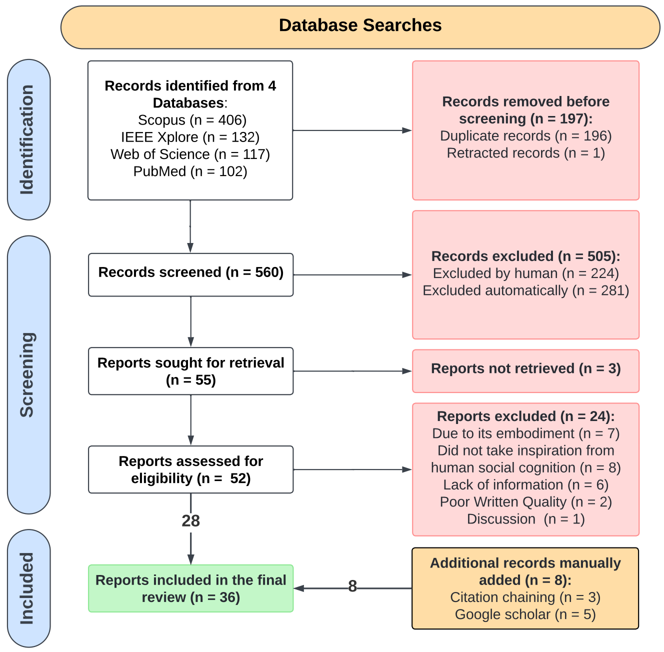

Figure 2: PRISMA flow diagram showing the flow of records through the process.

2.1 Information Sources and the Search Query

To collect relevant literature, the following databases were used[1]: *IEEE Explore*, *PubMed*, *Scopus* and *Web of Science*. To form the query, we took inspiration from the SPIDER (Sample, Phenomenon of Interest, Design, Evaluation, Research type) search strategy [10]. For our study, the only relevant aspects of the strategy were: Sample, Phenomenon of Interest and Source of Inspiration. We introduced *source of inspiration* as we wanted to look at how insights from human social cognition (and related fields) were applied in embodied agents. The search terms associated with each component are shown in Table 1. Each of those components was combined with an AND operator to form the search query. Moreover, the results were filtered by language (only records in English were considered) and type of record (all reviews/surveys were ignored). Duplicates and retracted items were removed using Zotero[2].

[1] The search was performed on 15th May 2024.
[2] It is the reference manager that we used to collect and store the records. Read more about it here.

Table 1: Explanation of the Adapted SPIDER with adapted components (Sample, Phenomenon of Interest, and Source of Inspiration) along with the search terms used.

***Adapted* SPIDER Tool**	**Explanation**	**Search Terms**
Sample	This term describes the sample that is being studied by the literature. We looked at embodied agents.	"humanoid" OR "embodied*agent" OR "robot" OR "embodied*AI" OR "physical agent"
Phenomenon of Interest	This term describes the phenomenon of the sample that we are interested in. For us, we will look at how agents interact in a social setting.	"social interact*" OR "social intellige*" OR "collaborat*" OR "cooperat*" OR "social behav*"
Source of Inspiration	This adapted term describes the source of inspiration behind the agent's behaviour. We will look at how insights from social neuroscience have been applied in agent social intelligence.	"neuromorph*" OR "social psychology" OR "social cognition" OR "social neuroscience" OR "social science" OR "cognitive neuroscience" OR "brain-inspired"

2.2 Screening and Selection

The collected records were screened by the author over multiple iterations. ASReview tool [11] – an active learning-based screening tool – was utilised to discard irrelevant records efficiently. The records were iteratively screened using the abstract and title. Inclusion and exclusion criteria used to screen are shown in Table 2. Out of the 560 unique records that were screened, 281 were discarded automatically by ASReview. Out of the 279 reviews that were manually screened, 119 were considered relevant in the first iteration. After the second iteration, only 55 records were considered relevant. Figure 2 shows the number of records that were identified and the number of records that were included and excluded in each step of the screening process. During the retrieval process, 3 records could not be located. Consequently, we proceeded with a full-text assessment of the remaining 52 records.

2.3 Data Charting

The process of extracting data from the included sources of evidence is called *Data Charting* [9]. During the full-text assessment, the author evaluated each paper against the inclusion and exclusion criteria presented in Table 2. As a result, 24 papers were excluded for various reasons, which are detailed in Figure 2. Following this assessment, data extraction was conducted using a structured annotation schema, as described in subsection A.1, with data collection carried out through Google Forms. It is important to note that this entire process was performed solely by the author. The comprehensive data extraction process from the filtered 52 papers has been meticulously documented and can be found in the subsection A.2. After data extraction, the studies were grouped by embodiment type, robot type, and focus areas. The results were then presented using graphs, pie charts, and tables in section 3, with a narrative summary provided in the same section.

Table 2: Inclusion and exclusion criteria used during screening.

Type	Criteria	Description
Inclusion	Human-like Embodiment	Include papers that use/discuss human-like embodied agents.
Inclusion	Inspiration from Human-human interactions	Include papers that have taken inspiration from human social behaviours.
Exclusion	Lack of Information	Exclude papers that do not provide relevant information (for example, workshop invitations).
Exclusion	Poor Quality	Papers with poor readability were excluded.
Exclusion	Language	Only papers written in English were considered.
Exclusion	Type of Record	Reviews and Surveys were excluded.

3 Results

3.1 Demographic Information

Out of the 36 papers included in the review, 50% of the papers were published in or after 2018 (see, Figure 3). The papers were categorised into 3 general focus areas (see Table 3).

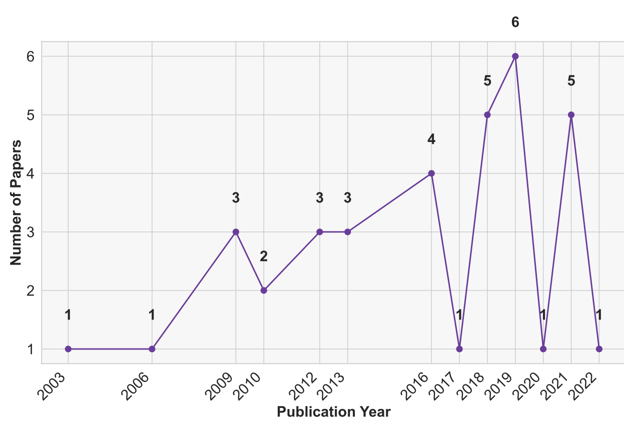

Figure 3: Number of papers included in the review, categorised by year of publication.

Table 3: Papers categorised by their general focus.

Focus Area	Primary studies found	Occurrences
Human-inspired behaviours	[12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [7], [32], [33], [34], [35], [36], [8]	27
Embodiment	[37], [38], [39], [6], [40], [41], [42], [43], [12], [44]	10
Experiment Methodology	[42], [43], [33], [34], [35], [36], [8]	7

3.2 Human-inspired Social Behaviours in Agents

RQ1: How have embodied agents taken inspiration from human social cognition, and what benefits do these mechanisms provide?

In the analysis of 27 reviewed studies focused on human-inspired behaviour in embodied agents, significant attention has been placed on leveraging non-verbal behaviours for enhancing agent-human interaction. Various studies emphasised the importance of mutual eye contact and gaze cues in improving anthropomorphism and joint action coordination. Additionally, insights from human cognitive processes, such as curiosity-driven and predictive learning mechanisms, have been instrumental in inducing emergent behaviours in these agents. Furthermore, leveraging the affordances of objects has improved agents' ability to infer intentions, thereby fostering altruistic behaviours.

To address **RQ1**, we analysed data from 27 publications focused on human-inspired social behaviours. These publications cover a range of sub-focus areas, illustrated in Figure 4. In this section, we will explore the different ways inspiration has been drawn from human behaviours and the benefits of these approaches.

3.2.1 High-Level Cognitive Architecture Design

Lazzeri et al. [12] propose using a hybrid deliberative/reactive paradigm to design a cognitive control architecture. In this approach, a high-level deliberative system manages tasks requiring complex reasoning and planning, while a low-level reactive system addresses real-time changes in a dynamic environment. They emphasise the importance of behaviour-based decomposition over a monolithic control structure. By building independent modules for each behaviour and having the deliberative module plan which behaviours to execute and when, the combination of these behaviours can lead to emergent functionality.

Vinanzi et al. [28] drew inspiration from developmental psychology to implement an artificial cognitive architecture capable of evaluating the trustworthiness of humans it interacts with. To achieve this, they built a Theory of Mind module, realised as a Bayesian Network. Additionally, they integrated an episodic memory system to help evaluate the trustworthiness of humans with whom the agent had no prior interactions. This cognitive architecture

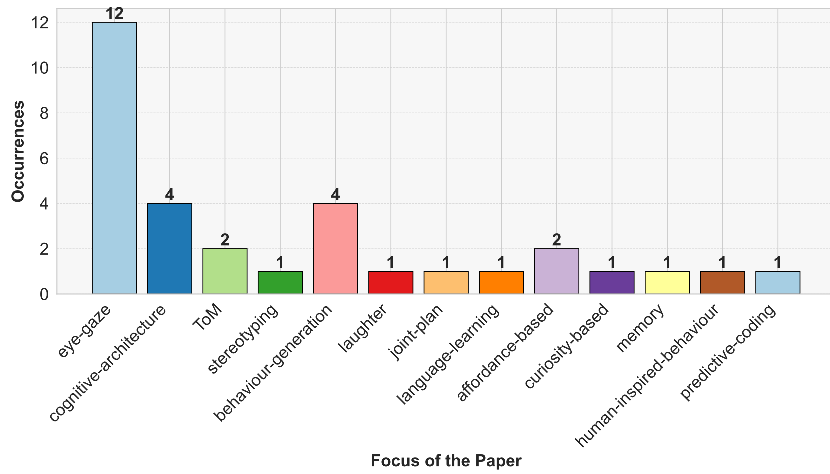

Figure 4: Distribution of the paper by focus area within human-inspired behaviour publications. Note that some papers might cover multiple focus areas. More details about each sub-focus area can be found in subsection A.3

produced results consistent with experiments from developmental psychology.

Eldardeer et al. [17] implemented a multi-sensory memory-based joint attention mechanism. The study proposed a biologically inspired cognitive architecture with four components: an audio-visual perceptual model, a decision-making element, a working memory and an action executor. The audio-visual perceptual module was biologically inspired through the integration of prior knowledge and multi-sensory perception. The working memory monitors essential information about the environment. The decision-making module took inspiration from how humans use different levels of confidence based on the urgency of the decision. All in all, the study showed that the memory-based cognitive architecture could facilitate effective joint attention in human-robot collaboration tasks.

3.2.2 Stereotypical Learning

One study [13] drew inspiration from human categorical thinking to streamline and accelerate interactions with unfamiliar individuals. While categorical thinking can have both positive and negative implications, it facilitates quick assessments of new partners. The study implemented a cluster-based categorical thinking algorithm for dyadic interaction scenarios, comprising two components: an agglomerative clustering method to create generalised models (stereotypes) and a classifier to map a new partner to one of these stereotypes. This approach enables an agent to utilise pre-formed stereotypes to guide action selection when encountering a new agent, bypassing the need for initial interaction-based learning. However, the study also acknowledged the limitations inherent in the simplified model used for partner interactions. The findings underscored the utility of such thinking in social scenarios requiring rapid action selection, such as search and rescue operations, where trial and error is not feasible for determining optimal actions.

3.2.3 Affordance-based Behaviour

Imre et al. [31] implemented a biologically-inspired computational model that utilises affordance computation to enhance intention inference and task execution, thereby generating altruistic behaviours in robots. The affordances of objects are computed using a Support Vector Machine (SVM) classifier, trained through real robot interactions. This study suggests that altruistic behaviours may emerge from basic sensorimotor processes, such as error minimisation, rather than complex cognitive processes.

Han et al. [18] introduced the Behaviour Hierarchy-Based Affordance Network (BHAN) to infer human intentions by learning and representing object affordances. Each object has its own BHAN, which details the possible actions (affordances) that can be performed with the object and the hierarchical relationships between these actions. Additionally, the authors connected multiple BHANs to form a Behaviour Hierarchy-Based Affordance Map (BHAM), capturing the hierarchical interactions between different objects. This framework enables robots to better understand and predict human intentions in tasks involving multiple objects, allowing them to adapt their behaviour appropriately. The learning of these networks is achieved through both autonomous and interactive processes.

3.2.4 Eye Gaze and Joint Attention

Several studies have highlighted the importance of endowing embodied agents with mutual eye contact capabilities. Mwangi et al. [22], Kozima et al. [19], Lombardi et al. [25], and Kompatsiari et al. [21] emphasised the importance of establishing eye contact as a precursor to achieving joint attention, which is a fundamental prerequisite for endowing robots with social interaction abilities. It has been shown to enhance the activation of the social brain network. Kompatsiari et al. [21] further demonstrated that mutual eye contact positively impacts human engagement and the attribution of human likeness to embodied agents. Additionally, Schellen et al. [24] found that eye contact can influence humans' tendency to lie in certain contexts. Lombardi et al. [25] utilised OpenPose[3] and an SVM classifier to detect mutual eye contact (see Figure 5). This automated approach not only facilitates the study of human social cognition without the need for manual annotation of mutual eye contact but also aids in establishing joint attention by indicating readiness for interaction.

In addition to mutual eye contact, research has highlighted the significance of equipping embodied agents with gaze-cueing capabilities. Khoramshahi et al. [20] demonstrated that gaze cues not only enhance the anthropomorphic qualities of embodied agents but also improve action prediction and coordination. These findings underscore the multifaceted role of gaze cues in facilitating more natural and effective interactions between humans and embodied agents. Furthermore, Kompatsiari et al. [34] indicated that robots capable of establishing eye contact prior to gaze cues can modulate the gaze cueing effect (GCE) – the reduction in reaction time when an agent provides valid gaze cues towards a target. This modulation occurs because eye contact activates the top-down control of attention orienting, which can either enhance or suppress the bottom-up reflexive component of attention orienting. According to Lallée et al. [33], gaze cues play a significant role in signalling turn-taking and coordinating joint action within dyadic interactions, particularly when participants adhere

[3] OpenPose is a tool that converts images into key points, which can be used as a feature vector with an SVM classifier

to a shared plan.

Duarte et al. [23] utilised discrete-time Markov Chains (DTMCs) to model stochastic human-like gaze behaviour, based on data collected from human-human interactions. In a related study, [8] endowed an iCUB robot with human-like gaze behaviours to demonstrate that such behaviours can enhance communication and improve human attunement towards robots. Their findings suggest that humans tend to attribute anthropomorphic traits, such as mental states and intentional agency, to robots that exhibit human-like gaze behaviours. Similarly, Huang and Mutlu [29] implemented an open-source Python toolkit for systematic social behaviour generation, which successfully generated human-like eye-gaze behaviour in robots.

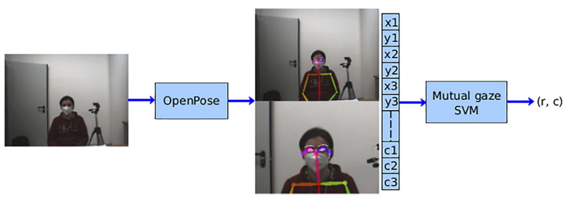

Figure 5: The image is fed into OpenPose, which generates key points. These key points are then used to construct a feature vector, subsequently inputted into an SVM classifier. The classifier returns the presence of eye contact (r) and the confidence level (c). Adapted from Lombardi et al. [25].

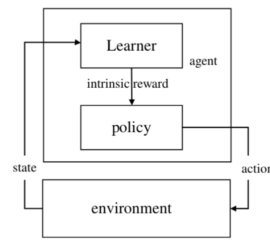

Figure 6: The agent's Learner module learns state-action correlations, with intrinsic rewards proportional to its learning progress. The optimal policy is the one that maximises the agent's learning. Adapted from Gordon [26].

3.2.5 Human-like Memory Models

Prescott et al. [14] took inspiration from how humans acquire a sense of self-awareness through Mental Time Travel (MTT) – the ability to mentally project oneself back in time to relive past events, or forward in time to imagine future events. The study created a biomimetic memory system, inspired by MTT, to enhance the social capabilities of robots. They chose to use Gaussian process latent variable models (GP-LVMs) to model human memory due to their ability to handle high-dimensional data in a probabilistic, nonparametric manner, allowing for efficient pattern compression and reconstruction. The study demonstrated that the theoretical models of human memory systems, including MTT and autobiographical memory, can be effectively implemented in social robots, enabling face, voice, action and touch gesture recognition. The use of GP-LVMs proved to be effective in creating synthetic memories that enable robots to recall past events and predict future scenarios. Robots equipped with these memory systems showed enhanced social interaction capabilities, making them more adept at engaging with humans in a socially meaningful way.

3.2.6 Predictive Learning

Hwang et al. [32] developed an agent utilising a stochastic hierarchical neural network combined with predictive learning mechanisms. The incorporation of stochastic neural dynamics enabled the model to adapt more effectively to fluctuating sensory inputs. Additionally, the implementation of predictive error minimisation facilitated the emergence of complex, adaptive behaviours in the model.

3.2.7 Curiosity-driven Learning

Gordon [26] investigated the advantages of equipping embodied agents with artificial curiosity, which extends Reinforcement Learning (RL) by incorporating a Learner module (see Figure 6). Unlike traditional RL, where rewards are externally defined, artificial curiosity provides internal rewards proportional to the learning progress of the Learner module. The study demonstrated that artificial curiosity in embodied agents led to emergent behaviours in both non-social and social environments. In social settings, these behaviours became more complex due to the diverse and information-rich nature of the environment.

3.3 Embodiment in Agents

RQ2: How has embodiment been manifested in artificial agents, what benefits does it provide, and what design principles can maximise these benefits?

Embodying an artificial agent provides it with diverse modes of communication to exchange information with its social partners. Embodiment can be manifested either physically, virtually or a mix of both. The choice of representation depends on the application, as certain characteristics of the representation might be useful for certain applications. Designers of embodied agents must ensure that as they improve the realism of appearance, they also enhance the realism of behaviour to prevent falling into the uncanny valley.

Out of the 36 papers reviewed, 27 featured uniquely embodied agents (physical or virtual). Figure 7 illustrates that most studies included physical embodiment (85.2%), compared to virtual embodiment via a screen (14.8%). Additionally, the majority of these studies utilised iCub robots[4] (46.4%) in their experiments, with a notable presence of NAO robots[5] (10.7%).

Lazzeri et al. [12] highlights the vital role of the body in facilitating the exchange of information between agents and the external world. Similar to humans, agents exert influence on their environment through bodily actions executed via actuators, while their intentions and goals are shaped by sensory input from the world. Deng et al. [4] introduce the embodiment hypothesis, which argues that the robot's physical presence provides the agent with modes of communication that can be used to convey intentions and desires in a natural way.

[4]iCub is a research-grade embodied robot developed for testing and developing embodied AI algorithms. Read more about it here.

[5]NAO robot is a humanoid that has been extensively used in research. Read more about it here.

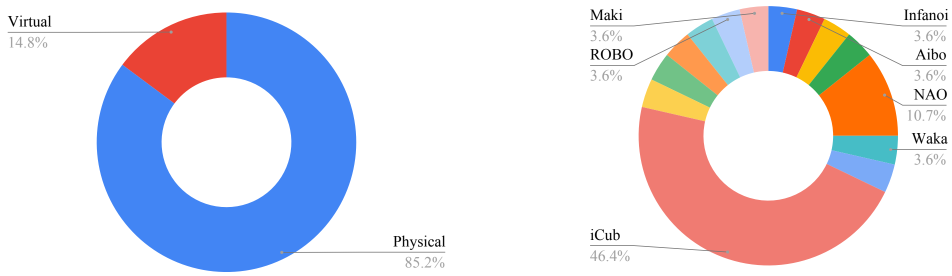

Figure 7: Overview of the embodiment types (**left**) and the specific robot types (**right**) used in the reviewed publications.

Mutlu [41] described five different manifestations of embodiment:

1. **Virtual Representation:** The agent is displayed through a screen.
2. **Physical Representation:** The agent is co-situated in the user's environment.
3. **Blended Frame:** The virtual agent interacts with the user's physical environment.
4. **Mediated Frame:** The physical embodiment is displayed to the user through a remote video stream.
5. **Immersive Frame:** The user interacts with the same environment as the virtual agent through virtual reality, or the virtual agent immerses itself in the user's environment through augmented reality.

Different forms of embodiment elicit different frames of mind in the users interacting with the agent representation. The study further argued that the best representation depends on the specific task and application. Virtual embodiments were deemed effective for conversational tasks, whereas physical embodiments excelled in guiding users through tasks that were situated in the real world. Interestingly, social presence – defined as the perception of artificial agents as social entities displaying human-like characteristics – appears to be unaffected by whether the agent is physically or virtually embodied [44]. For example, Lee et al. [38] found that physically embodied agents are particularly beneficial when interacting with isolated populations, as the presence of tactile interaction can significantly enhance social presence and facilitate meaningful social interactions.

According to Vernon [6], a specific sense of embodiment is advocated, one that entails a human-bodily form. This is essential for effective interaction, as it facilitates a shared understanding of the external environment. Morphological consistency is crucial for ensuring compatibility between the experiences of both agents, enabling seamless interaction.

While attaining a human-like robot is often considered important in robotics, Mori et al. [40] emphasise the importance of deliberately exploring nonhuman designs. Their theory, known as the uncanny valley phenomenon, posits that as robots become increasingly human-like in appearance, our acceptance of them initially rises before sharply declining. This phenomenon, influenced by both the realism of appearance and movement, has significant implications for robot design.

To avoid the uncanny valley, Chaminade and Cheng [42] propose that robots can be made more socially acceptable if human-like social behaviour[6] is implemented alongside a human-like appearance. While some robots, such as *Kaspar* [39] and *Kobian* [15], avoid the uncanny valley by staying behind it with non-human-like designs, it is more advantageous to cross the valley and reach the second peak of acceptance. This can be achieved by incorporating expressive emotions, making the robot appear alive, and tailoring designs for specific target users [37].

3.4 Synergising Efforts: Integrating Research in Embodied Agents and Social Cognition

RQ3: How can research in embodied agents and social cognition work together to synergise their effort?

Embodied agents offer a valuable platform for studying human behaviours due to their ecological validity and precise behavioural control. Insights gained from these studies can inform robot design, making them more attuned to the workings of the human brain. Therefore, fostering collaboration between researchers in social robotics and human social cognition is crucial and advocated by numerous studies.

The integration of research in embodied agents and social cognition presents a powerful synergy that enhances our understanding of human behaviour and informs the design of socially embodied agents. Embodied agents, characterised by their ecological validity and precise behavioural control, allow researchers to investigate mechanisms of social cognition in humans at both behavioural and neurological levels [34, 33, 43]. Unlike traditional screen-based paradigms, these agents can replicate natural social interactions more effectively, evoking genuine human mechanisms and facilitating a deeper exploration of social cognitive processes. The insights gained from these studies can then be used to enhance the engineering of socially embodied robots, creating a research loop as discussed by Chaminade and Cheng [42] (see Figure 8). Moreover, motion capture technologies enable the replication of natural human behaviours in these embodied agents while precisely controlling for specific non-verbal cues, thereby proving invaluable in experimental psychology [43].

Moreover, recent studies advocate for integrating objective measures alongside traditional subjective assessments[7] in the study of human-robot interaction [36, 34, 35]. Objective measures such as functional Near Infrared Spectroscopy (fNIRS)[8] provide insights into human neurological responses during interactions with robots, offering a more comprehensive understanding that complements subjective reports [36]. This approach not only

[6] The study specifically proposes social behaviour inspired by motor resonance. Motor resonance posits that the same neural structures are activated both when a given action is executed and when the same action is observed. For more information, refer to [42].

[7] Subjective assessments may include user surveys, interviews, and qualitative observations of participants' behaviours and experiences during interactions with robots.

[8] FNIRS utilises near-infrared light absorption to assess the concentrations of hemodynamic oxyhemoglobin (OxyHb) and deoxyhemoglobin (deOxyHb) in the cortex, serving as an indirect measure of neural activity [36].

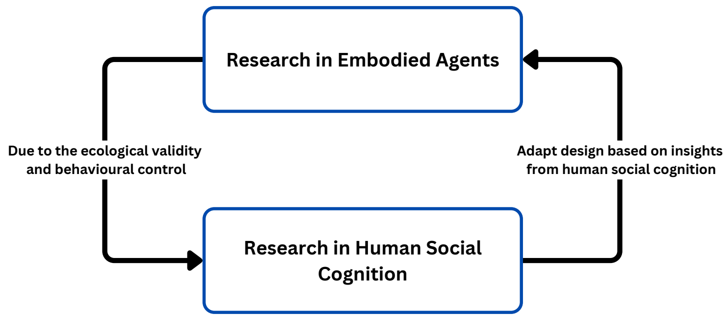

Figure 8: This figure highlights how researchers from the fields of embodied agents and human social cognition can collaborate to synergise their efforts. For a detailed explanation of each step, see the discussion in Section 3.4.

enhances our understanding of human responses but also guides the design of robots that are better aligned with human cognitive processes [35].

4 Discussion and Limitation

4.1 Exploration of human-inspired emergent behaviour generation

As depicted in Figure 4, among the 27 papers focusing on human-inspired behaviours, 12 specifically addressed eye gaze. While these non-verbal behaviours are pivotal for enhancing anthropomorphism, it is equally critical to advance mechanisms for generating human-inspired behaviours such as curiosity-driven learning or predictive learning. These efforts are essential for developing socially embodied agents capable of adapting to dynamic environments through emergent behaviours. We acknowledge the possibility of overlooking certain relevant papers in this area and emphasise the importance of exploring them in future research.

4.2 Choosing Between Virtual and Physical Embodiments

The majority of studies reviewed in our research utilised physically embodied agents (85.2%, see Figure 7). We suggest that researchers also consider incorporating virtual embodiments, which can offer distinct advantages over physical embodiments, particularly in terms of cost-effectiveness for certain tasks [41]. However, we emphasise that the choice between virtual and physical embodiments is task-dependent. While virtual embodiments may be more cost-effective, physical embodiments provide enhanced ecological validity for studying human behaviours [34]. Researchers and designers must carefully consider the specific requirements of each task to determine the most suitable embodiment.

4.3 Ethical Concerns of Embodied Social Agents

While this paper explores the various benefits of embodied social agents, it is imperative to address the ethical considerations inherent in their development and deployment. Establishing social bonds with embodied agents can offer significant advantages, yet it also raises ethical dilemmas. For example, concerns arise regarding the potential isolation of vulnerable populations, such as the elderly, who may increasingly interact with social robots in the absence of human companionship. Moreover, ethical challenges may emerge if these robots are designed or used in ways that prioritise their objectives over human welfare, potentially leading to exploitation. Acknowledging and addressing these ethical concerns is crucial for the responsible development and deployment of social robots [45].

4.4 Limitation and Future Work

While this review aimed to comprehensively analyse the literature on human social cognition in embodied agents, several limitations should be acknowledged. Firstly, time constraints imposed limitations on the scope of the review, leading to some studies not being thoroughly examined. However, all identified studies are included in the reference list to facilitate further exploration. Moreover, despite our efforts to conduct a thorough review, it is important to note that our findings may not be exhaustive. The field of human social cognition in embodied agents is vast and continually evolving, and it is possible that some relevant studies were overlooked. Additionally, the review process, while rigorous, relied on the judgement of a single author for screening and data charting. This introduces the potential for bias, as individual interpretations and preferences may influence the selection process.

To address these limitations in future research, collaborative validation or peer review could be implemented to ensure the comprehensiveness and objectivity of the study. Despite these limitations, this review provides valuable insights into the current state of research in the field of human social cognition in embodied agents.

5 Conclusion

To facilitate natural interaction between humans and artificial agents, it is essential to embody these agents and incorporate biologically inspired mechanisms into their design. In this systematic scoping review of 36 publications, we investigated the utilisation of such mechanisms in agent design and development, as well as the benefits of embodiment. Our analysis highlighted various inspirations, including human curiosity-driven learning, categorical thinking in interactions with unfamiliar agents, and the integration of human-inspired eye gaze. These implementations enhance anthropomorphism and facilitate emergent behaviours in agents, crucial for thriving in our dynamic environment. We observed that agents can be physically or virtually embodied depending on task-specific requirements, with both approaches equally effective in maintaining social presence.

Notably, our review highlighted a significant emphasis on human-inspired eye gaze behaviours and their pivotal role in enhancing anthropomorphism. However, there was relatively less attention given to other biologically inspired mechanisms, such as curiosity-driven learning and affordance-based learning. These mechanisms are essential for enabling agents to autonomously adapt and interact in unpredictable environments, representing an intriguing future research avenue. Moreover, fostering collaboration between researchers specialising in social cognition and those focusing on embodied agents will be crucial for advancing both fields synergistically.

Responsible Research

To ensure transparency throughout the review process, we meticulously documented our search strategy, databases utilised, and criteria for filtering in the methodology section (see section 2). We aimed to provide readers with a clear understanding of how the literature was identified and selected for inclusion. Additionally, to enhance transparency, we have publicly made available the Google Sheets [9] that was used to record the extracted data. This document details the reasons for excluding specific papers from the review and summarises the key takeaways from the included papers. This serves to enhance transparency by elucidating the rationale behind the exclusion of certain studies, enabling readers to assess the scope and rigour of our review comprehensively.

Furthermore, to maintain methodological rigour and adherence to best practices in systematic reviews, we reported our findings in accordance with the PRISMA for Scoping Reviews [9] guidelines. This standardised reporting framework ensures the comprehensive and transparent reporting of systematic review processes and results, thereby enhancing the credibility and reproducibility of our study's findings.

Finally, we acknowledge the use of generative AI tools GPT-3.5 and GPT-4 (by OpenAI)[10] for assisting in the writing process. While these tools provided significant help in enhancing the clarity and coherence of the text, we exercised our own judgement to evaluate and ensure the accuracy and reliability of the generated content. The specific prompt used was:

> "Could you please improve the coherence and readability of the given text?"

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A Appendix

A.1 Annotation Schema

Table 4: Annotation schema used to extract data from the papers.

Category	**Description**
Title	The title of the paper
Bibtex	The BibTeX reference for the paper
Publication Year (in xxxx format; for example 2013)	The year the paper was published
Did you include it in the final paper?	Indicates whether the paper was included in the final review
If you answered no to the above, explain why.	Reason for exclusion if the paper was not included
How did it take inspiration from Human Social Cognition?	Explanation of how the paper was inspired by human social cognition
Type of Embodiment	The type of embodiment used in the study (virtual or physical)
Robot used	Specific robot(s) used in the study
Focus of the paper (for example, joint attention, proxemics, etc)	The main focus or topic of the paper
Domain (if applicable)	The domain or field in which the study is situated
Challenges mentioned	Challenges or issues discussed in the paper
How was the inspiration realised (if applicable)? + What significance/contributions does this study have?	How the inspiration from human social cognition was implemented and the significance of the study
If the paper is a discussion paper, then what are they conveying that will benefit in building more social robots?	Key points from discussion papers that contribute to the development of social robots

A.2 Extracted Data and Reason for Exclusions

Table 5 displays all the records that underwent full-text assessment during the screening process. However, due to space restrictions, only select columns are shown. For a detailed table, please refer to the complete dataset available here. Table 6 displays the records that were excluded from the review, along with the reasons for their exclusion.

Table 5: Details of all records that underwent full-text assessment. For a comprehensive view, refer to the complete dataset here.

Title	Publication Year	Included	Type of Embodiment	Robot used	High Level Focus Area	Sub-focus area
Attention Coupling as a Prerequisite for Social Interaction	2003	Yes	Physical	Infanoid	human-inspired-behaviour	eye-gaze
Robot Command, Interrogation and Teaching via Social Interaction	2005	No				
The Haptic Creature Project: Social Human-Robot Interaction through Affective Touch	2008	No	Physical			
Are physically embodied social agents better than disembodied social agents?: The effects of physical embodiment, tactile interaction, and people's loneliness in human-robot interaction	2006	Yes	Physical	Aibo	embodiment	benefits
Embodied social interaction for service robots in hallway environments	2006	No				
KASPAR - a minimally expressive humanoid robot for human-robot interaction research	2009	Yes	Physical	KASPAR	embodiment	design, benefits
Social Behavior Modeling Based on Incremental Discrete Hidden Markov Models	2013	No				
Simulating the Emergence of Early Physical and Social Interactions : A Developmental Route through Low Level Visuomotor Learning	2014	No				
Infants' Brains Are Wired to Learn from Culture: Implications for Social Robots	2015	No				
Using Human Knowledge Awareness to Adapt Collaborative Plan Generation, Explanation and Monitoring	2016	No				
Social cognitive neuroscience and humanoid robotics	2009	Yes			embodiment, experiment	design
Clustering social cues to determine social signals: Developing learning algorithms using the "N-Most Likely States" approach	2016	No				
An Embodied Cognition Approach to Mindreading Skills for Socially Intelligent Robots	2009	Yes	Physical	Leanardo	human-inspired-behaviour	cognitive-architecture, ToM
Show, Attend and Interact: Perceivable Human-Robot Social Interaction through Neural Attention Q-Network	2017	No				

Title	Publication Year	Included	Type of Embodiment	Robot used	High Level Focus Area	Sub-focus area
Responsive Social Positioning Behaviors for Semi-Autonomous Telepresence Robots	2017	No				
Recognition of Gestural Behaviors Expressed by Humanoid Robotic Platforms for Teaching Affect Recognition to Children with Autism - A Healthy Subjects Pilot Study	2017	No				
Enaction as a Conceptual Framework for Developmental Cognitive Robotics	2010	Yes			embodiment	design
"Artificial humans": Psychology and neuroscience perspectives on embodiment and nonverbal communication	2010	Yes			embodiment, experiment	design
The Uncanny Valley	2012	Yes			embodiment	design
Effect of Explicit Emotional Adaptation on Prosocial Behavior of Humans towards Robots depends on Prior Robot Experience	2018	No				
MiRo: Social Interaction and Cognition in an Animal-like Companion Robot	2018	No				
Using Cluster-based Stereotyping to Foster Human-Robot Cooperation	2012	Yes	Physical	NAO	human-inspired-behaviour	stereotyping
Robot Behavior Toolkit: Generating Effective Social Behaviors for Robots	2012	Yes	Physical	Wakamaru	human-inspired-behaviour	behaviour-generation, eye-gaze
Human-humanoid robot social interaction: Laughter	2013	Yes	Physical	Kobian	human-inspired-behaviour	laughter
TTS-driven Synthetic Behaviour-generation Model for Artificial Bodies	2013	Yes	Virtual	iCUB	human-inspired-behaviour	behaviour-generation
Cooperative Human Robot Interaction Systems: IV. Communication of Shared Plans with NaÃ¯ve Humans using Gaze and Speech	2013	Yes	Physical	iCub	human-inspired-behaviour, experiment	joint-plan
Embodied Language Learning and Cognitive Bootstrapping: Methods and Design Principles	2016	Yes	Physical	iCUB	human-inspired-behaviour	language-learning
To Move or Not to Move? Social Acceptability of Robot Proxemics Behavior Depending on User Emotion	2021	No				
Behavior Hierarchy-Based Affordance Map for Recognition of Human Intention and Its Application to Human-Robot Interaction	2016	Yes	Physical	Mybot-KSR	human-inspired-behaviour	affordance-based

Title	Publication Year	Included	Type of Embodiment	Robot used	High Level Focus Area	Sub-focus area
Role of Gaze Cues in Interpersonal Motor Coordination: Towards Higher Affiliation in Human-Robot Interaction	2016	Yes	Virtual	virtual iCUB	human-inspired-behaviour	eye-gaze
The Importance of Mutual Gaze in Human-Robot Interaction	2017	Yes	Physical	iCUB	human-inspired-behaviour	eye-gaze
Designing the Mind of a Social Robot	2018	Yes	Physical	FACE	embodiment, human-inspired-behaviour	cognitive-architecture
Dyadic Gaze Patterns during Child-Robot Collaborative Gameplay in a Tutoring Interaction	2018	Yes	Physical	NAO	human-inspired-behaviour	eye-gaze
Human perception of intrinsically motivated autonomy in human-robot interaction	2022	No				
Social behaviour as an emergent property of embodied curiosity: a robotics perspective	2018	Yes			human-inspired-behaviour	curiosity-based
On the role of eye contact in gaze cueing	2018	Yes	Physical	iCUB	human-inspired-behaviour, experiment	eye-gaze
Joint action with iCub: a successful adaptation of a paradigm of cognitive neuroscience in HRI	2018	Yes	Physical	iCUB	human-inspired-behaviour, experiment	eye-gaze
Cognitive Architectures for Social Human-Robot Interaction	2016	No				
Memory and mental time travel in humans and social robots	2019	Yes	Physical	iCUB	human-inspired-behaviour	memory
Action alignment from gaze cues in human-human and human-robot interaction	2019	Yes	Physical	iCUB	human-inspired-behaviour	eye-gaze
Would a robot trust you? Developmental robotics model of trust and theory of mind	2019	Yes	Physical	Pepper	human-inspired-behaviour	cognitive-architecture, ToM
Gestural Behavioral Implementation on a Humanoid Robotic Platform for Effective Social Interaction	2014	No				
Behavioral and Emotional Spoken Cues Related to Mental States in Human-Robot Social Interaction	2015	No				
Facial Expression of Social Interaction Based on Emotional Motivation of Animal Robot	2016	No				

Title	Publication Year	Included	Type of Embodiment	Robot used	High Level Focus Area	Sub-focus area
Affordance-based altruistic robotic architecture for human-robot collaboration	2019	Yes	Physical	Baxter	human-inspired-behaviour	affordance-based, behaviour-generation
Planning for Social Interaction in a Robot Bartender Domain	2013	No				
From social brains to social robots: applying neurocognitive insights to human-robot interaction	2019	Yes			human-inspired-behaviour	human-inspired-behaviour
Workshop on Intention Recognition in HRI	2016	No				
Social interaction with robots and agents: Where do we stand, where do we go?	2009	No				
Synchrony as a Tool to Establish Focus of Attention for Autonomous Robots	2012	No				
A Neurorobotics Approach to Investigating the Emergence of Communication in Robots	2019	Yes	Physical	ROBOTIS OP2	human-inspired-behaviour	predictive-coding, behaviour-generation
A Literature Review of the Research on the Uncanny Valley	2020	Yes			embodiment	design
The virtual and the physical: two frames of mind	2021	Yes			embodiment	design
A Biological Inspired Cognitive Framework for Memory-Based Multi-Sensory Joint Attention in Human-Robot Interactive Tasks	2021	Yes	Physical	iCUB	human-inspired-behaviour	cognitive-architecture
Social Human-Robot Interaction of Human-care Service Robots	2018	No				
"Sociality and Normativity for Robots": An Introduction	2017	No				
Consciousnes-based emotion and behavior of pet robot with brain-inspired method	2017	No				
Social Cognition of Robots during Interacting with Humans	2015	No				
Robot Gaze Behavior Affects Honesty in Human-Robot Interaction	2021	Yes	Virtual	iCUB	human-inspired-behaviour	eye-gaze
Comparison of Human Social Brain Activity During Eye-Contact With Another Human and a Humanoid Robot.	2021	Yes	Physical	Maki	human-inspired-behaviour, experiment	eye-gaze

Title	Publication Year	Included	Type of Embodiment	Robot used	High Level Focus Area	Sub-focus area
Mind the Eyes: Artificial Agents' Eye Movements Modulate Attentional Engagement and Anthropomorphic Attribution	2021	Yes	Virtual	iCUB	human-inspired-behaviour, experiment	eye-gaze
Toward an Attentive Robotic Architecture: Learning-Based Mutual Gaze Estimation in Human-Robot Interaction	2022	Yes	Physical	iCUB	human-inspired-behaviour	eye-gaze
Physical vs. Virtual Agent Embodiment and Effects on Social Interaction	2016	Yes		NAO	embodiment	design

Table 6: Details of records excluded from the review, along with reasons for exclusion.

S No.	Title	Publication Year	Included	Reason for Exclusion
1	Robot Command, Interrogation and Teaching via Social Interaction	2005	No	It deals with use of grammatical constructions in language to drive interaction, which is not the human social cognition aspect we are interested in.
2	The Haptic Creature Project: Social Human-Robot Interaction through Affective Touch	2008	No	It does not meet the following selection criteria: "The study involves an embodied agent". It has an physical agent that is not specifically designed to be "animal-like". It does not meet the embodiment definition we set. They explicitly mention that. Moreover, this study itself is not complete, as they mention their future goals of the project. The study only had the wizard-of-oz prototype. They were in the process of developing an automated prototype. For these reasons, the study was avoided.
3	Embodied social interaction for service robots in hallway environments	2006	No	The embodiment is not the one we set out to explore.
4	Social Behavior Modeling Based on Incremental Discrete Hidden Markov Models	2013	No	It has no embodied agent that is involved in the study, so it was ignored.
5	Simulating the Emergence of Early Physical and Social Interactions: A Developmental Route through Low Level Visuomotor Learning	2014	No	It is not embodied in the way we want. It uses a robotic arm.
6	Infants' Brains Are Wired to Learn from Culture: Implications for Social Robots	2015	No	Though it is an interesting framework, it gives no information. I believe this paper is simply an introduction to a research program.
7	Using Human Knowledge Awareness to Adapt Collaborative Plan Generation, Explanation and Monitoring	2016	No	This paper was not included as it did not meet the following selection criteria: "The study involves a biologically-inspired (or human social-cognition-inspired) implementation in an embodied agent."
8	Clustering social cues to determine social signals: Developing learning algorithms using the "N-Most Likely States" approach	2016	No	No, because the paper uses a machine learning approach and takes no inspiration from human socio-cognitive processes. In fact they mention: “Our results indicate that systems can be developed to foster human-robot teaming without a complete understanding or representation of human socio-cognitive processes."
9	Show, Attend and Interact: Perceivable Human-Robot Social Interaction through Neural Attention Q-Network	2017	No	It does not meet the selection criteria: "The study involves a biologically-inspired (or human social-cognition inspired) implementation in an embodied agent" as it only uses a Multimodal Dee Attention Recurrent Q-Network.
10	Responsive Social Positioning Behaviors for Semi-Autonomous Telepresence Robots	2017	No	Though proxemics is relevant, it is a tele-presence robot, which does not have the embodiment we are looking for.

S No.	Title	Publication Year	Included	Reason for Exclusion
11	Recognition of Gestural Behaviors Expressed by Humanoid Robotic Platforms for Teaching Affect Recognition to Children with Autism - A Healthy Subjects Pilot Study	2017	No	It only validates different gestures, which isn't important to our goal.
12	Effect of Explicit Emotional Adaptation on Prosocial Behavior of Humans towards Robots depends on Prior Robot Experience	2018	No	This paper was excluded because it only had dialogue-based implementation and were not very relevant to what we are looking at. We consider it to no meet the criteria: "took inspiration from humans".
13	MiRo: Social Interaction and Cognition in an Animal-like Companion Robot	2018	No	Its embodiment is not humanoid. Moreover, it is an ongoing work.
14	To Move or Not to Move? Social Acceptability of Robot Proxemics Behavior Depending on User Emotion	2021	No	This paper is discarded as it does not follow the selection criteria: "The study is not a mere discussion/suggestion/review". This study focused on the human-side. It looked into how humans perceived the robot, when they were shown a video of VIVA and a human interacting. It did not focus on the implementation of human-inspired proxemics behaviour.
15	Human perception of intrinsically motivated autonomy in human-robot interaction	2022	No	It does not include an embodied agent in the sense we are looking for.
16	Cognitive Architectures for Social Human-Robot Interaction	2016	No	This paper in itself was a mere workshop invitation. So it was not included, however, papers for the workshop will be considered.
17	Gestural Behavioral Implementation on a Humanoid Robotic Platform for Effective Social Interaction	2014	No	This paper was excluded because it was about gesture to improve perception of the right emotional state. However, this does not take inspiration from social cognition, so we excluded it for this study.
18	Behavioral and Emotional Spoken Cues Related to Mental States in Human-Robot Social Interaction	2015	No	This study does not take inspiration from social cognition in human in any way.
19	Facial Expression of Social Interaction Based on Emotional Motivation of Animal Robot	2016	No	The paper was discarded due to its written quality.
20	Planning for Social Interaction in a Robot Bartender Domain	2013	No	Though this paper has embodied bar tender agent, and implements a whole architecture that integrates low-level sensing and high-level knowledge-based planning, it doesn't back the work by showing works of human social cognition.
21	Workshop on Intention Recognition in HRI	2016	No	It is a workshop paper, so it was not included in the review. Tried searching for papers from the workshop, but failed.
22	Social interaction with robots and agents: Where do we stand, where do we go?	2009	No	This paper was excluded as it was a workshop paper.
23	Synchrony as a Tool to Establish Focus of Attention for Autonomous Robots	2012	No	This paper was excluded due to its poor reading quality, which made it tough for the reviewer to extract data.

S No.	Title	Publication Year	Included	Reason for Exclusion
24	Social Human-Robot Interaction of Human-care Service Robots	2018	No	This paper was discarded as it was a workshop invitation. Papers presented in this workshop could not be retrieved as the shared link did not work.

A.3 Subfocus Areas

Table 7: Subfocus Areas of Papers with Descriptions

Subfocus Area	**Description**
Eye-Gaze	Studies focusing on the role of eye gaze in improving social interaction with embodied agents.
Cognitive Architecture	Studies discuss the design and implementation of cognitive architectures that take inspiration from human cognition.
Theory of Mind (ToM)	Studies that take inspiration from Theory of Mind to implement mental state attribution in artificial agents.
Stereotyping	Studies that implement human-like categorical thinking in embodied agents.
Behaviour Generation	Studies on mechanisms for generating human-like behaviours in agents, enhancing realism and engagement.
Laughter	Studies that focused on laughter recognition or generation in embodied agents.
Joint Plan	Exploration of agents' ability to form and execute plans collaboratively with humans or other agents.
Language Learning	Studies on how agents can learn and use human language for effective communication and interaction.
Affordance-Based	Research on how agents learn affordances and use that to generate behaviours.
Curiosity-Based	Investigations into mechanisms that drive agents to explore and learn from their environment autonomously.
Memory	Studies on the role of human-like memory systems in agents.
Human-inspired behaviour	Discussion papers that discuss how inspiration can be taken from humans while developing socially embodied agents.
Predictive Coding	Studies that use human-like predictive coding in embodied agents.