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Review

A survey of behavioural models for social robots

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Abstract:
The cooperation between humans and robots is becoming increasingly important in our society. Consequently, there is a growing interest in the development of models that can enhance the interaction between humans and robots. A key challenge in the Human-Robot Interaction (HRI) field is to provide robots with cognitive and affective capabilities, developing architectures that let them establish empathetic relationships with users.
Several models have been proposed in recent years to solve this open-challenge. This work provides a survey of the most relevant attempts/works. In details, it offers an overview of the architectures present in literature focusing on three specific aspects of HRI: the development of adaptive behavioural models, the design of cognitive architectures, and the ability to establish empathy with the user. The research was conducted within two databases: Scopus and Web of Science. Accurate exclusion criteria were applied to screen the 1007 articles found (at the end 30 articles were selected). For each work, an evaluation of the model is made. Pros and cons of each work are detailed by analysing the aspects that can be improved so that an enjoyable interaction between robots and users can be established.

Keywords: social robots; behavioural models; assistive robotics; cognitive architectures; empathy; human-robot interaction.

1. Introduction

Social Robotics is commonly defined as *the research field dedicated to the socially skillful robots*[1]. The main ability of social robots is to establish a natural interaction with humans. Human-Robot Interaction field of study tries to shape the interactions between one or more humans and one or more robots. Over the latest years, there is an increasing interest in HRI due to the increasing usage of robots not only in industrial fields, but also in other areas as schools [2], homes [3] and hospitals [4] and rehabilitation centres [5].
Consequently, in the near future, robots will concretely share environments with human beings in order to actively collaborate with them in specific daily tasks. The presence of a robot, in fact, could be a useful support during the management of daily activities [6] , the promotion of social inclusion [7] and the suggestion of healthy activities [8]. As robots need to work closely with humans, there is the growing necessity of developing behavioural models for social robots to have high quality interaction and high level of acceptability in providing useful and efficient services [9].

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This survey expresses this growing interest and the need to help the researches in this field to trim the large amount of work which is loosely related to the topic and rarely put into real practice and experimented.

To achieve fluent and effective human-like communication, robots must seamlessly integrate the necessary social behaviours for a given situation using a large number of patterned behaviours that people employ to achieve particular communicative goals. Robots should be endowed with the capability of understanding feelings, intentions and beliefs of the user which are not only directly expressed by the user, but that are also shaped by bodily cues (i.e. gaze, posture, facial expressions) and vocal cues (i.e. vocal tones and expressions) [10]. The non-verbal immediacy which characterizes communications between humans should be conveyed also in HRI. Moreover the ability to replicate human non-verbal immediacy in artificial agents is twofold. On one side, it allows the detection of emotional and cognitive state of the user, which is useful to develop proactive robots. On the other side, it allows to shape the behaviour of the robot so that to encode behaviour capabilities in interaction as those of humans. The latter case leads to the possibility to automatically generate new robotic behaviours, that the robot learns directly by the user.

The first attempts to solve this challenge have been performed by developing intelligent systems able to detect user's emotion [11] and by identifying the key-factors that should be adjusted to make the interaction smoother (i.e. interpersonal distance, mental state, user's feedback, and user's profile) [12]. More advanced steps should be performed so that robots are endowed with cognitive and affective capabilities that could provide them with tools to establish empathetic relationships with users and to gain social cognitive mechanisms that are necessary to be perceived as a teammate [13], [14].

The robot's ability to establish empathic relationships has a key role in persuading other humans, since it indicates the degree of perceived bodily and psychological closeness between people. In order to achieve this target, lot of efforts were progressively put in understanding how psychology and cognitive neuroscience could be integrated in the design process of artificial cognitive architectures. Indeed, the field of brain-inspired technologies has become a hot topic in the last years. For this reason, in the following sections are listed papers that took into account cognitive models for robots starting from a neurocognitive stand-point.

Specifically, researchers are working on the development of cognitive architectures approaching a fully cognitive state, embedding mechanisms of perception, adaptation, and motivation [15].

From the analysis of the state of the art, the papers of the review are grouped on the basis of three main application areas:

- **Cognitive architectures** - This term refers to research works where both abstract models of cognition and software instantiations of such models, employed in the field of artificial intelligence, are described [16]. Cognitive architectures have the fundamental role to enable artificial intelligence in robotic agents, in order to exhibit intelligent behaviours.

- **Behavioural adaptation criterion** – Papers belonging to this group describe robot's social abilities enhanced by the robot's capability of adapting its behaviour to the user's need and habits [17].

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- **Empathy** - In human-human relationships, this term explains the capacity to take the role of the other to adopt alternative perspectives [17]. Works clustered in this category present a particular emphasis on the attempts to reproduce this ability in robotic agents to establish an empathetic connection with the user, improving HRI.

In this review, several models and architectures used in social robots are presented to evaluate how these attempts fare in achieving an efficient robot-human interaction. A comparison with works presenting experimentation to demonstrate the persuasiveness of robots is also provided to highlight limitations and future trends. In details, the paper is organized as follows: in section 2, the research methodology for the review is explained. In section 3 and 4 the results and the discussions regarding the papers are shown. In section 5, a summary of the review and its conclusions are presented.

2. Materials and Methods

This section presents the methodology used in the paper to select the most appropriate recent developments as published in the literature, covering the topics of behavioural models for robots.

2.1. Study selection procedures

This paper reviews empirical studies published between 2010 and 2018 since most of the advances in this area have occurred within that timeframe. A bibliography was developed upon searches in Scopus and Web of Science electronic databases. Reference lists of included articles and significant review papers were examined to include other relevant studies. The search queries contained the following terms: "(cognitive AND robotics AND architectures) OR (learning AND assistive AND robots) OR (affective AND robot AND behaviours), OR (empathy AND social AND robots)".
Application of these search keys provided a total of 1007 hits: 672 hits in Web of Science in the field "Topic" and 335 hits in Scopus in "Article title, abstract, keywords" fields.
After deletion of duplicates, the titles and abstracts retrieved by the electronic search were read first, to identify articles deserving a full review; papers about users' emotion recognition and about emotions as unique input for HRI were excluded. Additionally, papers not written in English were excluded. A total of 47 works was selected at this stage.
Then, a full-text assessment was carried out. The reading process led to exclusion of 9 papers out of topic, 2 papers focusing only on definitions and taxonomy, 5 papers for missing the model's evaluation, and 4 papers focusing more on users' perception about robot's abilities without behavioural adaptation.
The final list of papers includes 30 studies which satisfy all the following selection criteria: (i) employment of cognitive architectures and/or behavioural models; (ii) explanation of cognitive architectures and/or behavioural models; (iii) research focus on robotic agent's capabilities; (iv) behavioural adaptation according to different strategies; and (v) analysis conducted on social or assistive robots. The studies' selection process is shown in Figure 1.

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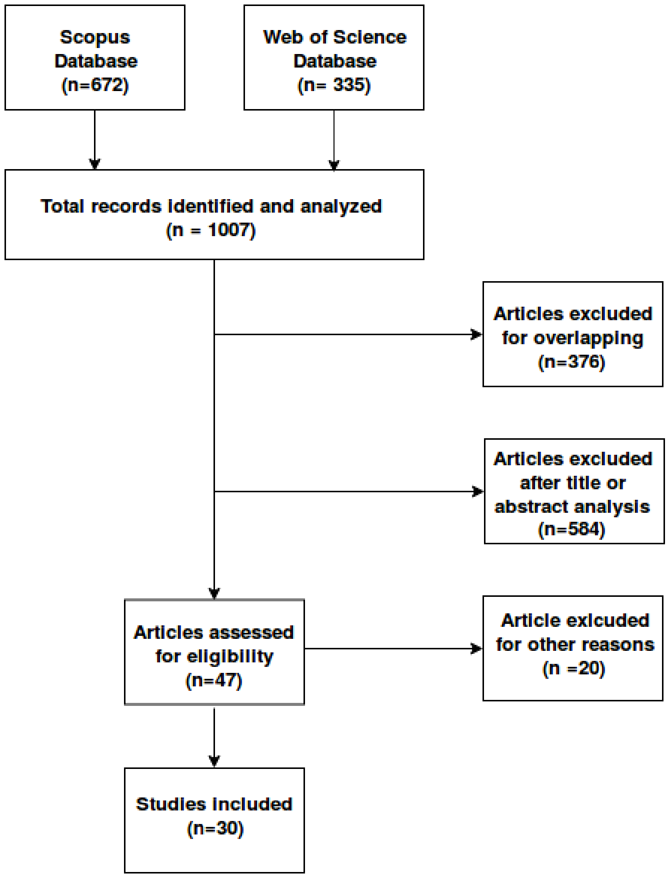

Figure 1 Selection process of relevant papers

3. Results

3.1. Application Overview

The interest toward behavioural architectures has grown, as shown in Figure 2. Particularly, of the fully evaluated papers, 4 papers (13,33%) were published before 2014 and 26 papers (86,67%) were published within the past five years.

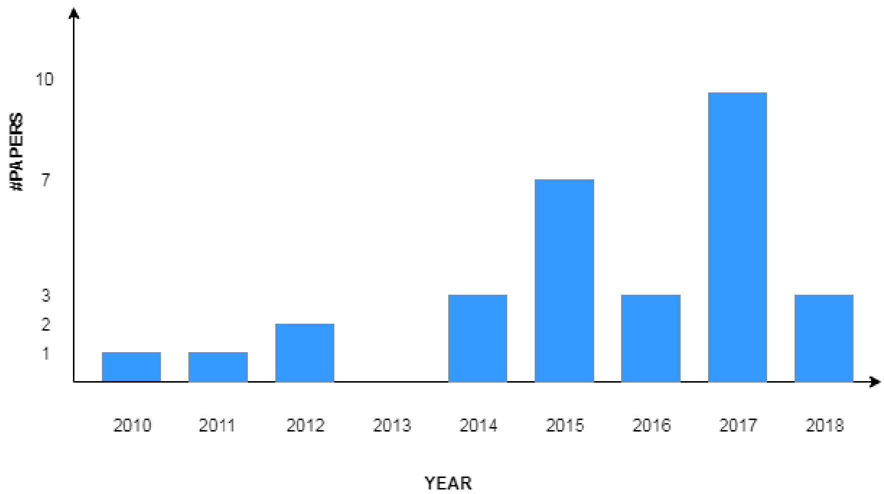

Figure 2 Number of papers analysed in this review, categorized by year of publication

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The selected papers can be divided first into two big groups: the works describing cognitive architectures, behavioural adaptation models and empathy models from a conceptual point of view (seven papers as summarized in Table 1), and the works presenting experimental studies (twenty-three papers summarized in Table 2). Additionally, the papers can be grouped subsequently on the basis of the three areas described in the introduction.

Most of the papers included in this review focus on behavioural adaptation strategies (43,34%), followed by cognitive architectures (33,33%), and empathy (23,33%) (Figure 3).

In the following paragraphs, papers reviewed are presented as organized in two macro-areas: works from a theoretical point of view only, and works that include experimental sessions. Then, inside each macro-area, papers are presented according to the sub-categories defined earlier.

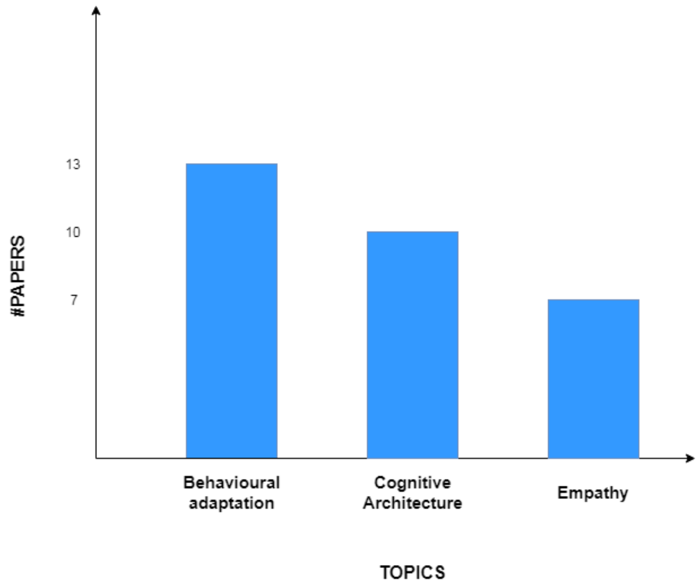

Figure 3 Number of papers, categorized by main application covered

3.2. Data Abstraction

Data were abstracted from each selected article, as reported in Tables 1–2. These tables give the main purpose of each work, the robot used, the extracted features, and a short description of the implemented model/algorithms. The last column reports the area to which they belong (cognitive architectures, behavioural adaptation criterion, empathy). In addition, for those papers which describe an experimental protocol, the number and the type of participants involved in the experimental session are also reported. The objective of the abstraction is to provide an overview of the papers included in this survey and to facilitate their comparison.

3.3. Theoretical works on the development of robotics behavioural models

In this section, published works on theoretical studies of robotics models are described. Occurrences of theoretical studies belong only to cognitive architectures and empathy application areas (Table 1).

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3.3.1. Concepts for cognitive application area

Human cognitive systems are often adopted as inspiration to develop a cognitive architecture for robots. In the last years, in fact, assistive and companion robots have accomplished advanced social proficiency whenever they were equipped with cognitive architectures. Relevant examples of this trend are listed below in this section.

In [14], cognitive architectures are described, citing the Learning Intelligent Distribution Agent, Soar, and the Adaptive Control of Thought-Rationale architecture with the aim to provide a set of commitments useful to develop intelligent machines. In this work are presented the Theory of Mind (ToM) and the "perceptual-motor simulation routines", two of the fundamental theories of social cognition. Particularly, the ToM would represent the inherent human ability in attribute mental states to other social agents. That is possible through the application of theoretical inference mechanisms on cues gathered by people during social interactions (e.g. facial expression could be used in order to probabilistically determine the person's emotional state). On the other hand, the paradigm of "perceptual-motor simulation routines" state that people would be able to understand others' mental state by the use of simulation mechanisms, which would help the subject to attribute a mental state to his\her interlocutor. The authors suggested their approach, Engineering Human Social Cognition (EHSC), which incorporates social signal processing mechanisms to allow a more natural HRI and focus on verbal and non-verbal cues to support interaction. Social signal processing is able to interpret social cues and then individual mental states. The authors underlined also that modelling recommendations have centred primarily on the perceptual, motor, and cognitive modelling of a robotic system that spans disciplinary perspectives. Indeed, this is the area that will require extensive work in the future. As such, the next steps in this area must include both research and modelling efforts that assess the issues and challenges of integrating the proposed types of models and formalisms. That effort can aid in the development of an integrated and working system based on these recommendations. These recommendations, if instantiated, would provide some basic perceptual, motor, and cognitive abilities, but future efforts should address whether these would also support more complex forms of social interaction. Such a capability would permit an artificial system to better express or perceive emotions while interacting and communicating with humans in even more complex social scenarios would require shared decision-making and problem-solving.

Among cognitive architectures to be implemented into social robots to improve HRI, [18] presented a work with the aim to develop a human-aware cognitive architecture. This system is conceived to provide robots with the ability to understand the human state, physical and affective, and then to interact in a suitable manner. Starting from cognitive models, the authors organized the architecture by considering a cognitive model that represents how memory is organized: a declarative memory for semantic and episodic facts, and procedural memory. According to this organization, the robot's tasks are encoded as a sequence of actions and events, thanks to a symbolic task planner, with the aim to verify if, and in what way, the task has already been executed.

To provide robots with believable social responses and to have more natural interaction, a theoretical model was developed by [19]. The proposed architecture is human brain-inspired and it is structured into four principal modules which encompasses anatomic structures and cognitive functions, namely the sensory system, the amygdala system, the hippocampal system, and the working memory. This brain inspired system provides robots with emotional memory, which is fundamental to be able to

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learn and adapt to dynamic environments. In particular, the authors focus on artificial emotional memory, which lets robots remember emotions, associate them with stimuli, and react in an appropriate way if unpleasant stimuli occur. External stimuli are pre-processed by the sensory system, composed of sensory cortex and thalamus; prediction and association between stimuli and emotions are via the amygdala system that provides emotional feedback to the hippocampal system. Finally, another brain-inspired architecture was developed in [20]. It focuses on the autonomous development of new goals in robotic agents. Starting from neural plasticity, the Intentional Distributed Robotic Architecture (IDRA) is an attempt to simulate a brain circuit composed of amygdala, thalamus, and cortex. The cortex is responsible for receiving signals from sensory organs; the thalamus develops new motivations in mammals, while the amygdala manages the generation of somatosensory responses. Elementary units, called Deliberative Modules (DM), enable a learning process that lets the robot learn and improve its skills during the execution of a task. This process is known IDRA. Working memory (acting as cerebral cortex) and goal generator (acting as thalamus) modules compose each DM. Amygdala is represented by instincts modules. Experiments were made to verify the ability of a NAO robot[1] in learning to distinguish particular object shapes and in exploring in an autonomous way and learning new movements. Sensing and actuation as main activities required for learning and cognitive development were tested: NAO was able to learn new shapes taking sensorial inputs and to compose new behaviours, consistent with these goals. The authors underlined their choice to opt for directly using the high-level representation of the neural function, even though a system that uses neural coding as basic representation could be integrated into IDRA.

3.3.2. Concepts for empathy area

Empathy is becoming an important field of social robotics and several behavioural models take this aspect into consideration.

In [21], it was shown how different models based on emotions were created to build empathetic and emotional robots. The main cues used in these models are movements, gestures, and postures. In another paper, the same authors explored different dimensions of artificial empathy and revealed different empathy models: a conceptual model of artificial empathy that was structured on the developmental axis of self-other cognition, statistical models based on battery level or temperature, and a four dimension empathy model were presented and described . The cues used in this article were unimodal and multimodal communication cues as opposed to the previous one that used movements.

In [22], it was discussed a conceptual model of artificial empathy with respect to several existing studies. This model is based on an affective developmental robotics which provides more authentic artificial empathy based on the concept of cognitive developmental robotics. The authors showed how the model worked using two different robots: an emotional communication robot called WAMOEBA and a humanoid robot called WE.

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[1] https://www.softbankrobotics.com/emea/en/robots/nao/find-out-more-about-nao. Retrieved July 2018.

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3.4. Experimental works on the development and implementation of behavioural model

In this section, published works on behavioural models with the experimental loop are shown and are divided into sub-categories according to the application area (Table 2).

INSERTING TABLE 2

3.4.1. Experimental works for cognitive architectures

Concerning cognitive architectures, [23] proposed a cognitive framework inspired by the human limbic system to improve HRI between humanoid robots and children during a game session. The robot's emotional activity was modelled with computational modules representing amygdala, hippocampus, hypothalamus, and basal ganglia and used to suggest users' optimal game actions. The results showed that this cognitive architecture provided an efficient mechanism for representing cognitive activity in humanoid robots. The children's attention level was higher compared to those of a game session without the use of the robot.

[24] aimed to use an Interactive Social Engagement Architecture (ISEA) and an interactive user interface to gather information from children. The authors tested the developed architecture with a NAO robot and two other humanoids with 186 children. The ISEA is able to integrate and combine human behaviour models, behaviour-based robotics, cognitive architectures, and expert user input to improve social HRI. Eight modules compose the framework presented: knowledge, user input, sensor processing, perceptual, memory, behaviour generation, behaviour arbitration, and behaviour execution modules. The knowledge module models human behaviours, while the perceptual module manages external sensor data from the environment, and processes and interprets data, sending results to the memory module. The behavioural generation module calculates which behaviour and communication strategies must be used and sends data to the behavioural generation module. Novel emergent behaviours can be obtained by combining newly generated behaviours with the stored behaviours in memory modules. Every time that behaviour is displayed, the robot's internal state is updated to keep track of the new data storage. Preliminary results showed that children seemed to find it more comfortable to establish an engagement with a robot, rather than with humans, in sharing information about their bullying experiences at school. Although this research is only midway through the grant award period, the developments and results are promising. Moreover, the authors said that slow and steady progress is occurring with the development of this Integrated Robotic Toolkit, but there is still significant and ongoing work to be explored with this approach.

[25] proposed an intention understanding system that consists of perception and action modules. It is an object-augmented model, composed of two neural network models able to integrate perception and action information to allow the robot to better predict the user's intention. The model was tested in a cafeteria with customers and clerks. The action module was able to understand the human intention and associates a meaning to predict an object related to that action. The combination of these modules resulted in an improved human intention detection.

Finally, [26] proposed a robotic system that could learn online to recognize facial expressions without having a teaching signal associated to a facial expression.

3.4.2. Experimental works on empathy

When a social robot interacts with human users, empathy represents one of the key factors to increase natural HRI. Emotional models are fundamental for social abilities to reach empathy with users.
In [27], for example, the authors evaluated and compared the emotion recognition algorithm in two different robots (NAO and Pepper) and created metrics to evaluate the empathy of these social robots.
In [28], the authors developed emotion-based assistive behaviour to be implemented in social assistive robots. According to the user's state, the model is able to provide abilities to the robot to show appropriate emotions, eliciting suitable actions in humans. The robot's environmental and internal information plus user affective state represent the inputs for the Brian robot[2] to alter its emotional state according to the well-being of a participant and to assistant in executing tasks. In this work, the robot emotional module is employed not to provoke emotional feelings, but rather in terms of assistive tasks that the robot should perform to satisfy the user's well-being.

The experiments show the potential of integrating the proposed online updating Markov chain module into a socially assistive robot to obtain compliance from individuals to engage in activities. Using robotic behaviour that focuses on the well-being of the person could be beneficial to the person's health. Moving to a fully encompassing target user group is needed to test the overall robot in its intended assistive applications.
In [29], the authors implemented an experiment with the I-Cat robot[3], aiming to provide a computer-based assistant that could persuade and guide elderly people to behave in a healthy way. Previous works demonstrated that combining the robot's empathy with the user's state contributed to a better appreciation of a personal assistant [30]. I-Cat features an emotional model that makes it able to smile and express sadness. Authors implemented natural cues such as understanding, listening, and looking, to perform different roles for the robot (educator, buddy, and motivator). The analysis was conducted by considering participants' personalities; the percentage of the total time that participants talked, laughed, and looked at the robot; and how many times the participants said "goodbye", as a sign of interpretation of the robot as a social entity. The aim of the work was to establish behaviours for an electronic personal assistant with a high level of dialogue, emotions, and social competencies. The findings showed that natural cues used by I-Cat provoked more empathy and social involvement with users. When non-social cues were used, users perceived the robot as less trustworthy and less persuasive, avoiding its suggestions.
During experiments, the physical characters were indeed found to be more trustworthy but less empathetic than the virtual character, which was not expected. This negative outcome on empathy might be due to specific constraints of the iCat: it makes a relatively high amount of noise when it moves, and the head and body movements may not be fluent enough. Another technical constraint was the (occasional) appearance of errors in the movements and speech, such as skipping choices of

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2 Brownsell, Alex (29 May 2013). *"Confused.com overhauls brand in search of 'expert' positioning"*. Marketing Magazine. *http://www.marketingmagazine.co.uk/article/1183890/confusedcom-overhauls-brand-search-expert-positioning*. *Retrieved July 2018*.

3 http://www.hitech-projects.com/icat/. Retrieved July 2018.

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the multiple choice questions. Furthermore, it may be that the three character roles did not capture important advantages of a physical character that can act in the real environment. For instance, more positive outcomes might show up with a character that helps to attend to a medicine box with a specific location in the house, compared to a virtual character that is not a real actor in the house.

In [15], the authors provided their contribution to social pervasive robotics by proposing an affective model for social robots, empathizing the concept of empathy. Behavioural adaptation according to users' needs and preferences resulted in preliminary tests that achieved a better social inclusion in a learning scenario. The first part of the model, called "Affective loop", was a module for the perception of humans, characterized by body-based emotion recognition that can recognize human emotions. According to the perception human module's outputs, the internal state of the robot changed, generating a complex emotional spectrum using a psycho-evolutionary theory of emotions. The user was able to visualize the robot's internal state and adjust some system parameters for the duration and intensity of each emotion. The user's interest in interaction was then monitored by the visual system: when it decreased, the robot changed its behaviour to socially involve the user and selected its emotion according to the user's state. Affective behaviours were also adapted to the goal of interaction in a cooperative task between robot and users.

Finally, a comparison between two different cultures was made in [31]. They made, in fact, a comparison between expression features of compassion, sympathy and empathy in British English and Polish using emotion models that had as inputs sensory cues.

3.4.3. Experimental works on behavioural model

An attempt to develop robots to be emotive and sociable like humans, showing a capability to adapt behaviour in a social manner, is presented in [32]. Starting from the Meyer-Briggs Theory on human personality, the authors mapped human psychological traits to develop an artificial emotional intelligence controller for the NAO robot. The proposed model was modelled as a biological system, as a structure of emotionally driven and social behaviour represented by three fuzzy logic blocks. Three variables were used as system input: "trigger event" that incites different psychological reactions, "behaviour profiler" that models event-driven behaviour to fit profiles of individuals whose behaviour needs to be modelled, and "behaviour booster/inhibitor" that augments or decreases the affective expressiveness. Social behaviour attributes were implemented in the NAO robot controller according to this model. The robot interacted with young researchers, recognizing calls and gestures, and locating people in the environment, showing personality traits of joy, sociability, and temperament. The model considers personality traits, social factors, and external/internal stimuli as human psychology does when interacting with others.

Combining the knowledge about personality traits discovered with Meyer-Briggs Theory and validated by [32] and experimental measurements of affective reactions from a live model performed by an actor, in [33] the authors developed a cognitive model of human psychological behaviour. This model includes personality types and human temperaments to be implemented into the Robothespian humanoid robot. The authors tuned the block scheme developed in [32] according to measurements from an actor performing as a behavioural live model. Different affective behaviours were played to create affective reactions to be added to the previous model.

Studies on proxemics, speed, and velocity provided interesting suggestions to improve HRI, especially in behaviour adaptation according to the user's movements and position. In [34], the authors investigated a robot's trajectories and speed when it follows a user in a real domestic environment to provide a comfortable social interactive behaviour. The authors presented a framework for people detection, state estimation, and trajectory generation that can regulate robotic behaviour. To select the appropriate behaviour, the robot used as input the state of the user and his/her localization, considering movements and the context. Trajectories and velocity were considered also in [35], with a robot moving with a social partner toward the same goal. The authors developed and tested a person-aware navigation system modifying a trajectory planner. The criterion to change the planner was the distance between robot and user, according to which the robot's behaviour adapted its velocity and trajectory to reach the goal, but remained close to the user at the same time. The approach described in this paper is limited because it only considers distance to the goal while ignoring the available free space. This model could be augmented to consider free-space features, such as free space in front of each social agent, distances to walls, and distances to other obstacles, to be more informed.

A similar work is presented by [36] with a model to interpret the user's behaviour and inclination toward interaction with an assistant robot. The robot was able to determine the user's behaviour through body movements and extraction of posture features. According to its interpretation, the robot decided if it should move closer or should wait for a better inclination from the user to interact. The major benefit of this model is that it does not use verbal instruction from the user, which allows the robot to assess the suitability of starting a conversation by using posture and movement analysis.

Behavioural adaptation according to users' preferences and feedback on robot's actions is presented in [37]. Two learning algorithms were applied to an internally developed adaptive robot, the EMOX (EMOtion eXchange) robot. After having identified the user's profile, the robot proposed a personalized activity, assisting and interacting with the user after the activity selection. The user's feedback after each activity was traced, letting the robot have a memory about the user's preferences to aid in suggesting a more appreciated activity later. The robot's architecture has observations of user behaviour, feedback, and environment to use as input. The robot's actions are the system output, determined through knowledge rules as interaction traces, users' profiles, decision process, and learning from the feedback process. The results showed that, even if the interaction modality, with hand gestures, was found difficult, most participants found the robot behaviour adaptable and pertinent to their preferences.

In [38], the authors presented a novel control architecture for the internally developed Brian 2.0 robot. The aim was to adapt the robot's behaviours according to user state, being a social motivator and assisting if needed. To be effectively integrated into society, robots should be provided with social intelligence to interact with humans. This architecture promoted the robot's abilities to support and motivate users during a game memory session to stimulate humans cognitively. Encouragement and assistance were provided through a modular learning architecture that determined the user's state and performances, modifying the robot's behaviour according to these inputs, recorded through sensors, cameras, and modules. The combination of the robot's emotional state module and intelligence layer led establishes the current robot's assistive action related to the user's state and

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adapts the robot's behaviour to the interactive scenario, using non-verbal modalities of communication.

In [39], the authors investigated a robot's behaviour by proposing a model that adapted to the visitor's intention. In a shopping mall, a humanoid robot was tested during approaching and interaction tasks. The robot was provided with two interaction strategies depending on users' behaviours: when visitors showed uncertain intentions, the "proactively waiting" strategy was used and the robot went toward them; the "collaboratively initiating" strategy, instead, was used when visitors' willingness to interact was seen and the robot started a conversation and moved closer to them. To reach a more natural context in interacting with robots, [40] presented an experiment with a social robot learning to perform word-meaning associations. The authors hypothesized that a different human attitude in approaching the robot could be obtained. The robot's design had the aim to evoke a strong social response from humans; social cues used influenced the tutoring of the human teacher and his behaviour. HRI interaction was measured through a language game, during which the learner assimilated a lexicon and associated meanings. Based on the teacher's feedback, the learner modified the word-meaning association. It could be considered as a sort of behavioural adaptation, applied in a different context that could improve the robot's social abilities. Through users' facial tracking, the robot was able to address participants during the interaction, emphasizing social involvement. Additional multi-modal social cues (gaze and verbal statement) to express its learning preference was used by the robot, thus modulating the interaction and positively influencing it.

In [41], the authors developed a spatial relationship model that considers interpersonal distance, body orientations, emotional state, and movements. On the basis of these inputs, the robot decides how to proceed, setting its voice and moving toward the user or not. As the robot comes close to the child, entering the "personal" distance zone, the current status of the user is re-evaluated to adapt better to the robot's actions. Children with cognitive disabilities interacted with the robot, executing free and structured game sessions. Robot tactile sensors led to understand tangible interaction, as an expression of touch-interaction through physical contact with the children. Depending on the touch-contact typology, the robot was able to select an appropriate behaviour using multimodal emotional expressions.

The robot's behaviour can be adapted depending on the user's emotion, seen as an emotional stimulus for the robot's cognitive architecture. In [42], the authors proposed a cognitive-emotional interactive model for interactive and communication tasks between young users and a robot. During the interaction, the emotional robot acted its emotions using facial expression, movements, and gesture as a consequence of the user's emotion, according to the Hidden Markov Model. The use of this model allowed the robot to regulate emotions as humans do, providing a better interaction. The model starts from the hypothesis that robots might know a human's cognitive process, in order to understand human's behaviours. To do that, an object-functional role perspective method allowed robots to understand humans' behaviours: objects are interpreted as object-functional roles and role interactions. An activity is interpreted as an integration of object role interactions, so the robot is able to predict and understand a human activity. Because this model is only involved in emotional intensity attenuation, the continuous prediction of spontaneous affect still needs to be improved in

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the future, and the authors are considering expanding the experiment sample size and seeking more effective evaluation approaches for affective computing.

Finally in [43], the authors proposed a model that used a child's affective states and adapted its affective and social behaviour in response to the affective states of the child.

4. Discussion

The aim of this work is to analyse the state of the art and thus to provide a list of hints regarding cognitive architectures, behavioural adaptation, and empathy. Future research efforts should lead to overcoming the limitation of the current state of the art, as summarized in Table 3

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Table 1 Challenges and opportunity

Type	Barriers/Limitations	Challenges and Opportunities	Research topics
Sensors Technology	Multimodal sensors [44]	A multisensory system should be implemented in the model of a robot to create an improved architecture	Development of a multisensory system that could be used to detect at the same time different social cues (i.e. vocal, facial and gaze cues.
	Reliable, and usable sensor technology [44]	Sensors should be designed to be reliable and acceptable in real-life situation to reduce the time-to-market	An effort could be the creation of sensors that can be used for a long time by the robot without getting damaged. Moreover sensors should be built and tested in order to become resistant to possible impacts that the robot can have during its work and should be more resistant to external agents (i.e. water)
Perception	Real-time learning [45], [17]	Real-time learning should be developed to adapt the behaviour of the robot according to the changing needs of the user	People preferences and knowledge change over time and a good system should be capable of adapting in real time to the changing needs of users A customization of the robot according to user needs could be obtained analysing in deep the voice and gestures that the robot should have according to the person it is approaching (i.e. children, aged people)
	Emotional state transitions [28]	Research on the emotional state module should be done more in deep	Future research should include a larger variety of emotional states and should detect and handle emotion transitions.
	Improving object detections [25]	Different approaches in the area of object detection should be investigated to obtain a strong model of the robot	Object detection and recognition are still challenging to perform in real-time and instead of using geometrical model or simple CNN , deep and sophisticated CNNs should be implemented to accomplish this task.
	Learning from the user [37]	The robot should be able to learn from the user in order to accomplish complex tasks	A model based on Learning from demonstration methods could be very useful to achieve this goal. Learning directly from the user lets the robot achieving better and complex skills.
Experimental	Experimental session [46], [33], [18]	The model should be implemented on a real robot and tested to evaluate the proposed	To have improvements in the HRI field, the model of a robot should be tested in dynamics environments (i.e. outdoor and indoor , in crowded or

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		artificial cognitive architecture in dynamical environments	not crowded places and with people from different ages.
Architecture Design	Brain-inspired architecture [20]	Research in robot's behavioural model should be conceived with a multidisciplinary approach to be able to adapt to the user's needs	A connection between the fields of engineering and neuroscience to create better models for social robots is a necessary element that has to be study in deep in future research.
	Modular and flexible architecture [10]	Robot should adapt to different context and different preferences which could change over time. Therefore, the architecture of a robot should be modular and flexible	The model of a robot should be adapted in the future to operate in different contexts (schools, hospitals , industries). Additionally, a cloud architecture should be implemented in order to first have the ability to offload intensive tasks to the cloud, second to access to a vast amount of data and third to access to shared knowledge and new skills.
	Behavioural consistency, predictability and repeatability [41]	These requirements should be investigated to obtain a complex model	Integrating those fields in the model of a robot could be obtained creating an algorithm that represents the episodic memory . This could bring to the creation of an artificial intelligent agent that can act more independently.
	Standardization	Having an high level of interoperability	In the future, systems with high interoperability should be created; this is currently an issue that has to be solved. An example is when some parts of the robot are implemented using different operative systems and a bridge between them doesn't always work well.
Ethical, legal and Social	Ethical and social aspects [10]	Ethical implications also should be investigated when creating a new model for a robot	In the future, the ethical and social implications of designing social robots with advanced HRI abilities should be studied in deep.
	Legal aspect	No rules can be found in the legal field of social robotics	A problem that should be overcome is the fact that social robots can't operate in environments with people without a supervision of an operator. The birth of a regulation for social robots could be an important step in this field.
	Cultural adaption [39]	The robot should be able to adjust parameters for different cultures	Many models work well when tested with people born in the country where they have been created, so the idea for the future is to test the work with new

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			robots and different cultures to obtain a generic model for a robot

It shows several areas that have to be analysed in future works as sensors technology, perception, architecture design and the presence/lack of an experimental phase.
Moreover, ethical, legal, and social aspects should be taken much more into consideration to build an efficient behavioural model for future robots.

4.1. Sensors technology

A crucial aspect in HRI is how robots manage to understand intentions and emotions of the users using social cues (i.e. posture and body movements , facial expression, head and gaze orientation, and voice quality). Sensors play a fundamental role because they are used to detect this cues which are then processed in the robot model. An issue related to sensors is the data acquisition that can face delays, so an effort for the future could be to design sensors that are reliable and usable in real-life situations. Moreover, the robot should have a multisensory to acquire different types of signals [44]. To achieve this goal, microphones, 2D and 3D vision sensors, thermal cameras, leap motion, Myo and face-trackers could be collected to create a system that gives a complete sensor coverage to the robot. Each device could cover a different area : microphones could be used for speech, Myo to collect IMU and EMG data, face-trackers to find head pose, gaze and FACS, vision sensors to acquire point cloud data, thermal cameras to detect objects in dark environments and a leap motion to track and estimate position of the hand.

4.2. Perception and learning from the user

A second ability that should be deeply analysed is the area of perception. Indeed the main problem of perception is to have a reliable real-time sensing and learning system, as expressed in [45]. In this paper, the authors show that people preferences and knowledge change over time and a good system should be capable of adapting in real time to these changes and should be able to learn from the user. To achieve the latter competence, advanced learning-based methods [47] should be used to satisfy user needs , increasing the performance of the robot [48] Additionally, future works should detect and handle the emotion transition since humans change steadily their emotions [28]. This topic is one of the main issue of HRI because the robot must have a real time data acquisition to handle the emotions transition and this is quite difficult to have due to delays during the data acquisition.
Another limitation of this area is the disconnection between perception and actions [25] and this problem should be overcome to have a reactive robot. In [17], the authors underlined this concept, saying that changes in the user profile should be promptly detected to adapt behaviour automatically. An effort that could be interesting to study in deep in the future is the possibility for the robot to achieve complex skills learnt from the user (for i.e. cleaning a table). In [37], the authors proposed that the robot should be able to change the internal model on the basis of what it learns from human beings , using the learning from demonstration approach.

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Moreover, it is worth underlining the importance to increase the number of non-verbal input parameters considered in the analysis, thus to make the robot more compliant and adaptable to the user's state and preferences [36].

4.3. Architecture design

Concerning architecture design more modular and more flexible architectures should be created , in the future: robots should be able, for example, to autonomously react to an unplanned event and complete risk analysis procedure should be performed in the design phase to correctly handle the unplanned situations [10], [39].

Behavioural consistency, predictability, and repeatability should be investigated since they are fundamental requirements in the design of socially assistive robots in different contexts, such as for children with autism as underlined in [41]. Addressing them requires an accurate case analysis, grounded on the current practice and on extensive experimentation. A possible approach could be the use of learning from demonstration to teach the robot some skills to achieve a better performance [48].

Moreover, a multidisciplinary approach should be pursued to design and develop reliable and acceptable behavioural models [20]. Psychology, biology, and physiology, among others, are areas of expertise, which should be part of the development process since they can help to improve the HRI experience [49]. Innovative behavioural models for assistive robots could be developed taking inspiration from the studies of human social models or from the study of a specific anatomical apparatus. In this manner, future research will not only consider the physical safety (of the robot and the human beings) but also psychological, anatomical and social spheres of humans [41].

It is important to underline that the robot might be appropriate not only in the context for which it was originally conceived (i.e. private home, hospital, residential facility) but also for people with different levels of residual abilities. In other words, the robot should be able to adapt to the variability and different cultural and social contexts [50].

Finally, a model of a robot should have a cloud architecture to have the ability to offload intensive tasks to the cloud, to access to a vast amount of data, to access to shared knowledge and not to lose information in case of connection problems.

4.4. Experimental phase

The advantage to test robotic solutions with real users is absolutely remarkable as underlined by the comparison between papers with or without the experimental sessions. Particularly, some works [18], [19], [33] remark on the importance of testing the proposed model as a fundamental step for future research. The main issue is that, in some scenarios, robots that completed a task during the simulation phase, then don't succeed in the experimental phase. This is the reason why testing the behaviour of the robot in a real environment is of extremely importance in order to find good parameters that work for the experimental phase. In addition, the architecture should be validated using physical robots that interact with users in dynamic environments (i.e. schools, industries, hospitals).

Finally, another limitation that can be found in several papers is the absence of a database (i.e. physical forces or emotional states_of the user). A database could be useful to collect information

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achieved from the experimental phase and could be useful not only for the researchers that are working on the project, but also for other researchers that want to use the data for their own projects.

4.5. Ethical, legal, and social aspects

Future research effort should include the ethical implications of designing robots that interact with people and the data should be acquired and correctly stored to guarantee privacy [10].
Concerning the other two aspects, in [39], the authors underlined that the robot should be able to adjust its parameters for different cultures that have different needs, in order to be able to satisfy for real user requests. Finally the birth of a regulation for social robots, like the one created for drones during the past years, could be an important step in order to have the possibility to use robot in crowded environments [51].

5. Conclusions

This paper focuses on behavioural adaptation, cognitive architectures and the establishment of empathy between social robots and users. The current state-of-the-art of existing systems used in this field is presented to identify the pros and cons of each work with the aim to provide recommendations for future improvements.
To establish a set of benchmarks to define an HRI similar to human-human interaction is an enormous challenge because of the complexity of non-verbal phenomena in social interaction. Its interpretation needs the support of psychological processes and neural mechanisms. The topic of behavioural model is huge, and several factors contribute to making robots more accepted, perceived as friends, and empathetic with users. A common limitation of the works presented is that, often, authors focused on a particular aspect of HRI emphasizing a communication strategy or a particular behaviour as reaction to the user's action. Because it is not easy to include behavioural adaptation techniques, cognitive architectures, persuasive communication strategies, and empathy in a unique solution, researchers are often limited to organize experimental studies, which include only some of these factors. This, unfortunately, provides useful information only to a limited part of persuasive robotics. To maintain the importance of each contribution, it is fundamental to include in a whole vision all the suggestions provided by each work. Although many improvements remain to be accomplished, the already satisfying results the authors have achieved are an optimum starting point to develop a better solution using knowledge of human cognitive and psychological structures.

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References

1. Goodrich, M.A.; Schultz, A.C. Human-Robot Interaction: A Survey. *Found. Trends® Human-Computer Interact.* **2008**.

2. Conti, D.; Trubia, G.; Buono, S.; Di Nuovo, S.; Di Nuovo, A. Evaluation of a robot-assisted therapy for children with autism and intellectual disability. In Proceedings of the Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); 2018.

3. Cavallo, F.; Aquilano, M.; Bonaccorsi, M.; Limosani, R.; Manzi, A.; Carrozza, M.C.; Dario, P. Improving Domiciliary Robotic Services by Integrating the ASTRO Robot in an AmI Infrastructure. In; 2014; pp. 267–282.

4. Fiorini, L.; Esposito, R.; Bonaccorsi, M.; Petrazzuolo, C.; Saponara, F.; Giannantonio, R.; Petris, G.D.; Dario, P.; Cavallo, F. Enabling personalised medical support for chronic disease management through a hybrid robot-cloud approach. *Auton. Robots* **2017**, *41*.

5. Turchetti, G.; Micera, S.; Cavallo, F.; Odetti, L.; Dario, P. Technology and innovative services. *IEEE Pulse* **2011**, *2*.

6. Limosani, R.; Manzi, A.; Fiorini, L.; Cavallo, F.; Dario, P. Enabling Global Robot Navigation Based on a Cloud Robotics Approach. *Int. J. Soc. Robot.* **2016**, *8*, 371–380.

7. Reppou, S.; Karagiannis, G. Progress in Automation, Robotics and Measuring Techniques. **2015**, *352*, 233–234.

8. Fasola, J.; Mataric, M. *A Socially Assistive Robot Exercise Coach for the Elderly*; 2013; Vol. 2;.

9. García-Soler, Á.; Facal, D.; Díaz-Orueta, U.; Pigini, L.; Blasi, L.; Qiu, R. Inclusion of service robots in the daily lives of frail older users: A step-by-step definition procedure on users' requirements. *Arch. Gerontol. Geriatr.* **2018**, *74*, 191–196.

10. Chidambaram, V.; Chiang, Y.-H.; Mutlu, B. Designing Persuasive Robots: How Robots Might Persuade People Using Vocal and Nonverbal Cues. *7th Annu. ACM/IEEE Int. Conf. Human-Robot Interact. (HRI '12)* **2012**, 293–300.

11. Cavallo, F.; Semeraro, F.; Fiorini, L.; Magyar, G.; Sinčák, P.; Dario, P. Emotion Modelling for Social Robotics Applications: A Review. *J. Bionic Eng.* **2018**, *15*.

12. Hall, E.T. *The hidden dimension*; Garden City, NY:Doubleday, 1966;

13. Wiltshire, T.J.; Smith, D.C.; Keebler, J.R. Cybernetic Teams: Towards the Implementation of Team Heuristics in HRI. In; Springer, Berlin, Heidelberg, 2013; pp. 321–330.

14. Wiltshire, T.J.; Warta, S.F.; Barber, D.; Fiore, S.M. Enabling robotic social intelligence by engineering human social-cognitive mechanisms. *Cogn. Syst. Res.* **2017**, *43*, 190–207.

15. Vircikova, M.; Magyar, G.; Sincak, P. The affective loop: A tool for autonomous and adaptive

Peer-reviewed version available at *Robotics* **2019**, *8*, 54; doi:10.3390/robotics8030054

emotional human-robot interaction. *Adv. Intell. Syst. Comput.* **2015**, *345*, 247–254.

16. Lieto, A.; Bhatt, M.; Oltramari, A.; Vernon, D. The role of cognitive architectures in general artificial intelligence. *Cogn. Syst. Res.* **2018**, *48*, 1–3.

17. Tapus, A.; Aly, A. User adaptable robot behavior. *Proc. 2011 Int. Conf. Collab. Technol. Syst. CTS 2011* **2011**, 165–167.

18. Pieters, R.; Racca, M.; Veronese, A.; Kyrki, V. Human-aware interaction: A memory-inspired artificial cognitive architecture. *CEUR Workshop Proc.* **2017**, *1855*, 38–39.

19. Raymundo, C.R.; Johnson, C.G.; Vargas, P.A. An Architecture for Emotional and Context-Aware Associative Learning for Robot Companions. In Proceedings of the Proceedings of the 24th IEEE International Symposium on Robot and Human Interactive Communication; 2015; Vol. 19, pp. 8799–8804.

20. Franchi, A.M.; Mutti, F.; Gini, G. From learning to new goal generation in a bioinspired robotic setup. *Adv. Robot.* **2016**, *1864*, 1–11.

21. Damiano, L.; Dumouchel, P.; Lehmann, H. Artificial Empathy: An Interdisciplinary Investigation. *Int. J. Soc. Robot.* **2015**, *7*, 3–5.

22. Horii, T.; Nagai, Y.; Asada, M.; Access, O. Imitation of human expressions based on emotion estimation by mental simulation. **2016**, 40–54.

23. Dağlarlı, E.; Dağlarlı, S.F.; Günel, G.Ö.; Köse, H. Improving human-robot interaction based on joint attention. *Appl. Intell.* **2017**, *47*, 62–82.

24. Bethel, C.L.; Henkel, Z.; Eakin, D.K.; May, D.C.; Pilkinton, M. Moving toward an intelligent interactive social engagement framework for information gathering. *SAMI 2017 - IEEE 15th Int. Symp. Appl. Mach. Intell. Informatics, Proc.* **2017**, 21–26.

25. Kim, S.; Yu, Z.; Lee, M. Understanding human intention by connecting perception and action learning in artificial agents. *Neural Networks* **2017**, *92*, 29–38.

26. Boucenna, S.; Gaussier, P.; Hafemeister, L. Development of first social referencing skills: Emotional interaction as a way to regulate robot behavior. *IEEE Trans. Auton. Ment. Dev.* **2014**, *6*, 42–55.

27. Bechade, L.; Dubuisson-Duplessis, G.; Pittaro, G.; Garcia, M.; Devillers, L. Towards metrics of evaluation of pepper robot as a social companion for the elderly. *Lect. Notes Electr. Eng.* **2019**, *510*, 89–101.

28. Ficocelli, M.; Terao, J.; Nejat, G. Promoting interactions between humans and robots using robotic emotional behavior. *IEEE Trans. Cybern.* **2015**, *PP*, 2911–2923.

29. Looije, R.; Neerincx, M.A.; Cnossen, F. Persuasive robotic assistant for health self-

management of older adults: Design and evaluation of social behaviors. *Int. J. Hum. Comput. Stud.* **2010**, *68*, 386–397.

30. Liu, K.; Picard, R. Embedded empathy in continuous, interactive health assessment. *CHI Work. Challenges Heal. Assess.* **2005**, 1–4.

31. Lewandowska-Tomaszczyk, B.; Wilson, P.A. Compassion, empathy and sympathy expression features in affective robotics. *7th IEEE Int. Conf. Cogn. Infocommunications, CogInfoCom 2016 - Proc.* **2017**, 65–70.

32. Rodić, A.D.; Jovanović, M.D. How to Make Robots Feel and Social as Humans Building attributes of artificial emotional intelligence with robots of human-like behavior. *Cogn. 2014 Sixth Int. Conf. Adv. Cogn. Technol. Appl.* **2014**, 133–139.

33. Rodić, A.; Urukalo, D.; Vujović, M.; Spasojević, S.; Tomić, M.; Berns, K.; Al-Darraji, S.; Zafar, Z. Embodiment of human personality with EI-Robots by mapping behaviour traits from live-model. *Adv. Intell. Syst. Comput.* **2017**, *540*, 438–448.

34. Granata, C.; Bidaud, P. A framework for the design of person following behaviors for social mobile robots. *2012 IEEE/RSJ Int. Conf. Intell. Robot. Syst.* **2012**, 4652–4659.

35. Feil-Seifer, D.; Matarić, M. People-aware navigation for goal-oriented behavior involving a human partner. *2011 IEEE Int. Conf. Dev. Learn. ICDL 2011* **2011**.

36. Sirithunge, H.P.C.; Viraj, M.A.; Muthugala, J.; Buddhika, A.G.; Jayasekara, P.; Chandima, D.P. Interpretation of interaction demanding of a user based on nonverbal behavior in a domestic environment. *IEEE Int. Conf. Fuzzy Syst.* **2017**.

37. Karami, A.B.; Sehaba, K.; Encelle, B. Adaptive artificial companions learning from users' feedback. *Adapt. Behav.* **2016**, *24*, 69–86.

38. Chan, J.; Nejat, G. Social intelligence for a robot engaging people in cognitive training activities. *Int. J. Adv. Robot. Syst.* **2012**, *9*, 1–13.

39. Kato, Y.; Kanda, T.; Ishiguro, H. May I help you? *Proc. Tenth Annu. ACM/IEEE Int. Conf. Human-Robot Interact. - HRI '15* **2015**, 35–42.

40. De Greeff, J.; Belpaeme, T.; Bongard, J. Why robots should be social: Enhancing machine learning through social human-robot interaction. *PLoS One* **2015**, *10*, 1–26.

41. Garzotto, F.; Gelsomini, M.; Kinoe, Y. Puffy: A Mobile Inflatable Interactive Companion for Children with Neurodevelopmental Disorder. *Lect. Notes Comput. Sci. (including Subser. Lect. Notes Artif. Intell. Lect. Notes Bioinformatics)* **2017**, *10514 LNCS*, 467–492.

42. Liu, X.; Xie, L.; Wang, Z. Empathizing with emotional robot based on cognition reappraisal. *China Commun.* **2017**, *14*, 100–113.

Peer-reviewed version available at *Robotics* **2019**, *8*, 54; doi:10.3390/robotics8030054

43. Boucenna, S.; Gaussier, P.; Andry, P.; Hafemeister, L. A Robot Learns the Facial Expressions Recognition and Face/Non-face Discrimination Through an Imitation Game. *Int. J. Soc. Robot.* **2014**, *6*, 633–652.

44. Sonntag, D. Persuasive AI Technologies for Healthcare Systems. **2016**, 165–168.

45. Admoni, H.; Series, B.S.-2014 A.F.S.; 2014, undefined Nonverbal Behavior Modeling for Socially Assistive Robots. *aaai.org*.

46. Ham, J.; Cuijpers, R.H.; Cabibihan, J.J. Combining Robotic Persuasive Strategies: The Persuasive Power of a Storytelling Robot that Uses Gazing and Gestures. *Int. J. Soc. Robot.* **2015**, *7*, 479–487.

47. Martins, G.S.; Santos, L.; Dias, J. BUM: Bayesian User Model for Distributed Learning of User Characteristics from Heterogeneous Information. *IEEE Trans. Cogn. Dev. Syst.* 2018.

48. Billard, A.; Siegwart, R. Robot learning from demonstration. *Rob. Auton. Syst.* **2004**, *47*, 65–67.

49. Di Nuovo, A.; Jay, T. Development of numerical cognition in children and artificial systems: a review of the current knowledge and proposals for multi-disciplinary research. *Cogn. Comput. Syst.* **2019**.

50. Martins, G.S.; Santos, L.; Dias, J. User-Adaptive Interaction in Social Robots: A Survey Focusing on Non-physical Interaction. *Int. J. Soc. Robot.* **2019**.

51. Clarke, R. The regulation of civilian drones' impacts on behavioural privacy. *Comput. Law Secur. Rev.* **2014**, *30*, 286–305.

52. Asada, M. Towards Artificial Empathy: How Can Artificial Empathy Follow the Developmental Pathway of Natural Empathy? *Int. J. Soc. Robot.* **2015**, *7*, 19–33.

53. Cao, H.L.; Van de Perre, G.; Kennedy, J.; Senft, E.; Esteban, P.G.; De Beir, A.; Simut, R.; Belpaeme, T.; Lefeber, D.; Vanderborght, B. A personalized and platform-independent behavior control system for social robots in therapy: development and applications. *IEEE Trans. Cogn. Dev. Syst.* **2018**, *8920*, 1–13.

54. Infantino, I.; Augello, A.; Maniscalto, U.; Pilato, G.; Vella, F.; Prestazioni, A.; Nazionale, C.; Malfa, V.U. La A Cognitive Architecture for Social Robots. *2018 IEEE 4th Int. Forum Res. Technol. Soc. Ind.* **2018**, 1–5.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 20 May 2019 doi:10.20944/preprints201905.0251.v1

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1 **Table 2 Summary of recently published works on persuasive robotics without experimentation loop**

Reference	Aim	Robot	Social cues	Models	Area
[44]	Development of an IoT toolbox toward AI-based persuasive technologies for healthcare systems	NAO	Gaze behaviour, facial behaviour, speech cues	A system that contains: - a sensor network architecture used to observe the environment and provide real-time access to the data for interpretation - a block containing context-aware applications (object detection, activity recognition) - a prediction block of future states	Cognitive architectures
[14]	Suggestions and overviews on social cognitive mechanisms	-	-	A model that takes into consideration social-cognitive mechanisms to facilitate the design of robots	Cognitive architectures
[19]	Theoretical architectural model based on the brain's fear learning system	-	Environmental cues	Theoretical architectural model that uses artificial neural networks (ANNs) representing sensory thalamus, sensory cortex, amygdala, and orbitofrontal cortex.	Cognitive architectures
[20]	Imitation of the neural plasticity, the property of the cerebral cortex supporting learning	NAO	Eyes behaviour	A model called Intentional Distributed Robotic Architecture (IDRA) that takes inspiration from the amygdala-thalamo-cortical circuit in the brain at its functional level	Cognitive architectures
[18]	Human-aware cognitive architecture to support HRI	Care-O-Bot 4	Eyes and vocal behaviours	Partially observable Markov decision process (POMDP) model	Cognitive architectures
[21]	Overview the research field aimed at building emotional and empathic robots focusing on its main	-	Gestures and postures cues	-	Empathy

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	characteristics and ongoing transformations				
[52]	A conceptual model of artificial empathy is proposed and discussed with respect to several existing studies	Emotional communication robot, WAMOEBA - WE humanoid robot	-	Conceptual model of artificial empathy	Empathy

Table 2 Summary of recently published works on persuasive robotics with experimentation loop

Reference	Aim	Robot	Social cues	Participants	Models	Area
[31]	Comparison between expression features of compassion, sympathy, and empathy in British English and Polish that need to be tuned in social robots to enable them to operate successfully	Generic assistive robots	Linguistic cues, facial cues movement cues physiological features	British English-speaking participants (mean age 23.2 years, 21 females) and 29 Polish-speaking subjects (mean age 25.6 years, 26 females)	Creating culture-specific emotion (compassion, sympathy and empathy) models	Empathy
[29]	Comparison of a text-based interface with a character persuading users	I-Cat	Gaze and posture cues	24 middle age adults age 45 to 65 years old	The model is based on persuasion and uses Big five questionnaire on personality	Empathy
[9]	Definition of metrics to build an empathic robot that helps elderly people	Pepper	-	42 participants (elderly people)	The model is based on an emotion recognition algorithm	Empathy
[28]	Emotion-based assistive behaviour for a socially assistive robot				Markov model that uses a human affective state	

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		Brian	Gestures and emotional state cues	34 subjects aged 17 to 68 years old	classifier and a non-verbal interaction and states analysis (NISA)	Empathy
[53]	A behaviour control system for social robots in therapies is presented with a focus on personalization and platform-independence	NAO Pepper	-	Children and elderly people	Model based on a Body Action Coding System (BACS)	Behavioural adaptation
[37]	Capacity of an intelligent system to learn and adapt its behaviour/actions	EMOX	Current user(s) attributes and current environment attributes cues	Children, teenagers, and adults	Markov Decision Processes (MDPs) model	Behavioural adaptation
[40]	How additional social cues can improve learning performance	Robot head mounted on an articulated robot arm	Gaze behaviour	41 healthy and young participants with an average age of 24 years old.	The interaction model of the robot is based on language games	Behavioural adaptation
[15]	Affective model for social robotics	NAO	-	Children age 5 to 7 years old.	Plutchik emotional model; uses Fuzzy rules and learning by demonstration	Empathy
[41]	Robot's ability in gestures' interpretation	Puffy	Visual, auditory and Tactile cues	19 children with an average age of 6 years old	Interactional Spatial Model which considers : interpersonal distance - relative (child-robot) bodily orientations - child's and robot's movements in space - child's emotional state - child's eye contact - robot's emotional state	Behavioural adaptation

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[38]	Definition of user state and task performance, adjusting robot's behaviour	Brian 2.0	-	10 healthy and young participants from 20 to 35 years old.	A hierarchical reinforcement learning approach is used to create a model that allow the robot to learn appropriate assistive behaviours based on the structure of the activity	Behavioural adaptation
[42]	Continuous cognitive emotional regulation model for robot	-	-	10 subjects	Hidden Markov Model; uses cognitive reappraisal strategy	Behavioural adaptation
[36]	Model for decision making on a user's non-verbal interaction demand	MIRob	Eyes behaviour	8 subjects from 25 to 58 years old.	A model to decide when to interact with the user. It observes movements and behaviour of the patient put them through a module called Interaction Demanding Pose Identifier. The data obtained are fed into the Fuzzy Interaction Decision Making Module in order to interpret the degree of interaction demanding of the user.	Behavioural adaptation
[25]	System inspired by humans' psychological and neurological phenomena	-	Eyes behaviour	-	Generic model; uses supervised multiple timescale recurrent neural networks	Cognitive architectures
[23]	A novel cognitive architecture for a computational model of the limbic				Dynamic neural fields (DNFs) model; used with	

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	system is proposed, inspired by human brain activity, which improves interactions between a humanoid robot and preschool children	Robotis Bioloid	Eyes, auditory, and sensory cues	16 pre-school children from 4 to 6 years old.	reinforcement and unsupervised learning-based adaptation processes	Cognitive architecture
[43]	A robotic system that can learn online is shown to recognize facial expressions without having a teaching signal associating a facial expression	-	Gestures, gaze direction, vocalization cues	20 persons	Theoritical model for online learning of facial expression recognition	Cognitive architecture
[26]	Studying how emotional interactions with a social partner can bootstrap increasingly complex behaviours such as social referencing	-	Facial expression cues	20 persons	Model that uses the child's affective states and adapts its affective and social behaviour in response to the affective states of the child	Behavioural adaptation
[39]	Model of adaptive behaviours to pedestrians' intentions	Robovie	Body and facial expression cues	The participants were visitors of the shopping mall where the robot was placed.	State transition model; used with an Intention-Estimation Algorithm	Behavioural adaptation
[34]	Framework for people detection, state estimation, and trajectories generation for an interactive social behaviour	Kompai	Body and facial expression cues	-	The model combines perception, decision, and action and uses fuzzy logic and SLAM algorithms	Behavioural adaptation
[35]	Person-aware navigation system	-	Body and facial expression cues	8 healthy and young subjects (7 male and 1 female) with an average age of 20.8 years.	The model weights trajectories of a robot's navigation system for autonomous movement using Algorithms in navigation-stack of ROS	Behavioural adaptation
[28]	Map of human psychological traits to make robots emotive and sociable	NAO	Body and facial expression cues	10 subjects	Emotional Intelligence (EI) model; uses Meyer Briggs	Behavioural adaptation

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					theory (MBT) and fuzzy logic	
[24]	To develop an integrated robotic framework including a novel architecture and an interactive user interface to gather information	NAO, Milo, and Alice	Body and facial expression cues	186 children from 8 to 12 years old	Interactive Social Engagement Architecture (ISEA) is designed to integrate behaviour-based robotics, human behaviour models, cognitive architectures, and expert user input to increase social engagement between a human and system	Cognitive architectures
[54]	Software architecture allowing a robot to socially interact with human beings, sharing with them some basilar cognitive mechanisms	NAO	non- verbal cues such as social signals	Children	Hidden Markov Model (HMM) used as a reasoning approach The model encoded social interaction and uses natural and intuitive communication channels, both to interpret the human behavioural and to transfer knowledge to the human	Cognitive architectures
[29]	To implement models obtained from biological systems to humanoid robot	Robothespian	Body and facial expression cues	237 subjects of different age, gender, and education	Model that uses Facial Action Coding System	Behavioural adaptation

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