Preprint - Article accepted for publication in the Int. Journal of Social Robotics - manuscript No.
(will be inserted by the editor)

Synchrony and Reciprocity: Key Mechanisms for Social Companion Robots in Therapy and Care

Tamara Lorenz · Astrid Weiss · Sandra Hirche

Received: date / Accepted: date

Abstract Studies and concepts for social companion robots in therapy and care exist, however, they often lack the integration of convincing behavioral and social key mechanisms which enable a positive and successfull interaction experience. In this article we argue that synchrony and reciprocity are two key mechanisms of human interaction which affect both in the behavioral level (movements) and in the social level (relationships). Given that both a change in movement behavior and social behavior are an objective in the contexts of aging-in-place, neurocognitive and neurophysical rehabilitation, and depression, these key mechanisms should also be included in the interaction with social companion robots in therapy and care. We give an overview on the two concepts ranging from a social neuroscience over a behavioral towards a sociological perspective and argue that both concepts affect each other and are up to now only marginally applied in human-robot interaction (HRI). To support this claim, we provide a survey on existing social companion robots for aging-in-place (pet robots and household robots), neurocognitive impairments (autism and dementia), neurophysical impairments (brain injury, cerebral palsy, and Parkinson's disease), and depression. We emphasize to what extend synchrony and reciprocity are already included into the respective applications. Finally, based on the survey and the previous argumentation on the importance of synchrony and reciprocity, we provide a discussion about potential future steps for the inclusion of these concepts to social companion robots in therapy and care.

Keywords Social Robots · Synchronization · Reciprocity · Rehabilitation · Social Neuroscience

1 Introduction

Research in cognitive psychology has demonstrated that most of our decisions are made unconsciously and/or automatically and even attitudes towards people and things are driven to a big part by processes that we cannot easily access [1]. Also human behavioral interaction usually emerges naturally. In the majority of cases, we do not think about movements. Instead, similar to many other decision making processes, we perform our movements automatically or subconsciously. However, if the flow of the interaction is not smooth due to, for example, a physical or cognitive impairment of our interaction partner, we recognize this and might even be irritated. We immediately know that there is something not as it should be, even if we cannot exactly name what it is [2]. Similar reactions can be observed in the interaction with a robotic partner, a phenomenon that is often referred to as the *uncanny valley phenomenon*, which appears not only due to anthropomorphic appearance features, but also due to a mismatch in expectations with respect to behavior [3]. Furthermore, even smallest deviations from expected social dynamics affect the interaction [4]. Thus, human expectations on

---

T. Lorenz and S. Hirche
Institute for Information-Oriented Control, Technische Universität München, Barerstr. 21, 80333 München, Germany
Tel.: +49-89-289-25736
Fax: +49-89-289-25724
E-mail: {t.lorenz,hirche}@tum.de

T. Lorenz
Department of Psychology, Department of Electrical Engineering & Computing, Department of Mechanical & Materials Engineering, University of Cincinnati, Edwards 1, 47 Corry Blvd. Cincinnati, OH 45221, USA

A. Weiss
ACIN Institute of Automation and Control, Vienna University of Technology
GusshausstraSSe 27-29/E376, 1040 Vienna, Austria
Tel.: +43 (1) 58801-376 618
Fax: +43 (1) 58891376-97
E-mail: astrid.weiss@tuwien.ac.at

behavior have to be taken into consideration when designing artificial companions, like social robots.

Among other applications, social companion robots have been designed in order to support caregivers and caretakers during psychological and physical therapy, as well as in the realm of elderly care. For the rehabilitation process and the ability to live with disabilities however, it is widely accepted that success does not only depend on treatment and medication. There are subjective factors such as social contacts and belief in recovery that play a role, as well as the physical interaction with the caregiver [5]. Therefore, it is essential to gain a better understanding of how we can shape the behavioral interaction between humans and robots. One common approach is to understand human behavioral principles and to enable the robot to engage in the same behavioral dynamic. Therefore, we follow the claim of Dautenhahn [6] that “the better we understand human psychology and human internal dynamics, the more we can hope to explain embodiment and empathetic understanding on a scientific basis. This knowledge can then be applied to artifacts”.

Although there are several verbal and non-verbal behavior mechanisms that can aid social human-robot interaction, such as dialog strategies [7], gaze [8] or proxemics [9], in the following we argue that movement synchrony and reciprocity can induce common ground to an interaction that subsequently supports higher level mechanisms. We will first introduce the concepts of synchrony and reciprocity from a social neuroscience and mere behavioral perspective. Then, we highlight their social implications from a sociological perspective, before we explain how theses concepts can be transferred to social human-robot interaction. After a short overview on what is understood by a social companion robot for therapy and care, we will provide a brief survey on existing social companion robots which already partly consider these mechanisms in the most prominent domains of robot-assisted therapy and care, namely: aging-in-place, neurocognitive impairments, neurophysical impairments, and depression. We will discuss the evidence provided by today’s existing social companion robots for therapy and care to show how synchrony and reciprocity can aid the physical interaction and with this also the social interaction with the robot, its acceptance, and subsequently even the rehabilitation process. Finally, we will outline how a future research agenda could take into account behavioral synchrony and reciprocity as two possible key mechanisms in the development of future social companion robots.

2 Synchrony and Reciprocity – Key-Mechanisms in Human Social Interaction

Our understanding on synchrony and reciprocity as key mechanisms for interaction is based on a social neuroscience perspective and focuses on the coordination of movements. The main assumption is that synchrony and reciprocity are inevitable and omnipresent in human-human interaction, which enables grounding and causes a positive interaction experience. Subsequently, from a sociological perspective we argue that these mechanisms support the perception of reciprocity on an intentional self-reflective level. Reciprocity as institutionalized interaction principle between humans is cross-culturally established, and studies on object-centered sociality [10] and the media equation theory [11] indicate that it also transfers to human-machine interaction.

First, we discuss the cognitive and behavioral requirements for synchrony and reciprocity and provide a brief introduction to the neural correlates; we then describe both key mechanisms from a social neuroscience perspective before building a bridge to the sociological concept of reciprocity as give-and-take interaction principle. Based on this we discuss the social implications that can derive from transferring synchrony and reciprocity to human-robot interaction.

2.1 Movement Synchronization and Synchronous Behavior

Movement synchronization is a coordination behavior that emerges inevitably during repetitive tasks [12, 13]. It is usually established when two actors perform the same action at the same time (described as phase dynamics, this would be an in-phase relation), but also when they perform complementary movements at the same time (anti-phase relation, turn-taking) [13].

Movement synchronization was mostly studied in undirected tasks such as when two people are rocking in chairs next to each other [14] or walk side-by-side [15]. However, it was shown that it also emerges in goal-directed movements like in pick-and-place tasks, which are common activities of daily living [16–19].

In general humans seem to have an intrinsic coordination and timer model that helps them estimating intervals between events [20]. Furthermore, there seems to be a coupling of intra- and interpersonal behavior during interaction to the extent that adjustments in intrapersonal coordination affect the coordination with another person, and vice versa [21, 22]. Finally, it was shown that reducing the variability in oneŠs own movements by means of synchrony can be a strategy to achieve predictability for the interaction partner [23].

What is described for behavior here, also counts for turn-taking in verbal and non-verbal communication as well as for other forms of social interaction such as mimicry and imitation [24, 25]. While mimicry can be understood as the replication of automated behaviors, imitation can be understood as a status or a short sequence of actions that I see my interaction partner performing and then consequently replicate [26, 27, 25]. Here it is important to note that imitation is not mere mirroring in the sense that one copies every little part of another’s movement. It is rather the replication of the action with regard to the outcome of the action [28] which leads to the acquisition of new skills [26].

Note: Distinguishing movement synchronization and imitation is not easy, as the terms synchrony and imitation are sometimes used interchangeably in literature. In the following we therefore refer to *movement synchronization* for immediate, repetitive and eventually rhythmic interactions - such as pick-and-place tasks or postural sway. By contrast, we refer to imitation, if actions happen at a latency and do not have a regular and repetitive temporal relation, for example the imitation of a body posture (also mimicry) or a single action. However, both phenomena (movement synchronization and imitation) are referred to as synchronous behavior.

2.2 Accessing Reciprocity for Movement Coordination

From a sociological perspective, social reciprocity as the principle of give-and-take is a fundamental interaction concept, which is apparent in all human societies and its universality applies cross-culturally [29]. The social norm of reciprocity (or reciprocation) says that "we should try to repay, in kind, what another person provided us" [29].

However, reciprocity can also be understood as an unconscious response to behavior, as a mutual feedback during movement coordination. One interesting phenomenon to illustrate this is the *interference effect*. The notion of movement interference covers human reactions to incongruent observations, i.e. I see you doing one thing, but I want to do something else [30–34]. It is is expressed in increased reaction times [30,31] and a higher variability in movement trajectories [32–34] during situations in which people perform incongruent movements while observing each other. To explain this, it is suggested that the interference effect is caused by an activation of the mirror neuron system due to the observed action which has to be inhibited because it interferes with the representation of the own action planning, see also Section 2.4. This finding shows different things: first, it shows that when they move, humans take into account the actions of their interaction partners and that these actions affect the own actions. Second, it also provides a tool with which it is possible to actually recognize, that an interaction is taking place.

2.3 Connecting Synchrony and Reciprocity

So far, synchrony and reciprocity are introduced as two distinct concepts. However, it is important to note, that synchrony and reciprocity are linked and intertwined. If two people coordinate incongruent movements, an interference effect should emerge. However, if the task allows for synchronization at the same time, interaction partners mutually adapt to each others movements and temporal delays [17]. This does not only show that synchrony is a very stable phenomenon in human interaction, it also shows that the adaptation process depends on reciprocal engagement.

This also becomes clear when thinking about learning from demonstration [35,36]. The concept of learning by demonstration is based in the continuous imitation (synchronization) of behavior between an instructor and a learner. During the learning process, the learner continuously repeats the behavior the instructor is demonstrating. At the same time, the instructor observes the attempts of the learner and can adjust his/her behavior in a way to point the learner's attention to certain features that have not been considered in the imitation process before. With this, the instructor provides reciprocal feedback to the learner, while the learner reciprocally demonstrates his/her learning process by a continuous adaptation to these features. Thus, learning from demonstration is a continuous process of synchrony and reciprocity on the behavioral level.

2.4 Cognitive Requirements and Neural Correlates for Synchronous and Reciprocal Interaction

Before interacting with another individual, we need to be able to form a representation of his/her actions in a way that we are able to predict what will happen in the next instant [37, 38]. Furthermore, we need to be able to infer the other individual's intentions, emotions and desires, an ability which is often referred to with the *Theory of Mind* (ToM) [39,40].

It is suggested that forming a representation has its neural correlate in the human equivalent to the *Mirror Neuron System* (MNS) [41]. Mirror neurons are located in the prefrontal cortex of the brain and react (fire) both if one executes a movement and if one only observes it. Thus, it is hypothesized that humans use their own experience and body schema to form a representation of what the other person is doing [42,43]. This then also includes that the MNS plays a role in synchrony, including imitation and mimicry of actions. Besides, the performance of actions is sometimes also related to certain emotional states, that are for example displayed in a facial expression. Thus, the MNS might also play a role in inferring the emotional state of a person and might therefore be essential to the notion of empathy [25].

Although there are doubts remaining that the mirror neurons "provide the basis for action understanding" in humans [44], it was shown that besides other neural structures and networks, mirror neurons fire during action perception, even for prima facie meaningless movements [45]. Therefore, the MNS may be one stepstone towards the processing of feedback information, namely by perceiving own and other's action for (there or elsewhere at a higher level) matching them to our own expression of intentions [46,44]. To this effect, the MNS would also allow for capturing reciprocity by helping us to recognize deviations from our own behavior to the other's behavior, which can then eventually be encoded as feedback.

2.5 Implications for Social Interaction with Humans and Robots

During synchronous behavior, one person sees that the other person is acting “like me” - which creates a feeling of similarity and rapport [47–49]. Vice versa, a greater feeling of rapport and sympathy between two individuals can also be measured by the degree to which they synchronize [50]. Thus, synchronous behavior is related to the emergence of compassion [51,47,48,52] and positive emotions [53,2]. Furthermore, by recognizing differences between own and other's actions, synchronous behavior links to the ability to learn from each other [27,25].

With regard to the interaction with robots, Krämer et al. [54] developed a theoretical framework that discusses different levels of sociability. They distinguish between a micro-, a meso-, and a macro-level of social abilities:

- On the *micro-level*, actual interaction and the prerequisites for communication take place; the relevant theoretical basis is offered by theories such as common ground, theory of mind, perspective taking and shared intentionality. This is also the level on which the two key mechanisms synchrony and reciprocity are affecting us, namely on a subconscious/automatic response level which can potentially be used to achieve a first grounding between a human and a robot.
- On the *meso-level*, relationship building is taking place; this is based on theories about the need to belong, reciprocity, social exchange, and social dynamics (e.g. dominance vs. submissiveness). Thus, on this level, also the relationship building to the robot would take place. Here, it can be assumed that the automatic grounding from the micro-level positively affects the interaction perception also on a reflective user level, i.e. the user perceiving the interaction with the robot as ŞmoreŤ social and natural. In this line, research in sociology of technology could demonstrate that humans also tend to attribute social interaction paradigms, such as reciprocity, to objects [10]. In other words, humans not only apply reciprocity expectations towards other humans, but in specific cases also to objects. This goes in line with the findings of the *media equation theory* [11] and the *computers as social actor* (CASA) paradigm [55] in which humans treat media and technology in a social manner. Thus, integrating synchrony and reciprocity, movement coordination could lead to an overall improvement of user acceptance in human-robot interaction on a reflective user level.
- On the *macro-level*, role assignment takes place, from the user as well as from the designer/ developer. Thus, this is the level on which the actual task progress will be visible and an outcome can be achieved.

As for the objective of this paper, we largely agree with Krämer et al. and argue within this line that the further investigation and inclusion of synchronization and reciprocity research from a social neuroscience perspective could result in substantial progress in the field of social companion robots.

3 Synchrony and Reciprocity – Transfer to Human-Robot Interaction

From what is reported above, synchronization and reciprocity seem to be very promising concepts to be included in human-robot interaction (see also Marin et al. [56]). However, the consequent next question is, how can these key mechanisms be reasonably transferred to HRI?

3.1 Mind Attribution and Reciprocity

Wheatley et al. [2] argue that a prerequisite for experiencing the benefits of synchrony between humans is the attribution of a mind to the respective other. Furthermore, they claim that mind attribution in humans requires a living facial expressiveness, certain vocal features and movement profiles that we attribute life to (see also [33,34]). They also argue that these features enable us to disentangle living beings from artificial entities. Thus, autonomous robots that have an artificial intelligence might function as a meta layer between living beings and artificial objects, and therefore might require further or different cues. This implies, that only if humans attribute a mindfulness to a robot, the positive aspects of grounding through behavioral synchrony can be achieved.

However, with regard to mind attribution and anthropomorphization of robots, many factors shaping the robot's appearance and behavior have to be considered. Besides, also with regard to mind attribution based on mere movement behavior, there exist contradicting findings. Some studies find evidence for it [57–59], some seem to disprove it [32,60]). One interesting illustration of this dilemma are the contradicting findings of Kilner et al. [32] and Oztop et al. [61]. Both studied the emergence of an interference effect between a human and a robot (see Section 2.2). While the effect was absent in the study by Kilner et al., it was found in the study of Oztop and colleagues. Kilner et al. showed that humans would not display reciprocal reactions to artificial motion and that the interference effect is limited to biological motion. However, their robot was a very simple version and probably it was hard to attribute any mind or intelligence to it [62]. In contrary, Oztop and colleagues replicated the study with the humanoid robot DB [63] and used recorded human motion profiles as basis for the robot motion generation.

Thus, either one of the two factors (anthropomorphism, motion profile), or more likely a combination of both play a role if the robot should be perceived as “having a mind” and subsequently as a social entity [64,65].

However, what was not explicitly considered in the above mentioned explanations for mind attribution is the concept of (provided or perceived-as-provided) feedback, of mutual engagement – of reciprocity. If we can argue that the emergence of even movement synchronization requires the attribution of a mind, then the question is: what links the two together?

If two humans are engaged in a repetitive task, they synchronize [16]. However, in the same task, movement synchronization does not emerge if a human performs it with a robot that follows a biological motion profile but acts non-adaptively, i.e. does not show engagement in the task [66,56]. Thus, mere repetitiveness and biological motion are not the crucial cues underlying emerging synchronization. Instead, if now the robot is online adapting to the human behavior, and with this provides behavioral feedback, synchronization is emerging naturally [67,18,19]. Although it is not proven yet if the human in this case also co-adapts to the robot, and with this engages in mutually reciprocal behavior, the adaptivity of the robot seems to be essential for the emergence of synchrony.

This not only demonstrates again that reciprocity and synchrony affect each other, it also raises the question if the mind attribution required for synchrony, and subsequently for the positive effects that emerge from it, are actually based on the consciously or unconsciously perceived reciprocal features of the interaction. If this indeed is the case, then reciprocity is one key factor for mind attribution and the emergence of synchrony is a tool for measuring it, also in HRI.

However, as Marin et al. [56] already outlined in 2009, todayŠs HRI is highly unidirectional and to our knowledge, at present there are no studies that tried to use synchrony and reciprocity for establishing a long-term connection between the human and the robot. Nevertheless, we think that including synchrony and reciprocity will not only improve the social interaction between humans and robots, it could also serve as an enabler and a motivator, especially in a robot-assisted therapeutic and rehabilitation context. Here, an improved social interaction between a patient and a robotic caregiver might even improve the outcome of the intervention [5, 68]. But if we want to include synchrony and reciprocity into the action repertoire of social companion robots, we need behavioral models that shape the interaction between humans and robots already on the micro-level (see Section 2.5).

3.2 Models for Human-Robot Movement Synchronization

Movement synchronization for robotic actions has been studied for various applications. For example, Revel and Andry [69] developed a neural network architecture that, through activation and inhibition of perception-action coupling, enables turn-taking between two robots. Hasnain et al. [70] used movement synchronization for selecting an interaction partner from a crowd of people and other groups [71,72] used imitation for robotic skill acquisition.

Although these models have a certain ability for reciprocal adaptation, up to now they are designed in order to either establish movement synchronization between robots, or to create a benefit for the robot. Therefore, Mörtl et al. [18] developed a behavioral model of movement synchronization that allows for a direct application in human-robot interaction in repetitive tasks. These models are based on data derived from human movement synchronization in the same task [16].

In order to transfer the findings from human movement synchronization to a robot, the Haken-Kelso-Bunz model [73] of two coupled oscillators was extended by Mörtl et al. [18] to enable both in-phase and anti-phase synchronization. Other than Revel and Andry [69] who propose differently coupled neural oscillators to capture (in-phase) synchronization as well as turn-taking (anti-phase), this model allows for both patterns to emerge. As Lorenz et al. [66] could show that when humans interact with a non-adaptive robot, movement synchronization does not emerge as it does not fulfill the user’s need for reciprocity, the model from Mörtl et al. [18] allows for an adjustment of the robotŠs adaptation. However, this model is still limited in terms of its applicability to higher level tasks, like for example picking and placing objects. Therefore, the model from [18] was extended in [19], allowing not only the synchronization of the continuous interaction dynamics, but also for the recognition and synchronization of events.

3.3 Measuring Synchrony and Reciprocity in HRI

If synchrony and reciprocity should be used in direct applications in human-robot interaction, there is of course also a need for measuring this behavior. In general, as the current hypothesis is that synchrony and reciprocity should be applied to human-robot interaction as it is present in human-human interaction, the same measurement methods that are applied in human-human interaction should be applicable in human-robot interaction.

In this context, different measures exist to evaluate a robotic system from a user perspective. We can distinguish between (1) self- assessments, (2) interviews, (3) behavioral measures, (4) psycho-physiological measures, and (5) task performance metrics [74]. However, the biggest challenge in measuring the perceived social reciprocity, that evolves through automatic responses from movement, is that this effect can only be measured over time. Therefore, measuring synchrony and reciprocity most often means, dealing with the analysis of time series. As there are extensive reviews on measuring methods for synchrony like in [75,76], only a brief introduction on the measures used in [16,66,18] should be provided in this paper, as they were also already applied in HRI.

Measuring behavioral synchrony requires some kind of action data recording that can be derived from video annotations or motion tracking systems. With the latter, motion data is recorded as 3D position time series $x_1(t)$ and $x_2(t)$ of the two interaction partners. Hereof the phase signals $\theta_1(t)$ and $\theta_2(t)$ can be derived with different methods as described and discussed in [18]. One possible method is to transfer the (quasi-) harmonic movements of one person into its velocity-position state-space $(x, \dot{x})$. For both agents, the individual phase $\theta(t)$ can be derived from the state-space trajectory by

$$\theta(t) = \arctan\left(\frac{\dot{x}(t)}{-x(t)}\right), \tag{1}$$

in which $\dot{x}(t) = \frac{\dot{x}(t)}{|\hat{\dot{x}}|}$ and $x(t) = \frac{x(t)}{|\hat{x}|}$ are the normalized velocity and position. The constants $\hat{\dot{x}}$ and $\hat{x}$ denote the extrema of velocity and position observed in the motion trajectory. After both $\theta_1(t)$ and $\theta_2(t)$ are obtained, the relative phase $\Phi(t)$ is calculated as

$$\Phi(t) = \theta_2(t) - \theta_1(t). \tag{2}$$

Having derived the relative phase signal between the interaction partners, one possibility of assessing movement synchronization is the cross-spectral coherence [1], a measure of correlation between the two phase time series. The cross spectral coherence is derived from the circular variance (CV) of the relative phase by

$$Coherence = 1 - CV = \left| \frac{1}{N} \sum_{j=1}^{N} \mathrm{e}^{i\Phi(t_j)} \right|, \tag{3}$$

where N is the number of relative phase observations $\Phi(t_j)$, see also [77]. The cross spectral coherence can vary between 0 and 1. If the relative phase is uniformly distributed, the coherence would equal 0, while a perfect synchronization would be determined by a coherence equaling 1.

If synchronization between interaction partners is not instructed but emerges naturally, then the coherence between them is usually weaker than in the instructed case [13,78]. It was also observed that in these cases, the phase relation is not stable in the sense of a steady-state coordination, but subject to repetitive change [13,79]. Thus, for determining whether in-phase or anti-phase relation is emerging, the distribution of the relative phase is derived. Therefore, the observations $\Phi(t_j)$ are clustered into a determined amount of phase regions (most often nine $\frac{\pi}{9} = 20°$-phase regions) and accumulated over all performed trials within one condition, see Figure 1. This accumulated data is then depicted in a diagram in which the abscissa is clustered into phase regions and the ordinate shows the percentage of accumulated relative phase. This diagram, showing the *distribution of relative phase* provides an overview on how often the phase difference between interaction partners was for example in a phase difference of 0° and thus in an in-phase relation or 180° and thus in an anti-phase relation.

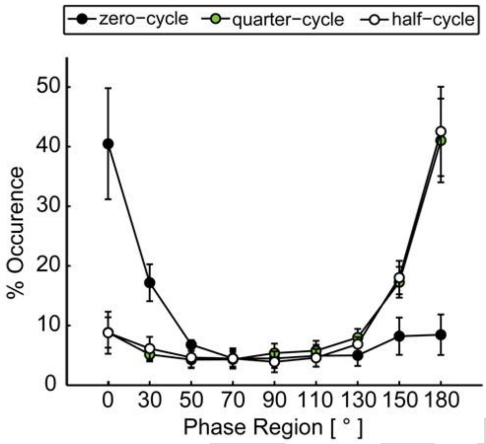

Fig. 1 Example for distribution of relative phase taken from [17]. The abscissa shows the relative phase regains, the ordinate shows the percentage of how often the relative phase was calculated to be in the respective phase region. The plot shows that in the zero-cycle condition, the two agents were mainly synchronized in in-phase relation (0°-phase difference) while in the other two conditions, agents tended to mainly synchronize in anti-phase (180°- phase difference).

A further typical method for determining synchronous behavior is Cross Recurrence Quantification (CQR), which enables the discovery of similarities in temporal patterns across different time series, see [80,81].

Measuring the reciprocity of the interaction is a bit more challenging as it requires to measure and to quantify the ongoing adaptation process in real-time. One approach to measure the interpersonal adaptation in human-human interaction is described in [17]. Here the time series were considered in segments, which allowed for an analysis of the behavioral adaptation of the individuals to the experimental situation. However, an analysis of the reciprocal behavior is always bound to the interaction situation. Besides, first studies showed that the effect of reciprocity might carry over to other tasks which do not involve reciprocal elements [82].

Another aspect that needs to be considered is that the effect of synchronized human-robot movement use, especially in therapy and care, might not be directly self-reported by the user, but be observable in his/her changing relationships to others, for instance in autism or depression therapy.

---

[1] The cross-spectral coherence is also called mean phase coherence or synchronization index (*SI*).

4 Social Companion Robots for Therapy and Rehabilitation – Overview

In general a companion robot is defined as a robot that "(i) makes itself *useful*, i.e. is able to carry out a variety of tasks in order to assist humans, e.g. in a domestic home environment, and (ii) behaves *socially*, i.e. possesses social skills in order to be able to interact with people in a socially acceptable manner" [83]. It is considered that companion robots can be above all valuable for older adults and homebound people. For instance the robot companions EU flagship project, intended robot companions to be "a new generation of machines that will primarily help and assist elderly people in daily activities at home, in their workplace and in other environments" [84]. They expect that future robot companions will be

- *strong machines* that can take over burdensome tasks for the user.
- *graceful and soft machines* that will move smoothly and express immediate responses to their users.
- *sentient machines* that are context-aware and offer multi-modal communication channels and are trustable.

Clearly this type of companion robot is still a futuristic vision and further progress in the development of components is required, as more adaptive and complex behavior also leads to an increased number of needed sensors, more degrees of freedom, and higher computational power requirements, etc. However, the field of socially intelligent robotics is constantly improving and creates robots "capable of exhibiting natural-appearing social qualities" [85]. Social companion robots are often also called socially assistive robots [86]. They specifically focus on helping people through social rather than physical interaction. Thus, socially assistive robots are intended to improve the quality of life for specific user groups. Today, the populations with the largest estimated benefits for social robot assistance are: elderly people, individuals with physical impairments who undergo rehabilitation therapy, and individuals with cognitive disabilities and developmental and/or social disorders [85].

According to Fong et al. [87] social robots can offer three major advantages for therapy and care:

- Robots can provide a stimulating and motivating influence that makes living conditions or particular treatments more pleasant and endurable.
- By acknowledging and respecting the nature of the human patient as a social being, the social robot represents a humane technological contribution.
- In many areas of therapy, teaching social interaction skills is in itself a therapeutically central objective, an effect that is important in behavioral therapeutic programs, e.g. for autistic children, which can potentially be used across a range of psychological, developmental or social behavioral disorders.

As socially assistive robots should enrich the social world of i.e. elderly or patients, a key ingredient for their behavior is therefore interactivity. If companion robots and users with special needs should cooperate by exploiting both parties' strengths and weaknesses towards forming some kind of relationship, the interaction with the robot benefits if it is able to offer certain social abilities [88]. However, identifying suitable social abilities in humans and implementing them as robot behavior is one of the big challenges in the development of companion robots [85].

5 Synchrony and Reciprocity – Applications in Social Robot-Assisted Therapy

In the following we will outline different fields of social robot assisted therapy and care. We tackle the interaction with healthy older adults, patients with neurocognitive and neurophyiscal impairments, and people with depression. In this context we will put a special emphasis on the role of synchrony and reciprocity. Thus, as there is a tremendous amount of literature on social robots and robots in general that assist patients and take care, the following section is not meant to be a detailed review, but rather an overview on how synchrony and reciprocity are currently taken into account in HRI.

5.1 Aging-in-Place

One goal of social companion robots for (healthy) older adults is to increase their well-being and to enable them to stay at home as long as possible. Social companion robots can thereby for instance reduce loneliness. For example companion robots were developed that fulfill some roles of pets (see Figure 2). The most prominent example is *Paro* [89], a seal type mental commitment robot. It has been developed for those who cannot take care of real animals and those who live in places where pet-animals are forbidden. Paro is designed to provide three types of effects: psychological, such as relaxation and motivation, physiological, such as improvement in vital signs, and social effects such as instigating communication among persons and caregivers. A related example is the real-life-looking robotic cat *NeCoRo*, which mimics the reactions of a real cat to enable natural communication with humans [90]. It reacts to speech and touch with moving its tail or eyes and meows, hisses or purrs. Similarly, the teddy bear robot *The Huggable* [91] is designed for use in hospitals and nursing homes. The Huggable is a new type of robotic companion capable of active relational and affective touch-based interactions with a person. The robot features a full body, multi-modal sensitive skin system capable of detecting affective and social touch.

These pet-like robots focus above all on the social aspect of reciprocity, namely helping or taking care of some-

Fig. 2 Social robots for elderly care (from left to rigth): Paro, Huggable, NeCoRo.

Fig. 3 Social robots for elderly care (from left to rigth): Care-O-Bot, MobiNa, Hector, and Hobbit.

one. This nurturing behavior provides the basis for the interaction. However, also other aspects of reciprocity or synchrony are considered for this type of social companion robot when they are used for neurocognitive impairment therapy (see Section 5.2.2).

A further type of social companion robots for elderly care are those that take over household tasks in order to enable independent aging-in-place (see Figure 3). One of the most popular examples is the *Care-O-Bot* research platform [92], developed at the Fraunhofer Institute for Manufacturing Engineering and Automation (IPA). Care-O-Bot is designed as general purpose robotic butler which can fetch and carry objects and also detect emergency situations (e.g. a fallen person) and contact help. Similarly *MobiNa*, a small (vacuum-sized) robot was developed by Fraunhofer, specifically aiming at performing fallen person detection and video calls in emergency. Another prominent example is the robot *Hector* developed within the EU project CompanionAble [93]. Hector is designed as a robotic assistant for older adults integrated in a smart home environment and a remote control center to provide the most comprehensive and cost efficient support for older people living at home.

In general these robots focus on task-based support in everyday life. An exception is the care robot Hobbit [94], which is developed to support aging-in-place. Its interaction abilities are based on social reciprocity [95]. The idea is that not only the robot takes care of the human, instead the human should also take care of the robot and help it in situations where the robot could not achieve a goal on its own. At present, this behavior is implemented in simple give-and-take dialogues[2], which are studied in a controlled laboratory setting. The results look promising with regard to the positive effects that these dialogs increase the belief in own ability to complete a task (*self efficacy*) of the human and ease the interaction [82]. Long-term field trials exploring these effects further are currently in preparation.

Overall, when it comes to social companion robots for the support of aging-in-place, mainly the mechanism of social reciprocity is considered so far. Further investigation in how far behavioral and motor synchrony and reciprocity could be helpful to meet the aim of developing robots that increase human well-being on a more fundamental level beyond pure task-support and short-term reduced feeling of loneliness.

One interesting example in this regard is described by Fasola et al. [96]. Here, the social robot Bandit (see Figure 5) is implemented as an exercise coach for elderly people. The user is encouraged to play an imitation game with the robot in which the user has to imitate the robot's behavior. The robot then provides verbal feedback on the user's performance. Here, synchrony is included by means of imitation of movements and reciprocity is included in the form of verbal feedback, both with the attempt to increase the interaction motivation of the user. Although at the current stage, synchrony and reciprocity are implemented in one or the other modality, this might be a good starting point to also explore the possibility for grounding of the interaction by also enabling the robot to adapt to the user's movements.

5.2 Neurocognitive Impairments

People with cognitive disabilities and developmental and social disorders are another target user group for socially assistive robots. Here, typical contexts are education, therapy, and training. All robots for this target group are intended to generate "carefully designed, potentially therapeutic interaction between human users and themselves, involving elicitation, coaching, and reinforcement of social behavior" [97].

5.2.1 Autism

The British National Autistic Society describes Autism Spectrum Disorder (ASD) as a "lifelong developmental disability that affects how a person communicates with, and relates to, other people." [98]. People suffering from ASD have problems with social communication, social interaction, and social imagination. This means they have problems interpreting the facial expressions and body language of others, they have problems understanding social rules and emotions and might also have learning disabilities in general. Another symptom is repetitive sensory-motor movements and problems in language acquisition [99]. Thus, autistic people have problems integrating into daily social life and need special social training. While healthy children usually learn through imitating their parents which is assumed to influence the development of basic empathic social skills [100]. Children who are later diagnosed with autism do not at all or only show a reduced imitative behavior [101]. And as a neuroscientific explanation to this, in the past years there was more and more support to the notion that the emergence of autism

---

[2] For example, the robot explicitly asks "can I return the favour?".

Fig. 4 Social robots for neurocognitive impairment therapy (from left to rigth): Robota, Roball, Probo, Kaspar, Keepon

is connected with a dysfunction of the MNS [102–104], and that this defect is already present in toddlers.

Nevertheless, this also bears possibilities for treatment. Autistic children who are imitated by adults in repeated sessions show improved social behavior (see Field et al. [105] for a review). With regard to movement synchronization, a new approach was recently introduced from dance therapy. Behrends et al. [106] outline a novel concept that includes phases of synchronous movements both in a simultaneous and in a turn-taking manner and also include new dance elements which patients have to imitate. The main purpose of this approach is to study how this overall concept of synchronous and reciprocal behavior can enhance empathy in autistic people. So in general, synchrony and reciprocity play a major role in autism therapy. As it was found that autistic children sometimes even respond better to interaction with robots than to other humans [107] or also with inanimate objects [108], including social robots into therapy for autistic people seems promising.

Numerous studies have shown that social robots can support autistic people in enhancing social skills through eliciting joint attention [109], mediating sharing and turn-taking between the patient and a therapist and encouraging imitative or synchronous behaviors [97, 110]. Prominent examples for robots used in this research area are the humanoid robotic doll, *Robota* [111], which has been developed within the AURORA project, the spherical robot ball *Roball* [112], the humanoid robot *Kaspar* [113], developed by the Adaptive System Research Group at University of Hertfordshire, the expressive small creature-like robot Keepon [114] designed for simple, natural, nonverbal interaction, and the elephant-like robot *Probo* [115], developed at Vrije Universiteit Brussel (see Figure 4).

Just recently, several reviews have been published covering a variety of aspects in the field of robot assisted therapy for autism [116–118, 97]. In the most recent review, Boucenna et al. [116] provide an overview of all interactive technologies for intervention in autism. Among other aspects, the authors highlight the use of social robots in therapy because of their ability to imitate and being imitated. Nevertheless, they recognize a need for an evaluation tool for the interaction between humans and robots and propose to focus on interpersonal synchrony. This seems to be a very promising idea as synchrony is relatively easy to access [75] and underlies many different cognitive processes that are affected in autism.

Taking mere rhythm and full body movements into account, Keepon [114] has to be highlighted, see Fig.4. Different to other social robots Keepon has no arms or legs with which it could apply human or animal-like behavior. It can simply move its head (and thus direct gaze to encorage joint attention [119]), rock left right or “bobb” up and down. With these abilities Keepon was already successfully tested to attract attention of and promote interaction with autistic children. In these and other studies, Kozima et al. [114] realized that a common theme was the use and natural emergence of rhythmic interaction in the form of synchronous or turn-taking behavior. They thus implemented a system on Keepon that can detect rhythms in various modalities and synchronize to them. First observations with (so far only healthy) children show promising results with regard to mutual movement coordination.

Another promising example for the implementation of synchrony and reciprocity to robot-supported autism therapy is provided by the graded cueing paradigm. In a pilot study with a NAO robot, Greczek et al. [120] implemented an imitation game for autistic children, with the additional feature that the robot is able to provide both verbal and gestural feedback to the childrens’ performance. Results showed that a feedback as provided by the graded cueing model was promising, potentially due to its variable and minimalistic reciprocal nature.

Addressing the benefits and pitfalls of social robot assisted therapy for autistic patients, Diel et al. [118] offer a critical review. In their outline of future requirements for research on social robots in autism, amongst others they mention the different mechanisms that are shown when people with autism respond to objects versus biological motion. People with autism fail to recognize social stimuli in moving objects as depicted with a moving triangle cartoon or point clouds [121]. However, they can be supported in recognizing these movement as biological movements by providing additional information by audio-visually synchronized cues [122]. Keeping in mind the differences in movement interference for biological and artificial motion (Section 3.1) this might be a good measure for validate whether or not autistic children perceive the reciprocity in motion during interaction with a robot. Also this might elicit further if and how robotic behavior can effectively prepare for a social interaction with another person. Nevertheless, this approach also has to be treated with care: Cook et al. [123] tested the appearance of the interference effect in autistic adults and discovered its absence, both in response to biological and non-biological motion.

In summary, it can be stated that behavior synchronization and reciprocity are very helpful tools for autism therapy and are most likely also applicable in autism therapy with social robots. Due to enhanced responsiveness of autistic patients to robots [107], therapy might even be improved (but see [124]). Further investigation is required to check whether or not the neurocognitive effects present in healthy interaction also hold for autistic people, be it in interaction with other humans or with social robots.

5.2.2 Dementia

Dementia is a progressive brain degenerative group of diseases that affects the patient's memory, sense of orientation, ability to concentrate and mood (including apathy and depression). Furthermore, it can lead to withdrawal form social activity and isolation [125]. Therefore it is important for the patients' most possible well-being to include them into interaction with others (relatives, care-takers, fellows). One possibility in non-robotic treatments is animal therapy [126]. A key aspect of animal therapy is that the reciprocal interaction with the animal being a meaningful task ("I am needed"), reduces aggression and encourages prosocial behavior. The patients can pet and talk to the animals and receive a response. They experience social reciprocity. On the robotic side this is for example achieved by introducing the Paro robot [89, 127] or similar pet robots [128] into the patient's surrounding (see also Section 5.1). These pet robots serve as a substitute for real pets with the advantage of not causing defensive reactions or health issues (e.g. allergies) while being socially responsive by providing reciprocal interaction [129]. Studies with social pet robots have shown that similar effects as with real animals can be achieved in terms of calming down patients, improving communication and social integration as well as reducing stress levels for both patients and caretakers, see [130] for reviews.

A promising attempt on using the basic principles of synchrony in terms of performing simple movements together is integrated within the modular robotic rolling pins (RP) which are specifically designed to meet the needs of dementia patients (dimension and weight suitable for easy manipulation, simple interaction modalities, stimulation of familiar sensory-motor patterns) [131]. The RPs are coupled in a master-slave principle in that the therapist can perform a gesture or movements that the patient should imitate, while the RP is providing feedback on success via acoustic, visual or tactile feedback. With this, also a reciprocal behavior is induced: if the patient fails to synchronize or imitate, both patient and therapist have the ability to mutually adapt to each other (i.e. by slowing down). Thus, the RPs provide enhanced reciprocal feedback, which might be necessary for stimulating social interaction in dementia patients. First results by Marti et al. [131] show promising tendencies regarding motivation to interact as well as interaction duration.

Other investigations aim to include imitation of movements using social robots such as NAO [132] or Bandit [133]. Although Martin et al. [132] only report preliminary results on robot mediated exercise, dance therapy seems to be a very promising approach. Nyström and Lauritzen [134] could show that demented people responded to expressive dance predominantly with synchronous movements. They point out that synchrony appears to be a fundamental behavior with which demented people can interact with the "healthy" world, despite other communication deficits. Overall, for supporting dementia patients and their surrounding, the concept of reciprocity seems to play a major role and social robots appear to be very effective in providing it. In the future however, a further emphasis should also be put on robot induced synchronous behavior which might considerably improve the patient's social integration.

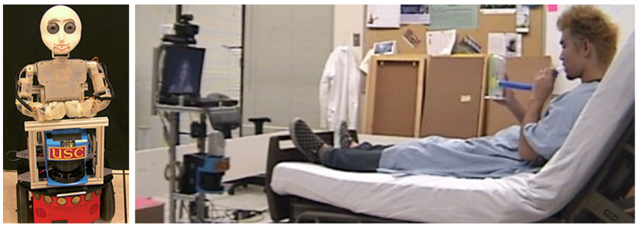

Fig. 5 Social robots for rehabilitation and training: Bandit and Clara

5.3 Neurophysical Impairments

We consider neurophysical impairments to cover all diseases or injuries that cause a deficit in motor function. These are for example brain injury (i.e. stroke), Parkinson's disease, Epilepsy, Cerebral Palsy, Multiple Sclerosis, etc.. All of these diseases require intensive training in order to (re)establish or maintain motor function, which is a primary need not only to participate in a social life (including quality of life), but sometimes also a requirement for extended survival. The main application for assistive robots here are support of motor function and motor rehabilitation for upper or lower limb [135, 136]. Thus, the primary robot-assisted rehabilitation is not social, rather physical.

However, social companion robots can above all offer novel means for monitoring, motivation, and coaching, whereas post-stroke rehabilitation can be considered the largest application domain today [85]. One example is the hands-off therapist robot *Bandit* [137] that assists, encourages, and socially interacts with patients in post-stroke rehabilitation training. Another example is *Clara* [138], a therapist robot assisting humans with spirometry exercise (see Figure 5).

Besides, in a study in which healthy participants were physically connected through a robotic device, Ganesh et al. [139] showed that people profit not only from mere guidance during haptic interaction, they also take out additional task-related information from the haptic interaction with their partner, which enabled them to improve their performance to a higher extent in the given time. Although the authors mention that more research on the modalities is required, rehabilitation efficiency could benefit from haptic informational exchange, also with a robot. Thus, reciprocal effects of interaction sometimes bear even more information and support than visible on the first glance. In the following we will review social robot assisted rehabilitation techniques for neurophysical impairments which make use of these underlying mechanism such as imitation, movement synchronization, and reciprocity in general.

5.3.1 Brain Injury

If the central nervous system (CNS) is damaged due to stroke or traumatic injury, the damage can result in motoric, cognitive or perceptual deficits - most often even in a combination of all. Neuroscientific findings however could proof that the CNS can actually recover and the physical, cognitive or perceptual function can at least partially be reestablished [140]. One of the keywords here is neuroplasticity – the reorganization and recreation of neural structures in the brain [141].

At first glance, brain injury as a physical impairment does not come with cognitive or social requirements in therapy. However, rehabilitation requires a lot of training which has to be repetitive, functional, meaningful, and challenging for the patient [142]. Rehabilitation after stroke leads to best results when performed at high intensity levels, which for the patient can be very frustrating. Thus, one possibility to support rehabilitation by means of social robots is by increasing treatment compliance with games [143] or by providing motivating feedback [137, 144–146]. Although these systems are successful in stimulating task performance, so far almost no evidence is provided on their impact on rehabilitation of i.e. motor function.

One exception is presented by Wade et al. [146] who showed that equipping a socially assistive robot with multimodal perception abilities and including these into feedback provided to the patient can improve motor performance as measured by smoothness. Their robot Bandit can track the patient's performance and generates task-inspired verbal feedback with synchronized gestures while additionally being able to demonstrate the task if the patient does not act appropriately [145]. Although their results are far from clinical evidence, Wade et al. [146] suggest that providing reciprocity by linking actual task-performance to feedback might actually have an impact on future task performance. However, as Bandit was also demonstrating tasks in case of patient's failure, another possibility to interpret the results from Wade et al. is by means of the action observation therapy introduced by Ertelt et al. [147]. The action observation therapy makes use of the idea that the human brain does not only process motor information when we actually move, but also when we observe movement [104], see also Section 2.4. In a study with stroke patients, Ertelt et al. showed that by priming physical training with action observation of daily life tasks, the motor function of the upper limb was significantly improved when performing these actions – also compared to a control group that was watching geometric figures and letters as control prime to the same physical training. Using fMRI they were able to show that previously inactive motor areas in the brain that are connected to learning by imitation, were reactivated, see also [148]. Thus, seeing an action that one is to perform right after – and nothing else is imitation – supports the same mechanisms as in initial motor learning in early childhood [100, 27]. As robot motions can trigger imitative behavior [60, 107], robot assisted therapy in rehabilitation after stroke does not necessarily have to be reduced to reciprocal motivation and encouragement. Rather combining these approaches with imitative features might elicit more positive results.

5.3.2 Cerebral Palsy

Cerebral palsy is a childhood disability that is caused by damage to the motor control centers of the developing brain (pre-or postnatal) which causes upper and lower limb motor coordination problems and problems with force generation [149]. An intensive physical therapy can enhance the development of motor function [150]. In this context, robot-assisted therapy is especially promising as it enables adaptive support with training enhancement. However, the training is intense and especially for children usually boring. Fasoli et al. [150] highlight that here robot-assisted therapy is the way to go as it provides children with social interaction, competition, and reward for improved performance. In this context, serious games in virtual reality seem to provide a good method to engage children into therapy, especially in combination with robotic assistance [151]. To our knowledge the only social robot to appear to support in the rehabilitation of cerebral palsy is KineTron which motivates children to participate in a movement training game [152]. However, there is only a pilot study reported and no disease-specific training applied yet. Thus, for the social robot-aided treatment of cerebral palsy, synchrony and reciprocity are not implemented yet. Similar to the effects of post-stroke rehabilitation the two concepts could however aid to motivate reciprocal training enhancement by feedback or by imitation tasks.

5.3.3 Parkinson's Disease

Parkinson's disease is a progressive neurodegenerative disorder of the central nervous system that affects the overall motor control. One problem in Parkinson's disease is the instability of movements and gait [153]. In healthy people, almost everybody has already experienced that gait patterns automatically become synchronized when walking next to each other [15] (see also Section 2.1). With regard to Parkinson patients, it was observed that these interpersonal synchronization processes can be instrumentalized to improve patient's gait [154]. These positive effects have also been shown in the interaction with the Walk-Mate, a virtual robot that displays auditory cues which adapt to the patient's gait patterns by means of nonlinear oscillation processes [155]. Moreover, Uchitomi et al. [156] showed, that these positive effects towards an establishment of healthy gait patterns emerges due to the mutual coupling, the reciprocity between the patient and the Walk-Mate. A similar auditory stimulation as reported for Parkinson patients was also reported for multiple sclerosis, a neurodegenerative disease that affects muscle performance [157]. Thus, the very basic component of social interaction, namely mere interpersonal synchronization during walking, has a positive effect on the patient's behavior while other, non-adaptive signals, cannot evolve the same effect (see also [158]).

5.4 Depression

Depression is a psychiatric illness that is characterized by the cardinal symptoms of persistent and pervasive low mood and by the loss of interest or pleasure in usual activities [159]. Depression can occur as a psychiatric condition on its own and the emergence of depression in otherwise healthy persons is still subject to ongoing research. However, the risk of depression due to loneliness or social isolation is known to be increased for elderly [160, 161]. Besides that, depression is usually comorbid to all diseases and impairments mentioned above. It can result from social isolation in autism or dementia or be a result of reduced mobility and loss of functionality after brain injury or in neurodegenerative diseases [159].

In treating major or moderate depression, David et al. [162] outline that robot-based therapy can have a great impact. They highlight the use of robot replacements for animal therapy (see also Section 5.1 and 5.2.2) which, by their unpredictable responsive behavior to touch, create a feeling of well-being and reduce social isolation and depression [163]. They also mention a new robot RETMAN which was initially included in Rational Emotive Behavior Therapy Cartoons for children. Preliminary results suggest that RETMAN can help to alleviate distress and dysfunctional feelings in children. However, no further details are given on the social interactive abilities of the robot.

In the treatment of depression, one big problem is the treatment adherence (the extent to which patients stick to their therapy recommendations) [164]. Thus, in the EU project help4mood a virtual agent is developed which assesses the current individual emotional state and provides therapeutic empathic feedback with the goal to change the state perception of the patient [165]. So far only pilot study results are reported which draw a mixed perspective. Adherence was not improved in every case. One problem might be that the empathy provided by the agent was not matching the patient's expectations i.e. in terms of the ability to understand emotions and was thus not able to provide correct feedback [165, 166, 85]. Similarly, it was found that positive effects on loneliness (an indicator of depression) are rather achieved with embodied robots than with virtual agents due to their higher social presence [96, 167].

Another virtual agent that is under development to assess depression based on non-verbal cues is SimSensei [168]. Here the goal is to enable the virtual agent to engage the patients into structured interviews by using natural language and nonverbal sensing to identify the presence of non-verbal indicators of psychological distress. Although the development of SimSensei is based on real-world interaction data with interviewers, no studies on the applicability of the system are provided so far. Here, it would be interesting to evaluate in which way a provided virtual feedback or synchronous behavior by the virtual agent can improve the assessment of the depression level.

A successful approach to show emotions is provided with the story-telling robot [169, 90]. Here children were encouraged to tell a story about their experiences that will then be depicted by means of a robot that has to be able to express emotions as movements. The children can control the robot with their own movements to express emotions (the robot is imitating the movements). Besides revealing underlying emotions that might be too hard to tell directly, the story-telling robot can also be used for physical training (an emotion must be expressed by a certain movement that has relevance for rehabilitation) or autism therapy (learning different ways of expressing emotions that are directly mirrored) and improves the adherence to training by being involved in a creative and expressive task with immediate feedback. The reciprocity of this interaction does not only provide the therapist with very important information, it also creates a feedback to the patients that they are in control about what is happening, which is important for psychological well-being [161] and get the possibility to learn and reflect something about their own behavior.

6 Discussion

In this article we emphasize that synchrony and reciprocity are two key mechanisms underlying multiple human interactional principles. Therefore we also consider them as key mechanisms to be included in Human-Robot Interaction, especially when robots are ought to assist in elderly care, therapy or rehabilitation.

6.1 Implications

For aging in place, social companion robots are up to now mainly intended to reduce loneliness or mediate social interaction with other humans (pet-like companions), and household assistance (service robots for household chores and emergency handling). So far, little has been explored on how synchrony and reciprocity can be used to enhance the interaction with these robots and subsequently improve the well-being of the older adult. However, first studies indicate the potential of social reciprocity in the interaction to enhance self-efficacy of the human and acceptance of the robot. Therefore we argue that besides useful functionalities that clearly need to be provided to enable independent living at home for older adults, synchrony and reciprocity may add to the long-term acceptance of the robot as caregiver and enhance the (perceived) quality of the care.

For neurocognitive impairments, especially imitation and behavioral and social reciprocal behavior is essential, as it provides a subliminal link to the healthy social world. Here, robots have striking advantages as they can i.e. behave like pets with the possibility, but not the need to be taken care for. Like real animals they successfully calm down dementia patients by providing reciprocal feedback and offer them a way out of their social isolation. Besides, especially in autism, robots are perceived as social entities. They can act as mediator or role model and thus function as a “trainer” of social interaction without the high risk for the patient of being exposed to the complexity of real social interaction [118, 85]. Here, although sometimes being termed in different ways, the concept of reciprocity is already well-established. However, although it has been shown that especially synchrony can foster social behavior such as empathy and perspective taking [106], not much work has been done with regard to including these mechanisms into social-robot-assisted therapy.

The latter is also the case for social companion robots in the rehabilitation of neurophysical impairments, in which the support of social robots is still mainly limited to providing motivation and guidance. Although one could argue that motivation could also be provided by other media, apparently the embodiment of the agent plays a relevant social role [96, 167]. Thus, by enabling this embodied agent (the assistive robot) to function as a model or interaction partner for physical activity (be it with or without contact), one could potentially have an even greater impact on rehabilitation. Also, what is underrepresented so far is the use of synchrony as a tool to form rapport and connectedness between the patient and the robot. If designed carefully, a synchronization task could thus make the patient perform rehabilitation movements by providing a model for task imitation and create a connectedness with the agent which can be motivating in terms of a team experience.

When it comes to the treatment of depression, besides interaction with pet-robots and first approaches with virtual agents, not much work has been done in supporting the needs of patients with the help of assistive robots. Thus, here we see a need for filling the gap and we believe that social robots can be of great utility. As it is known that depression can be improved by means of physical activity, robots could also take over a motivating and encouraging role. Furthermore, they could act as role models, i.e. by mirroring and imitating the actual behavior of the patient to draw his/her own attention to it or by mimicking the patient’s mood. Similarly, these imitative mechanisms could be turned around and the robot could encourage the patient to imitate a positive behavior. However, it will require a deeper understanding of neural mechanisms in depression for being able to understand in which way synchrony and reciprocity can be of benefit for a depressed person.

6.2 Future Directions

So what could a future research agenda for social companion robots in therapy and care look like? First of all we are convinced that social reciprocal strategies add on top of synchronous behavior and thus both have to be combined to evoke the full potential for social robots in elderly care, therapy, and rehabilitation. On the other hand, reciprocal movement feedback supports the attribution of mind to the robot and enables the synchronization process and with it behavioral adaptation and (learning by) imitation. Thus, a twofold strategy can come into place in which synchrony serves as a basis. Initially, the robot has to capture the patient’s attention. Already here, synchrony can be taken as a feedback method, i.e. the robots adapts to a person’s movements and by this shows non-verbally: you have my attention [70, 71]. Then, the robot needs to infer the person’s state for being able to act and react appropriately. This actual state can be for example imitated by the robot, to mirror the actual state of the patient and thus create awareness. At the same time the robot could also reverse the perceived state and with this encourage the patient to imitate i.e. a more positive/active/social behavior. Both scenarios (imitating/being imitated) can be designed to evoke nurturing behavior in the human and with this close the social reciprocal circle, which will increase well-being of the person. In the same line, the robot could also use the captured state to start joint activities which could include synchrony and reciprocity based actions. Here the robot could at the same time function as a

- *motivator*: while using movement synchronization or turn-taking as timing models the robot can at the same time employ the underlying effects of synchrony for creating a more social atmosphere and fostering a joint activity through the creation of rapport.

- *role model*: by frequently demonstrating the task the robot encourages the patient/care-receiver to imitate it and has thus influence on performance and potentially also on learning and the human's mood.
- *therapy assistant*: as it could monitor and show the task progress, the robot provides multi-modal feedback and can additionally demonstrate reciprocity by adapting the task to the patient's requirements. Thus, the patient perceives a reaction to his/her own actions which will feed back into motivation, as the task is more accomplishable.

Thus, by combining synchrony and reciprocity and implementing them into care-taking and therapy, one could not only increase the robot's acceptance, one could also create a successful and enjoyable process.

In general however, there are still unsolved questions in social neuroscience like: how is reciprocity perceived, how do we adapt to each other, how do we infer actions, and last but not least, how is this all embodied and does the embodiment itself make the difference? Furthermore one has to keep in mind that because this knowledge on human interaction is still not totally explained, when it is implemented to robotic behavior it can also be irritating due to a perceived mismatch in robot appearance and motion [170]. Thus, in order not to enter another dimension of the uncanny valley, we should put an emphasis on understanding human synchrony and reciprocity mechanisms in more detail.

Aonther unsolved question is that in most cases it is unclear if the positive effects for patients remain or can even be further enhanced. Also, due to the fact that in almost every study conducted so far, humans were actually present and payed special attention to the patient, which might covariate with the positive results. Thus, both the development of social robots and the inclusion of synchrony and reciprocity into the rehabilitation process will require more long-term and randomized clinical studies and potentially also a new study design. For really testing benefits, it might be useful to create robots that patients can take home, that can interact with patients on a daily basis over a longer period of time, maybe combined with telehealthcare and monitoring.

However, when robots enter the society in such a delicate and private area like therapy and care, also ethical considerations have to be taken into account. Besides, also the consequences of using subliminal mechanisms such as synchrony and reciprocity in human-robot interaction are an ongoing topic of extensive ethical considerations. A prominent example are the five ethical rules for robotics, which are published by the Engineering and Physical Science Council (EPSRC) [3] in order to serve as principles for designers, builders, and users of robots. The message of these rules is that âĂIJrobots are products: as with other products, they should be designed to be safe and secureâĂİ, and that they âĂIJshould be designed and operated to comply with existing law, including privacyâĂİ. These and similar guidelines adequately cover assistance and adaptation mechanisms as they are understood in this article. Problematic is that the perspective of these approaches considers robots as products. And in fact robots *are* products, they *are* machines. Nevertheless, anthropomorphizing effects can also lead to the fact that robots are understood as companions by their users. For instance, Sparrow [171] argued that the relationships between users and robot companions "are predicated on mistaking, at a conscious or unconscious level, the robot for a real animal. For an individual to benefit significantly from ownership of a robot pet they must systematically delude themselves regarding the real nature of their relation with the animal. [...] Indulging in such sentimentality violates a (weak) duty that we have to ourselves to apprehend the world accurately. The design and manufacture of these robots is unethical in so far as it presupposes or encourages this."

Since, the whole question of deception, and the possibility of the willing collusion of the users themselves, is a complex one [172], the EPSRC recommends that âĂIJthe illusion of emotions and intent should not be used to exploit vulnerable usersâĂİ and that the best way to protect consumers is to remind them of the robotâĂŹs artificial nature by incorporating âĂIJa way for them to âĂŸlift the curtainâĂŹ (to use the metaphor from The Wizard of Oz)âĂİ. Nevertheless, the crucial question remains if transparency concerning automatic mechanisms such as synchrony and reciprocity is sufficient to distance the user from the robotic product - especially if we take into account, that the human nature is profoundly social. Such mechanisms can influence users on an unconscious level despite superficial transparency.

In summary, we think that the two key mechanisms synchrony and reciprocity might significantly add to the positive outcome of a robot-assisted therapy and rehabilitation process, even beyond the currently known applications. There are possibilities for an enrichment of the rehabilitation process as social robots can also make use of the non-prevalent underlying social behavioral mechanisms that are induced by synchrony and reciprocity. Besides, synchrony and reciprocity are easy to measure and might provide an essential tool for capturing the success of human-robot social interaction [173, 56, 13, 174, 75]. Thus, researchers should foster the robot's ability to stimulate social behavior in humans by means of synchrony and reciprocity. Furthermore, they should combine and include these mechanisms in already existing applications. With this, we cannot only learn a lot about our own nature and help people that struggle with the absence of, loss of, or limits in physical and social interaction.

---

[3] http://www.epsrc.ac.uk/research/ourportfolio/themes/ engineering/activities/principlesofrobotics/

Acknowledgements This work was supported in parts by the European Union Seventh Framework Programme (FP7/ 2007-2013) through the ERC Starting Grant "Con-Humo" under grant agreement No. 337654 and "Hobbit" under grant agreement No. 288146, from the EU Framework Programme Horizon 2020 through "RAMCIP" under grant agreement No.643433, and from the Austrian Science Foundation (FWF) under grant agreement T623-N23, V4HRC.

References

1. Jan De Houwer. What are implicit measures and why are we using them. *The handbook of implicit cognition and addiction*, pages 11–28, 2006.
2. Thalia Wheatley, Olivia Kang, Carolyn Parkinson, and Christine E. Looser. From Mind Perception to Mental Connection: Synchrony as a Mechanism for Social Understanding. *Social and Personality Psychology Compass*, 6(8):589–606, August 2012.
3. Masahiro Mori, Karl F. MacDorman, and Norri Kageki. The uncanny valley [from the field]. *Robotics & Automation Magazine, IEEE*, 19(2):98–100, 2012.
4. Agnieszka Wykowska, Ryad Chellali, Md Mamun Al-Amin, and Hermann J Müller. Does observing artificial robotic systems influence human perceptual processing in the same way as observing humans? In *Social Robotics*, pages 327–337. Springer, 2012.
5. Michael R. Bury. Social aspects of rehabilitation. *International Journal of Rehabilitation Research*, 10(5):25–29, 1987.
6. Kerstin Dautenhahn. I could be you: The phenomenological dimension of social understanding. *Cybernetics & Systems*, 28(5):417–453, 1997.
7. Luc Steels. Evolving grounded communication for robots. *Trends in cognitive sciences*, 7(7):308–312, 2003.
8. Bilge Mutlu, Toshiyuki Shiwa, Takayuki Kanda, Hiroshi Ishiguro, and Norihiro Hagita. Footing in human-robot conversations: how robots might shape participant roles using gaze cues. In *Proceedings of the 4th ACM/IEEE international conference on Human robot interaction*, pages 61–68. ACM, 2009.
9. Michael L. Walters, Kerstin Dautenhahn, René Te Boekhorst, Kheng Lee Koay, Dag Sverre Syrdal, and Chrystopher L Nehaniv. An empirical framework for human-robot proxemics. 2009.
10. Karin Knorr Cetina. Sociality with objects. *Theory, culture & society*, 14(4):1–30, 1997.
11. Byron Reeves and Clifford Nass. *The Media Equation: How People Treat Computers, and New Media Like Real People and Places*. Cambridge University Press, 1996.
12. Johann Issartel, Ludovic Marin, and Marielle Cadopi. Unintended interpersonal co-ordination: "can we march to the beat of our own drum?". *Neuroscience letters*, 411(3):174–9, January 2007.
13. Richard C. Schmidt and Michael J. Richardson. Dynamics of interpersonal coordination. In Armin Fuchs and Viktor K. Jirsa, editors, *Coordination: Neural, Behavioral and Social Dynamics*, Understanding Complex Systems, pages 281–308. Springer Berlin Heidelberg, 2008.
14. Michael J. Richardson, Kerry L. Marsh, Robert W. Isenhower, Justin R. L. Goodman, and Richard C. Schmidt. Rocking together: dynamics of intentional and unintentional interpersonal coordination. *Human movement science*, 26(6):867–91, December 2007.
15. Niek R. van Ulzen, Claudine J. C. Lamoth, Andreas Daffertshofer, Gün R. Semin, Peter J. Beek, Niek R. Van Ulzen, and R Semin. Characteristics of instructed and uninstructed interpersonal coordination while walking side-by-side. *Neuroscience letters*, 432(2):88–93, February 2008.
16. Tamara Lorenz, Alexander Mörtl, Björn Vlaskamp, Anna Schubö, and Sandra Hirche. Synchronization in a goal-directed task: Human movement coordination with each other and robotic partners. In *20th IEEE International Symposium on Robot and Human Interactive Communication*, pages 198–203, Atlanta (GA), July 2011. IEEE.
17. Tamara Lorenz, Björn N. S. Vlaskamp, Anna-Maria Kasparbauer, Alexander Mörtl, and Sandra Hirche. Dyadic movement synchronization while performing incongruent trajectories requires mutual adaptation. *Frontiers in Human Neuroscience*, 8, June 2014.
18. Alexander Mörtl, Tamara Lorenz, Björn N. S. Vlaskamp, Azwirman Gusrialdi, Anna Schubö, and Sandra Hirche. Modeling inter-human movement coordination: synchronization governs joint task dynamics. *Biological cybernetics*, 106(4-5):241–59, July 2012.
19. Alexander Mörtl, Tamara Lorenz, and Sandra Hirche. Rhythm patterns interaction - synchronization behavior for human-robot joint action. *PloS one*, 9(4):e95195, January 2014.
20. Richard B. Ivry and Thomas C. Richardson. Temporal control and coordination: the multiple timer model. *Brain and cognition*, 48(1):117–32, February 2002.
21. Verónica C. Ramenzoni, Tehran J. Davis, Michael A. Riley, Kevin Shockley, and Aimee A. Baker. Joint action in a cooperative precision task: nested processes of intrapersonal and interpersonal coordination. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, 211(3-4):447–57, June 2011.
22. Manuel Varlet, Ludovic Marin, Julien Lagarde, and Benoît G Bardy. Social postural coordination. *Journal of experimental psychology. Human perception and performance*, 37(2):473–83, April 2011.
23. Cordula Vesper, Robrecht P. R. D. van der Wel, Günther Knoblich, and Natalie Sebanz. Making oneself predictable: reduced temporal variability facilitates joint action coordination. *Experimental brain research. Experimentelle Hirnforschung. Expérimentation cérébrale*, 211(3-4):517–30, June 2011.
24. Robin Clark. Social and physical coordination. *Interaction Studies*, 13(1):66–79, January 2012.
25. Marco Iacoboni. Imitation, empathy, and mirror neurons. *Annual review of psychology*, 60:653–70, January 2009.
26. Aude G. Billard. Imitation. In M. A. Arbib, editor, *Handbook of Brain Theory and Neural Networks*, pages 566–569. MIT Press, 2002.
27. Andrew N. Meltzoff. Imitation and other minds: The "Like Me" hypothesis. In S. Hurley and N. Chater, editors, *Perspectives on Imitation: From Neuroscience to Social Science*, volume 2, pages 55–77. MIT Press, Cambridge, MA, 2 edition, 2005.
28. Harold Bekkering, A Wohlschläger, and Merideth Gattis. Imitation of gestures in children is goal-directed. *The Quarterly journal of experimental psychology. A, Human experimental psychology*, 53(1):153–64, February 2000.
29. Robert B. Cialdini. *Influence: Science and practice*. Pearson education Boston, MA, 2009.
30. Natalie Sebanz, Günther Knoblich, and Wolfgang Prinz. Representing others' actions: just like one's own? *Cognition*, 88(3):B11–B21, July 2003.
31. Marcel Brass, Harold Bekkering, and Wolfgang Prinz. Movement observation affects movement execution in a simple response task. *Acta psychologica*, 106(1-2):3–22, January 2001.
32. James M. Kilner, Yves Paulignan, and Sarah-Jayne Blakemore. An Interference Effect of Observed Biological Movement on Action. *Current Biology*, 13(6):522–525, March 2003.
33. James Kilner, Antonia F. De C. Hamilton, and Sarah-Jayne Blakemore. Interference effect of observed human movement on action is due to velocity profile of biological motion. *Social neuroscience*, 2(3-4):158–66, January 2007.
34. James Stanley, Emma Gowen, and R. Chris Miall. Effects of agency on movement interference during observation of a moving dot stimulus. *Journal of experimental psychology. Human perception and performance*, 33(4):915–26, August 2007.

35. Nathan Koenig, Leila Takayama, and Maja Matarić. Communication and knowledge sharing in human-robot interaction and learning from demonstration. *Neural networks : the official journal of the International Neural Network Society*, 23(8-9):1104–12, 2010.
36. Brenna D. Argall, Sonia Chernova, Manuela Veloso, and Brett Browning. A survey of robot learning from demonstration. *Robotics and Autonomous Systems*, 57(5):469–483, May 2009.
37. Natalie Sebanz and Günther Knoblich. Prediction in Joint Action: What, When, and Where. *Topics in Cognitive Science*, 1(2):353–367, April 2009.
38. Elliot C. Brown and Martin Brüne. The role of prediction in social neuroscience. *Frontiers in human neuroscience*, 6(May):147, January 2012.
39. David Premack and Guy Woodruff. Does the chimpanzee have a theory of mind? *Behavioral and Brain Sciences*, 1:515–526, 12 1978.
40. Simon Baron-Cohen, Alan M. Leslie, and Uta Frith. Does the autistic child have a "theory of mind"? *Cognition*, 21(1):37–46, October 1985.
41. Giacomo Rizzolatti. The mirror neuron system and its function in humans. *Anatomy and embryology*, 210(5-6):419–21, December 2005.
42. Catherine L. Reed. What is the body schema? In Andrew N. Meltzoff and Wolfgang Prinz, editors, *The Imitative Mind : Development, Evolution, and Brain Bases*, chapter 13, pages 233–244. Cambridge University Press, 2002.
43. Marco Iacoboni, Istvan Molnar-Szakacs, Vittorio Gallese, Giovanni Buccino, John C. Mazziotta, and Giacomo Rizzolatti. Grasping the intentions of others with one's own mirror neuron system. *PLoS biology*, 3(3):e79, March 2005.
44. Gregory Hickok. Eight problems for the mirror neuron theory of action understanding in monkeys and humans. *Journal of cognitive neuroscience*, 21(7):1229–43, July 2009.
45. Marco Iacoboni, Roger P. Woods, Marcel Brass, Harold Bekkering, John C. Mazziotta, and Giacomo Rizzolatti. Cortical mechanisms of human imitation. *Science (New York, N.Y.)*, 286(1999):2526–2528, 1999.
46. Bradford Z. Mahon and Alfonso Caramazza. A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology Paris*, 102:59–70, 2008.
47. Gün R. Semin. Grounding Communication: Synchronization. In A.W. Kruglansky and E.T. Higgins, editors, *Social psychology: Handbook of basic principles*, pages 630–649. NY: The Guilford Press, New York, 2007.
48. Piercarlo Valdesolo, Jennifer Ouyang, and David DeSteno. The rhythm of joint action: Synchrony promotes cooperative ability. *Journal of Experimental Social Psychology*, 46(4):693–695, July 2010.
49. Tanya L. Chartrand and John A. Bargh. The chameleon effect: the perception-behavior link and social interaction. *Journal of personality and social psychology*, 76(6):893–910, June 1999.
50. Lynden K. Miles, Louise K. Nind, and C. Neil Macrae. The rhythm of rapport: Interpersonal synchrony and social perception. *Journal of Experimental Social Psychology*, 45(3):585–589, May 2009.
51. Piercarlo Valdesolo and David Desteno. Synchrony and the social tuning of compassion. *Emotion (Washington, D.C.)*, 11(2):262–6, April 2011.
52. Michael J. Hove and Jane L. Risen. It's All in the Timing: Interpersonal Synchrony Increases Affiliation. *Social Cognition*, 27(6):949–960, December 2009.
53. Scott S. Wiltermuth and Chip Heath. Synchrony and cooperation. *Psychological science*, 20(1):1–5, January 2009.
54. Nicole C. Krämer, Sabrina Eimler, Astrid von der Pütten, and Sabine Payr. Theory of companions: what can theoretical models contribute to applications and understanding of human-robot interaction? *Applied Artificial Intelligence*, 25(6):474–502, 2011.
55. Clifford Nass, Jonathan Steuer, and Ellen R. Tauber. Computers are social actors. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '94, pages 72–78, New York, NY, USA, 1994. ACM.
56. Ludovic Marin, Johann Issartel, and Thierry Chaminade. Interpersonal motor coordination: From humanâĂŞhuman to humanâĂŞrobot interactions. *Interaction Studies*, 10(3):479–504, December 2009.
57. Jeremy Hogeveen and Sukhvinder S. Obhi. Social interaction enhances motor resonance for observed human actions. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, 32(17):5984–9, April 2012.
58. Valeria Gazzola, Giacomo Rizzolatti, Bruno Wicker, and Christian Keysers. The anthropomorphic brain: the mirror neuron system responds to human and robotic actions. *NeuroImage*, 35(4):1674–84, May 2007.
59. Lindsay M. Oberman, Joseph P. McCleery, Vilayanur S. Ramachandran, and Jaime A. Pineda. EEG evidence for mirror neuron activity during the observation of human and robot actions: Toward an analysis of the human qualities of interactive robots. *Neurocomputing*, 70(13-15):2194–2203, August 2007.
60. Clare Press. Action observation and robotic agents: learning and anthropomorphism. *Neuroscience and biobehavioral reviews*, 35(6):1410–8, May 2011.
61. Erhan Oztop, David W. Franklin, Thierry Chaminade, and Gordon Cheng. Human-Humanoid Interaction: Is a Humanoid Robot perceived as a Human? *International Journal of Humanoid Robotics*, 2(4):537–559, December 2005.
62. Thierry Chaminade. A Social Cognitive Neuroscience Stance on Human-Robot Interactions. In *The International Conference SKILLS 2011*, volume 1, page 4, December 2011.
63. CG Atkeson, JG Hale, Frank Pollick, M. Riley, S. Kotosaka, S. Schaul, T. Shibata, G. Tevatia, A. Ude, S. Vijayakumar, E. Kawato, and M. Kawato. Using humanoid robots to study human behavior. *IEEE Intelligent Systems*, 15(4):46–56, July 2000.
64. Thierry Chaminade, David W. Franklin, Erhan Oztop, and Gordon Cheng. Motor interference between Humans and Humanoid Robots: Effect of Biological and Artificial Motion. *Proceedings. The 4nd International Conference on Development and Learning, 2005.*, pages 96–101, 2005.
65. Thierry Chaminade, Delphine Rosset, David Da Fonseca, Bruno Nazarian, Ewald Lutcher, Gordon Cheng, and Christine Deruelle. How do we think machines think? An fMRI study of alleged competition with an artificial intelligence. *Frontiers in human neuroscience*, 6(May):103, January 2012.
66. Tamara Lorenz, Alexander Mörtl, and Sandra Hirche. Movement synchronization fails during non-adaptive human-robot interaction. In *2013 8th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pages 189–190. IEEE, March 2013.
67. Yusuke Maeda, Atsushi Takahashi, Takayuki Hara, and Tamio Arai. Human-robot cooperative rope turningâĂŤan example of mechanical coordination through rhythm entrainment. *Advanced Robotics*, 17(1):67–78, January 2003.
68. Elizabeth Broadbent, Rebecca Stafford, and Bruce A. MacDonald. Acceptance of healthcare robots for the older population: Review and future directions, October 2009.
69. Arnaud Revel and Pierre Andry. Emergence of structured interactions: from a theoretical model to pragmatic robotics. *Neural networks : the official journal of the International Neural Network Society*, 22(2):116–25, March 2009.
70. Syed K. Hasnain, Philippe Gaussier, and Ghiles Mostafaoui. Synchrony as a tool to establish focus of attention for autonomous

robots. *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2423–2428, October 2012.

71. Caroline Grand, Ghilès Mostafaoui, Syed Khursheed Hasnain, and Philippe Gaussier. Synchrony Detection as a Reinforcement Signal for Learning: Application to Human Robot Interaction. *Procedia - Social and Behavioral Sciences*, 126:82–91, March 2014.
72. Aris Alissandrakis, C.L. Nehaniv, and K. Dautenhahn. Synchrony and perception in robotic imitation across embodiments. *Proceedings 2003 IEEE International Symposium on Computational Intelligence in Robotics and Automation. Computational Intelligence in Robotics and Automation for the New Millennium (Cat. No.03EX694)*, 2:923–930, 2003.
73. H Haken, J. A. S. Kelso, and H Bunz. A theoretical model of phase transitions in human hand movements. *Biological Cybernetics*, 51(5):347–356, February 1985.
74. Cindy L. Bethel and Robin R. Murphy. Review of human studies methods in hri and recommendations. *International Journal of Social Robotics*, 2(4):347–359, 2010.
75. Emilie Delaherche, Mohamed Chetouani, Ammar Mahdhaoui, Catherine Saint-Georges, Sylvie Viaux, and David Cohen. Interpersonal Synchrony: A Survey of Evaluation Methods across Disciplines. *IEEE Transactions on Affective Computing*, 3(3):349–365, July 2012.
76. Michael A Riley and Guy C Van Orden. *Tutorials in contemporary nonlinear methods for the behavioral sciences*. National Science Foundation, 2005.
77. Thomas Kreuz, Florian Mormann, Ralph G. Andrzejak, Alexander Kraskov, Klaus Lehnertz, and Peter Grassberger. Measuring synchronization in coupled model systems: A comparison of different approaches. *Physica D: Nonlinear Phenomena*, 225(1):29–42, January 2007.
78. Richard C. Schmidt and Beth O'Brien. Evaluating the Dynamics of Unintended Interpersonal Coordination. *Ecological Psychology*, 9(3):189–206, September 1997.
79. Armin Fuchs and Viktor K. Jirsa, editors. *Coordination: neural, behavioral and social dynamics*. Springer-Verlag Berlin Heidelberg, 2008.
80. Kevin Shockley, Matthew Butwill, Joseph P. Zbilut, and Charles L. Webber. Cross recurrence quantification of coupled oscillators. *Physics Letters A*, 305(1-2):59–69, November 2002.
81. Michael J. Richardson, Stacy Lopresti-Goodman, Marisa Mancini, Bruce Kay, and Richard C. Schmidt. Comparing the attractor strength of intra- and interpersonal interlimb coordination using cross-recurrence analysis. *Neuroscience letters*, 438(3):340–5, June 2008.
82. Lara Lammer, Andreas Huber, Astrid Weiss, and Markus Vincze. Mutual care: How older adults react when they should help their care robot. In *AISB2014: Proceedings of the 3rd international symposium on New Frontiers in Human-Robot interaction*, 2014.
83. Kerstin Dautenhahn, Sarah Woods, Christina Kaouri, Michael L. Walters, Kheng Lee Koay, and Iain Werry. What is a robot companion-friend, assistant or butler? In *Intelligent Robots and Systems, 2005.(IROS 2005). 2005 IEEE/RSJ International Conference on*, pages 1192–1197. IEEE, 2005.
84. Paolo Dario, Paul F.M.J. Verschure, Tony Prescott, Gordon Cheng, Giulio Sandini, Roberto Cingolani, Rüdiger Dillmann, Dario Floreano, Christophe Leroux, Sheila MacNeil, et al. Robot companions for citizens. *Procedia Computer Science*, 7:47–51, 2011.
85. Adriana Tapus, Mataric Maja, Brian Scassellatti, et al. The grand challenges in socially assistive robotics. *IEEE Robotics and Automation Magazine*, 14(1), 2007.
86. David Feil-Seifer and Maja J. Mataric. Socially assistive robotics. *Robotics & Automation Magazine, IEEE*, 18(1):24–31, 2011.
87. Terrence Fong, Illah Nourbakhsh, and Kerstin Dautenhahn. A survey of socially interactive robots. *Robotics and Autonomous Systems*, 42(3-4):143–166, March 2003.
88. D. Mitchell Wilkes, A. Alford, Robert T. Pack, T. Rogers, R.A. Peters, and Kazuhiko Kawamura. Toward socially intelligent service robots. *Applied Artificial Intelligence*, 12(7-8):729–766, 1998.
89. Takanori Shibata, Teruaki Mitsui, Kazuyoshi Wada, Akihiro Touda, Takayuki Kumasaka, Kazumi Tagami, and Kazuo Tanie. Mental commit robot and its application to therapy of children. In *Advanced Intelligent Mechatronics, 2001. Proceedings. 2001 IEEE/ASME International Conference on*, volume 2, pages 1053–1058. IEEE, 2001.
90. Alexander V. Libin and Elena V. Libin. Person-robot interactions from the robopsychologists' point of view: The robotic psychology and robotherapy approach. In *Proceedings of the IEEE*, volume 92, pages 1789–1803, November 2004.
91. Walter D. Stiehl, Jeff Lieberman, Cynthia Breazeal, Louis Basel, Levi Lalla, and Michael Wolf. Design of a therapeutic robotic companion for relational, affective touch. In *Robot and Human Interactive Communication, 2005. ROMAN 2005. IEEE International Workshop on*, pages 408–415. IEEE, 2005.
92. Birgit Graf, Ulrich Reiser, Martin Haegele, Kathrin Mauz, and Peter Klein. Robotic home assistant care-o-bot® 3-product vision and innovation platform. In *Advanced Robotics and its Social Impacts (ARSO), 2009 IEEE Workshop on*, pages 139–144. IEEE, 2009.
93. Christof Schroeter, Steffen Mueller, Michael Volkhardt, Erik Einhorn, Claire Huijnen, Herjan van den Heuvel, Andreas van Berlo, Andreas Bley, and H-M Gross. Realization and user evaluation of a companion robot for people with mild cognitive impairments. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pages 1153–1159. IEEE, 2013.
94. David Fischinger, Peter Einramhof, Walter Wohlkinger, Konstantinos Papoutsakis, Peter Mayer, Paul Panek, Tobias Koertner, Stefan Hofmann, Antonis Argyros, Markus Vincze, Astrid Weiss, and Christoph Gisinger. Hobbit-the mutual care robot. 2013.
95. Lara Lammer, Andreas Huber, Wolfgang Zagler, and Markus Vincze. Mutual-care: Users will love their imperfect social assistive robots. In *Work-In-Progress Proceedings of the International Conference on Social Robotics*, pages 24–25, 2011.
96. Juan Fasola and Maja Mataric. A Socially Assistive Robot Exercise Coach for the Elderly. *Journal of Human-Robot Interaction*, 2(2):3–32, June 2013.
97. Brian Scassellati, Henny Admoni, and Maja Matarić. Robots for use in autism research. *Annual review of biomedical engineering*, 14:275–94, January 2012.
98. National Autistic Society. What is autism?, 2014.
99. John R. Hughes. A review of recent reports on autism: 1000 studies published in 2007. *Epilepsy & behavior : E&B*, 13(3):425–37, October 2008.
100. Andrew N. Meltzoff and M. Keith Moore. Newborn infants imitate adult facial gestures. *Child development*, 54:702–709, 1983.
101. Geraldine Dawson, Deborah Hill, Art Spencer, Larry Galpert, and Linda Watson. Affective exchanges between young autistic children and their mothers. *Journal of abnormal child psychology*, 18(3):335–45, June 1990.
102. Marco Iacoboni and Mirella Dapretto. The mirror neuron system and the consequences of its dysfunction. *Nature reviews. Neuroscience*, 7(12):942–51, December 2006.
103. Justin H. G. Williams, Andrew Whiten, Thomas Suddendorf, and David I. Perrett. Imitation, mirror neurons and autism, June 2001.
104. Sooyeon Kim. Neuro-cognition and social-cognition: application to exercise rehabilitation. *Journal of exercise rehabilitation*, 9(6):496–9, January 2013.
105. Tiffany Field, Jacqueline Nadel, and Shauna Ezell. Imitation Therapy for Young Children with Autism. In Tim Williams, editor, *Autism Spectrum Disorders - From Genes to Environment*, pages 287–298. InTech, 2006.
106. Andrea Behrends, Sybille Müller, and Isabel Dziobek. Moving in and out of synchrony: A concept for a new intervention fostering

empathy through interactional movement and dance. *The Arts in Psychotherapy*, 39(2):107–116, April 2012.
107. Andrea C. Pierno, Morena Mari, Dean Lusher, and Umberto Castiello. Robotic movement elicits visuomotor priming in children with autism. *Neuropsychologia*, 46(2):448–54, January 2008.
108. Kerstin Dautenhahn and Iain Werry. Towards interactive robots in autism therapy: Background, motivation and challenges. *Pragmatics & Cognition*, 12(1):1–35, 2004.
109. Ravindra S. De Silva, Katsunori Tadano, Mastake Higashi, Azusa Saito, and Stephen G. Lambacher. Therapeutic-assisted robot for children with autism. *2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3561–3567, October 2009.
110. John-John Cabibihan, Hifza Javed, Marcelo Ang, and Sharifah Mariam Aljunied. Why Robots? A Survey on the Roles and Benefits of Social Robots in the Therapy of Children with Autism. *International Journal of Social Robotics*, 5(4):593–618, August 2013.
111. Aude Billard, Ben Robins, Jacqueline Nadel, and Kerstin Dautenhahn. Building robota, a mini-humanoid robot for the rehabilitation of children with autism. *Assistive Technology*, 19(1):37–49, 2007.
112. François Michaud and Serge Caron. Roball, the rolling robot. *Autonomous robots*, 12(2):211–222, 2002.
113. Kerstin Dautenhahn, Chrystopher L. Nehaniv, Michael L. Walters, Ben Robins, Hatice Kose-Bagci, N. Assif Mirza, and Mike Blow. Kaspar–a minimally expressive humanoid robot for human–robot interaction research. *Applied Bionics and Biomechanics*, 6(3-4):369–397, 2009.
114. Hideki Kozima, Marek P. Michalowski, and Cocoro Nakagawa. Keepon. *International Journal of Social Robotics*, 1(1):3–18, 2009.
115. Bram Vanderborght, Ramona Simut, Jelle Saldien, Cristina Pop, Alina S Rusu, Sebastian Pintea, Dirk Lefeber, and Daniel O David. Using the social robot probo as a social story telling agent for children with asd. *Interaction Studies*, 13(3):348–372, 2012.
116. Sofiane Boucenna, Antonio Narzisi, Elodie Tilmont, Filippo Muratori, Giovanni Pioggia, David Cohen, and Mohamed Chetouani. Interactive Technologies for Autistic Children: A Review. *Cognitive Computation*, pages 1–16, May 2014.
117. Serge Thill, Cristina A. Pop, Tony Belpaeme, Tom Ziemke, and Bram Vanderborght. Robot-assisted therapy for autism spectrum disorders with (partially) autonomous control: Challenges and outlook. *Paladyn*, 3(4):209–217, April 2013.
118. Joshua J. Diehl, Lauren M. Schmitt, Michael Villano, and Charles R. Crowell. The Clinical Use of Robots for Individuals with Autism Spectrum Disorders: A Critical Review. *Research in autism spectrum disorders*, 6(1):249–262, January 2012.
119. Stephen Grossberg and Tony Vladusich. How do children learn to follow gaze, share joint attention, imitate their teachers, and use tools during social interactions? *Neural networks : the official journal of the International Neural Network Society*, 23(8-9):940–65, 2010.
120. Jillian Greczek, Edward Kaszubski, Amin Atrash, and Maja Mataric. Graded cueing feedback in robot-mediated imitation practice for children with autism spectrum disorders. In *The 23rd IEEE International Symposium on Robot and Human Interactive Communication*, pages 561–566. IEEE, August 2014.
121. Ami Klin, Warren Jones, Robert Schultz, and Fred Volkmar. The enactive mind, or from actions to cognition: lessons from autism. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences*, 358(1430):345–60, February 2003.
122. Ami Klin, David J. Lin, Phillip Gorrindo, Gordon Ramsay, and Warren Jones. Two-year-olds with autism orient to non-social contingencies rather than biological motion. *Nature*, 459(7244):257–61, May 2009.
123. Jennifer Cook, David Swapp, Xueni Pan, Nadia Bianchi-Berthouze, and Sarah-Jayne Blakemore. Atypical interference effect of action observation in autism spectrum conditions. *Psychological medicine*, 44(4):731–40, March 2014.
124. Audrey Duquette, François Michaud, and Henri Mercier. Exploring the use of a mobile robot as an imitation agent withÂăchildren with low-functioning autism. *Autonomous Robots*, 24(2):147–157, October 2007.
125. 2014 Alzheimer âĂŹ s Disease Facts and Figures. Technical report, Alzheimer's Association, 2014.
126. Susan L. Filan and Robert H. Llewellyn-Jones. Animal-assisted therapy for dementia: a review of the literature. *International psychogeriatrics / IPA*, 18(4):597–611, December 2006.
127. Takanori Shibata. Therapeutic Seal Robot as Biofeedback Medical Device: Qualitative and Quantitative Evaluations of Robot Therapy in Dementia Care. *Proceedings of the IEEE*, 100(8):2527–2538, August 2012.
128. Marcel Heerink and J. Albo-Canals. Exploring Requirements and Alternative Pet Robots for Robot Assisted Therapy with Older Adults with Dementia. In *5th International Conference on Social Robotics, ICSR 2013*, pages 104–115, Bristol, UK, 2013.
129. Michaela Pfadenhauer. On the sociality of social robots. A sociology-of-knowledge perspective. *Science, Technology & Innovation Studies*, 10(1):135–153, 2013.
130. Elaine Mordoch, Angela Osterreicher, Lorna Guse, Kerstin Roger, and Genevieve Thompson. Use of social commitment robots in the care of elderly people with dementia: a literature review. *Maturitas*, 74(1):14–20, January 2013.
131. Patrizia Marti, Leonardo Giusti, and Henrik H. Lund. The role of modular robotics in mediating nonverbal social exchanges. *Robotics, IEEE Transactions on*, 25(3):602–613, 2009.
132. Francisco Martín, Carlos E. Agüero, José M. Cañas, Meritxell Valenti, and Pablo Martínez-Martín. Robotherapy with dementia patients. *International Journal of Advanced Robotic Systems*, 10:1, 2013.
133. Ross Mead and Maja J. Matarić. The power of suggestion: Teaching sequences though assistive robot motions. In *Proceedings of the 4th ACM/IEEE international conference on Human robot interaction - HRI '09*, page 317, New York, New York, USA, 2009. ACM Press.
134. Krister Nyström and Sonja Olin Lauritzen. Expressive bodies: demented persons' communication in a dance therapy context. *Health (London, England : 1997)*, 9(3):297–317, July 2005.
135. Herman Igo Krebs and Neville Hogan. Robotic therapy: the tipping point. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*, 91(11 Suppl 3):S290–7, November 2012.
136. PaweÅĆ Maciejasz, Jörg Eschweiler, Kurt Gerlach-Hahn, Arne Jansen-Troy, and Steffen Leonhardt. A survey on robotic devices for upper limb rehabilitation. *Journal of neuroengineering and rehabilitation*, 11(1):3, January 2014.
137. Jon Eriksson, Maja J. Mataric, and C. Winstein. Hands-off assistive robotics for post-stroke arm rehabilitation. In *Proc. IEEE International Conference on Rehabilitation Robotics (ICORRï£·05)*, pages 21–24, 2005.
138. Kyong Il Kang, Sanford Freedman, Maja J. Mataric, Mark J. Cunningham, and Becky Lopez. A hands-off physical therapy assistance robot for cardiac patients. In *Rehabilitation Robotics, 2005. ICORR 2005. 9th International Conference on*, pages 337–340. IEEE, 2005.
139. Gowrishankar Ganesh, Atsushi Takagi, Rieko Osu, Toshinori Yoshioka, Mitsuo Kawato, and Etienne Burdet. Two is better than one: physical interactions improve motor performance in humans. *Scientific reports*, 4:3824, January 2014.
140. Christian Grefkes and Nick S. Ward. Cortical reorganization after stroke: how much and how functional? *The Neuroscientist: a*

review journal bridging neurobiology, neurology and psychiatry, 20(1):56–70, March 2014.

141. Thomas Elbert, Brigitte Rockstroh, Daniela Bulach, Marcus Meinzer, and Edward Taub. New developments in stroke rehabilitation based on behavioral and neuroscientific principles: constraint-induced therapy. *Der Nervenarzt*, 74(4):334–342, April 2003.
142. Gert Kwakkel, Boudewijn J. Kollen, and Hermano I. Krebs. Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. *Neurorehabilitation and neural repair*, 22(2):111–21, 2009.
143. A.M. Howard. Robots Learn to Play: Robots Emerging Role in Pediatric Therapy. In *FLAIRS Conference*, pages 3–8, St. Pete Beach, Florida, USA, 2013. AAAI.
144. Adriana Tapus, Cristian Tapus, and Maja J. Mataric. Hands-Off Therapist Robot Behavior Adaptation to User Personality for Post-Stroke Rehabilitation Therapy. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pages 1547–1553. IEEE, April 2007.
145. Ross Mead, Eric Wade, Pierre Johnson, Aaron St. Clair, Shuya Chen, and Maja J Mataric. An architecture for rehabilitation task practice in socially assistive human-robot interaction. In *19th International Symposium in Robot and Human Interactive Communication*, pages 404–409. IEEE, September 2010.
146. Eric Wade, Avinash Rao Parnandi, and Maja J. Mataric. Using socially assistive robotics to augment motor task performance in individuals post-stroke. *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 2403–2408, September 2011.
147. Denis Ertelt, Steven Small, Ana Solodkin, Christian Dettmers, Adam McNamara, Ferdinand Binkofski, and Giovanni Buccino. Action observation has a positive impact on rehabilitation of motor deficits after stroke. *NeuroImage*, 36 Suppl 2:T164–73, January 2007.
148. Pablo Celnik, Brian Webster, Davis M. Glasser, and Leonardo G. Cohen. Effects of action observation on physical training after stroke. *Stroke*, 39(6):1814–20, June 2008.
149. Christopher Morris. Definition and classification of cerebral palsy: a historical perspective. *Developmental medicine and child neurology. Supplement*, 109(1964):3–7, March 2007.
150. Susan E. Fasoli, Barbara Ladenheim, Joelle Mast, and Hermano I. Krebs. New horizons for robot-assisted therapy in pediatrics. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*, 91(11 Suppl 3):S280–9, November 2012.
151. Karin Brütsch, Tabea Schuler, Alexander Koenig, Lukas Zimmerli, Susan Mérillat Koeneke, Lars Lünenburger, Robert Riener, Lutz Jäncke, and Andreas Meyer-Heim. Influence of virtual reality soccer game on walking performance in robotic assisted gait training for children. *Journal of neuroengineering and rehabilitation*, 7:15, January 2010.
152. Volodymyr Kozyavkin, Oleh Kachmar, and Iryna Ablikova. Humanoid Social Robots in the Rehabilitation of Children with Cerebral Palsy. In *2nd Patient Rehabilitation Research Techniques Workshop*, pages 1–2, Oldenburg, Germany, 2014.
153. Jeffrey M. Hausdorff. Gait dynamics in Parkinson's disease: common and distinct behavior among stride length, gait variability, and fractal-like scaling. *Chaos (Woodbury, N.Y.)*, 19(2):026113, June 2009.
154. Hirotaka Uchitomi, Yoshihiro Miyake, Satoshi Orimo, Yoshiaki Wada, Kazuki Suzuki, Michael J. Hove, and Tatsunori Nishi. Interpersonal synchrony-based dynamic stabilization in walking rhythm of Parkinson's disease. In *The 2011 IEEE/ICME International Conference on Complex Medical Engineering*, pages 614–620. IEEE, May 2011.
155. Yoshihiro Miyake. Interpersonal Synchronization of Body Motion and the Walk-Mate Walking Support Robot. *IEEE Transactions on Robotics*, 25(3):638–644, June 2009.
156. Hirotaka Uchitomi, Leo Ota, Ken-ichiro Ogawa, Satoshi Orimo, and Yoshihiro Miyake. Interactive rhythmic cue facilitates gait relearning in patients with Parkinson's disease. *PloS one*, 8(9):e72176, January 2013.
157. Yoram Baram and Ariel Miller. Auditory feedback control for improvement of gait in patients with Multiple Sclerosis. *Journal of the neurological sciences*, 254(1-2):90–4, March 2007.
158. Takeshi Muto, Barbara Herzberger, Joachim Hermsdoerfer, Yoshihiro Miyake, and Ernst Poeppel. Interactive cueing with Walk-Mate for hemiparetic stroke rehabilitation. *Journal of neuroengineering and rehabilitation*, 9(1):58, January 2012.
159. Robert Peveler. ABC of psychological medicine: Depression in medical patients. *BMJ*, 325(7356):149–152, July 2002.
160. David C. Steffens, Ingmar Skoog, Maria C. Norton, Andrea D. Hart, JoAnn T. Tschanz, Brenda L. Plassman, Bonita W. Wyse, Kathleen A. Welsh-Bohmer, and John C. S. Breitner. Prevalence of Depression and Its Treatment in an Elderly Population. *Archives of General Psychiatry*, 57(6):601–607, 2000.
161. Jorge Gallego-Perez, Manja Lohse, and Vanessa Evers. Robots to motivate elderly people: Present and future challenges. In *Proceedings - IEEE International Workshop on Robot and Human Interactive Communication*, pages 685–690. Ieee, August 2013.
162. Daniel David, Silviu-Andrei Matu, and Oana Alexandra David. Robot-Based Psychotherapy: Concepts Development, State of the Art, and New Directions. *International Journal of Cognitive Therapy*, 7(2):192–210, June 2014.
163. Kazuyoshi Wada, Takanori Shibata, T. Saito, K. Sakamoto, and K. Tanie. Psychological and Social Effects of One Year Robot Assisted Activity on Elderly People at a Health Service Facility for the Aged. In *Proceedings of the 2005 IEEE International Conference on Robotics and Automation*, number April, pages 2785–2790. IEEE, 2005.
164. Alison L. Neil, Philip Batterham, Helen Christensen, Kylie Bennett, and Kathleen M. Griffiths. Predictors of adherence by adolescents to a cognitive behavior therapy website in school and community-based settings. *Journal of medical Internet research*, 11(1):e6, January 2009.
165. Adrián Bresó, Juan Martínez-Miranda, and Juan M. García-Gómez. Leveraging Adaptive Sessions Based on Therapeutic Empathy Through a Virtual Agent. In *6th International Conference on Agents and Artificial Intelligence (ICAART 2014)*, pages 46–55, Angers, France, 2014.
166. Richard Thwaites and James Bennett-Levy. Conceptualizing Empathy in Cognitive Behaviour Therapy: Making the Implicit Explicit. *Behavioural and Cognitive Psychotherapy*, 35(05):591–612, July 2007.
167. Adriana Tapus, Cristian Tapus, and Maja Mataric. The role of physical embodiment of a therapist robot for individuals with cognitive impairments. In *RO-MAN 2009 - The 18th IEEE International Symposium on Robot and Human Interactive Communication*, pages 103–107. IEEE, September 2009.
168. Jonathan Gratch, Louis-Philippe Morency, Stefan Scherer, Giota Stratou, Jill Boberg, Sebastian Koenig, Todd Adamson, and Albert Rizzo. User-state sensing for virtual health agents and telehealth applications. In *Studies in Health Technology and Informatics, Volume 184: Medicine Meets Virtual Reality 20*, pages 151 – 157. IOS Press Ebooks, 2013.
169. Catherine Plaisant, Allison Druin, Corinna Lathan, Kapil Dakhane, Kris Edwards, Jack Maxwell Vice, and Jaime Montemayor. A storytelling robot for pediatric rehabilitation. In *Proceedings of the fourth international ACM conference on Assistive technologies - Assets '00*, pages 50–55, New York, New York, USA, 2000. ACM Press.
170. Ayse Pinar Saygin, Thierry Chaminade, Hiroshi Ishiguro, Jon Driver, and Chris Frith. The thing that should not be: predictive coding and the uncanny valley in perceiving human and

humanoid robot actions. *Social cognitive and affective neuroscience*, 7(4):413–22, April 2012.

171. Robert Sparrow. The march of the robot dogs. *Ethics and Inf. Technol.*, 4(4):305–318, November 2002.
172. Amanda Sharkey and Noel Sharkey. Granny and the robots: Ethical issues in robot care for the elderly. *Ethics and Inf. Technol.*, 14(1):27–40, March 2012.
173. Olivier Oullier, Gonzalo C de Guzman, Kelly J. Jantzen, Julien Lagarde, and J. A. Scott Kelso. Social coordination dynamics: measuring human bonding. *Social neuroscience*, 3(2):178–92, January 2008.
174. Alessandra Sciutti, Ambra Bisio, Francesco Nori, Giorgio Metta, Luciano Fadiga, Thierry Pozzo, and Giulio Sandini. Measuring Human-Robot Interaction Through Motor Resonance. *International Journal of Social Robotics*, 4(3):223–234, March 2012.

Tamara Lorenz is an Assistant Professor at the University of Cincinnati where she is both affiliated with the Psychology and the Engineering Department. She received her diploma in mechanical engineering from Technische Universität München in 2008 and her PhD from the Graduate School of Systemic Neurosciences at Ludwig-Maximilians University (LMU) in Munich, Germany in 2015. During her PhD she was affiliated with both the General and Experimental Psychology Department at LMU and the Chair of Information-Oriented Control at Technische Universität München. Her research interests are the dynamics of human interaction and their relevance and usability for Human-Robot Interaction (HRI). Therefore she explores movement synchronization, adaptation and behavior during human joint action and during the interaction with robots in order to create models for safe and acceptable HRI.

Astrid Weiss is a postdoctoral research fellow in Human-Robot Interaction at the Vision4Robotics group at the ACIN Institute of Automation and Control at Vienna University of Technology (Austria). Her research focuses on Human-Robot Cooperation in vision-based tasks. It is mainly inspired by the approach of transferring findings from human-human studies to human-robot interaction in order to improve intuitiveness and acceptance. Her general research interests are user- centered design and evaluation studies for Human- Computer Interaction and Human-Robot Interaction with a focus on in-the-wild studies and controlled experiments. She is especially interested in the impact technology has on our everyday life and what makes people accept or reject technology. Before her position in Vienna she was a postdoc researcher at the HCI & Usability Unit, of the ICT&S Center, University of Salzburg, Austria and at the Christian Doppler Laboratory on ”Contextual Interfaces” at University of Salzburg.

Sandra Hirche holds the TUM Liesel Beckmann Distinguished Professorship and heads the Chair of Information-oriented Control in the Department of Electrical and Computer Engineering at Technische Universität München, Germany (since 2013). She received the diploma engineer degree in Aeronautical and Aerospace Engineering in 2002 from the Technical University Berlin, Germany, and the Doctor of Engineering degree in Electrical and Computer Engineering in 2005 from the Technische Universität München, Munich, Germany. From 2005-2007 she has been a PostDoc fellow of the Japanese Society for the Promotion of Science at the Fujita Laboratory at Tokyo Institute of Technology, Japan. Prior to her present appointment she has been an associate professor at Technische Universität München. Her research interests include cooperative control, distributed control, and event-triggered control with applications in human-in-the-loop systems, intelligent human-machine interaction, haptics, networked systems, and robotics. Since 2014 she is Associate Editor for the IEEE Transactions on Control Systems Technology. She has been serving as Associate Editor for the ŞIEEE Transactions on Haptics” (2011-2014), and for ”Nonlinear Analysis: Hybrid Systems” (2010-2014).