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**UNIVERSITY OF
PLYMOUTH**

**Teaching Robots Social Autonomy From In Situ
Human Supervision**

by

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DOCTOR OF PHILOSOPHY

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Abstract

TEACHING ROBOTS SOCIAL AUTONOMY FROM IN-SITU HUMAN SUPERVISION

Emmanuel Senft

To reach the potential promised to robots in interaction with humans, robots need to learn from them. Knowledge of expected robot behaviours does not lie in engineers' hand but in the end-users. As a consequence, to reach new applications and enter daily lives, end-users need to be provided with a way to teach their robot to interact in the way they desire.

The thesis explored by this work is that a robot can learn to interact meaningfully with humans in an efficient and safe way by receiving supervision from a human teacher in control of the robot's behaviour. This work original contribution to knowledge is a new teaching framework applicable to robotics and addressing the thesis: the Supervised Progressively Autonomous Robot Competencies (SPARC) and its evaluation in three studies. SPARC aims at enabling non-technical users to teach a robot in high stakes environments such as Human-Robot Interaction (HRI). SPARC provides the teacher with control over the robot to ensure that every action executed by the robot has been actively or passively approved by the teacher. This framework has been applied to teach a robot to tutor children in an educational game, and the autonomous robot achieved similar results to a supervised one.

Throughout evaluating SPARC, this work contributes to extend our knowledge on how humans teach autonomous agents and the impacts of features of the teacher-robot interface on the teaching process. It is found here that a supervised robot learning from a human could reduce the workload required to express a useful robot behaviour. Furthermore, providing the teacher with the opportunity to control the robot's behaviour improves substantially the teaching process and can lead to an autonomous robot interacting efficiently with humans.

reopening?

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Chapter 1

Introduction

Should I frame it as an HRI problem? - alternative: remove first two sentences and update the end^{ES}

Human-Robot Interaction (HRI) explores the challenges of developing robots to interact in human environments and how human beings react to such robots. While not being present in every home yet, robots are quickly propagating through society, for instance as vacuum cleaners, pets, assistants or even friends (Belpaeme et al., 2012). To interact in human environments robots require a way to make sense of their sensory inputs and act on the social world; in other words, they need to be sociable (Breazeal, 2004). However, interacting socially with humans is a complex task: the social interaction happens on multiple levels and combines elements from multiple fields (Fong et al., 2003) and social norms used by humans are also transferred to robots (Bartneck & Forlizzi, 2004). Providing robots with such a complex action policy is a challenge, and will not be solved by programming by hand a static controller covering all the possible aspects and conditions. To interact meaningfully with humans, robots need to learn, constantly expanding and refining their action policy. We propose using the experts in humans interactions, the humans themselves to teach robots to interact socially. By providing control over the robot's actions to a human teacher, robots could learn efficient policies for social interactions from in-situ human supervision. Interactively learning from humans presents a change of paradigm compared to traditional machine learning, as the human has an opportunity to guide the learning, making it more efficient (Fails & Olsen Jr, 2003; Amershi et al., 2014). Furthermore, by initially framing this work in the context of HRI we added to the interaction a large set of constraints; consequently a method working in such a complex environment would have applications beyond HRI e.g. to Machine Learning (ML) and Artificial Intelligence (AI).

maybe the reopening is abrupt, might be worth going more in depth about what we have been doing^{ES}

1.1 Scope

As shown in Goodrich & Schultz (2007) only a subset of HRI is designed to be inherently social. Using Goodrich and Schultz's definition of HRI, as the study of robots for use by or with humans, an important part of the field does not treat robots as social agents. They are often considered as asocial entities having a task to complete or simply tools to be used by humans. However, as demonstrated by Fincannon et al. (2004), even when used as a teleoperated machines, robots still provoke social reactions and expectations from humans. Fong et al. (2003) make, among others, the distinction between "evocative robots" and "socially interactive robots". Evocative robots rely on human tendency to anthropomorphise to succeed in their task, while for "socially interactive robots" the social side of the interaction is key. However in HRI, the sociality of the interaction might not be intended but simply emerge as a by-product of the interaction. As a consequence, in this work we will refer to "social robots" as robots interacting in humans environments and considered as "social agents" by the humans interacting with them. The intentions of the robot designer or the actual robot's sociality are of minor importance if the humans interacting with the robot project social competencies or expectations on the robot. Regardless on the initial intentions, a robot interacting with humans needs to manage these expectations to ensure the safety and comfort of its human partners. In summary, as soon as a robot interacts with humans, the social side of the interaction needs to be taken into account, the robot needs to be able to interact socially.

Enabling a robot to interact socially with humans is a complex task. The robot needs to make sense a large input space, from low level sensory feedback (e.g. joint angles or camera pixels) to high level concepts (e.g. hand-coded events or learned features). And based on the interpretation of these inputs and rules defining a behaviour, the robot needs to select an action or a plan to achieve an assigned goal. As this task covers most of the areas of robotics (Fong et al., 2003), this section will precise the scope of the research conducted in this thesis.

1.1.1 Frame

The context of the research conducted here is finding a way for robots to interact efficiently with humans. It has been argued by many researchers (Dautenhahn, 2004; Billard et al., 2008) that robots need to adapt to their users and be able to learn from them. Social robots cannot apply a one-size-fits-all policy programmed in advance by

engineers and suited to every possible interaction partners. Robots need the capability to learn an interactive behaviour, improving their skills as they interact in the world and personalising their policy to their users; and enabling such a learning is focus of this thesis.

Throughout this thesis we make the assumption that a human knows how the robot should interact. A person, generally not the engineers initially developing the robot, possesses some expertise which should be transferred to a robot. This expertise is not related to theoretical knowledge in ML, robotics or other scientific fields but defines how the robot should behave. For instance, it could take the form of the steps of a therapy a robot should deliver to the child (known by a therapist) or more simply a senior's preferences and desires concerning a robot companion's behaviour. As a consequence, robot users should be able to teach their robot, to transfer their knowledge to their robot without requiring technical expertise.

Although the ultimate goal of this research is to explore how robots could learn to interact socially and efficiently with humans; by making the assumption that the interactive knowledge should be provided by a human, the resulting question of this thesis is: *How humans could teach robot to interact?*. As such, this research work aims to provide a convenient and efficient way for domain experts to inculcate robots with their interactive knowledge. In other words, this research explores the requirements on an interaction frameworks allowing humans to teach robot to interact socially in human environments and the impacts such a framework would have on the interaction.

1.1.2 Type of Interactions

By focusing the research on using humans to teach robots, we add a second human-robot interaction to the application interaction: the interaction between the robot and the teacher. This results in two intertwined human-robot interactions: the application interaction, between the application target and the robot and the teaching interaction, between the teacher and the robot (cf. Figure 1.1). And the end goal of teaching interaction is to achieve high standards in the application interaction. This results in a general triadic interaction between a human target, a robot and a human teacher.

While having been pursued by considering mostly HRI as an application interaction, the work presented in this thesis is applicable to teaching a robot, or more generally agents, many type of interactions, not only with humans. Indeed, interacting with a human is a

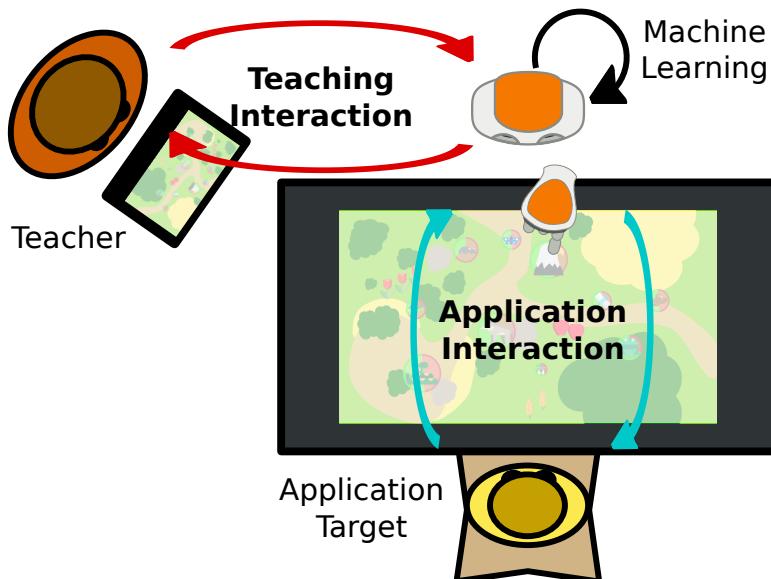


Figure 1.1: The typical interaction used in this research: a robot interacts with a target in an application interaction and learns from a domain expert through a teaching interaction.

high stake scenario, where misbehaving can be costly, where datapoints for learning can be tedious to acquire and with a high diversity between different partners. Other types of interaction could be less constrained, complex or with lower stakes. Consequently, by addressing a challenging task (teaching a robot to interact socially with humans), this approach is also be suited to a wide range of other tasks (such as manipulation, classification or navigation). In the more general case, a user has a task they would like an artificial agent to complete and they can teach it. Through the teaching interaction, the human can supervise the agent, demonstrating it what it should do and teaching it an efficient action policy in the application interaction with the target.

1.2 The Thesis

rephrase^{ES} The main thesis this document seeks to put forward is as below.

A robot can learn to interact meaningfully with humans in an efficient and safe way by receiving supervision from a human teacher in control of the robot's behaviour.

rephrase^{ES} Additional research questions are also introduced here. These research questions are used to support and direct the experimental research conducted in pursuit of demonstrating the primary thesis.

RQ1 *What are the requirements of a robot controller to ensure a behaviour suited to*

HRI?

By interacting with humans, robots enter the social world and have to conform to human expectations while ensuring they can reach their goal. This research question studies which constraints interacting in the human world put on the robot's controller.

RQ2 *What interaction framework would allow a human to teach a robot while validating the requirements from RQ1?*

This research question address what principles of interaction could lead to an efficient teaching interaction between a robot and a human whilst validating the requirements from RQ1.

RQ3 *Could a robot decrease its supervisor's workload by learning from their supervision?*

Controlling a robot is a significant workload for the human supervisor. This question explores if including a learning component in the robot behaviour could alleviate the human workload by taking over some of the mental and physical requirements of the robot control. Additionally, this question explores if this learning impacts the performance in the task.

RQ4 *How providing the teacher with control over the learner's actions impacts the teaching process?*

Teaching robots has a unique property compared to teaching humans in the fact that the teacher could have total control over the learner's actions. This question explores if this control could lead to a faster and a more efficient learning while lightening the process for the teacher.

RQ5 *How teaching a robot to interact socially impacts the two humans involved in the overall triadic interaction?*

When using humans to teach robots, two interactions are linked, this questions studies if this teaching could happen while validating the requirements from RQ1 and the potential impact of this coupling of interactions on the teaching process.

RQ6 *After receiving supervision from a human, could a robot behave autonomously in a social context?*

After having been taught, a robot can be deployed to interact autonomously in the real world. This questions analyses the robot's behaviour when interacting autonomously and explores the efficiency of a teaching in situ in providing the robot an autonomous behaviour validating principles from RQ1.

1.3 Approach and Experimentation

1.3.1 New Teaching Framework

improve^{ES} To address the requirement on a robot controller emerging by addressing RQ1, in this work, we propose the Supervised Progressively Autonomous Robot Competencies (SPARC), a novel teaching framework intended to provide a way for non-experts in robotics to safely teach a robot to interact with humans. This research work describes and justifies this approach and evaluates its impact through three studies.

1.3.2 Study Design

To address the main thesis of this work and RQ3 to RQ6, we designed and ran three studies, each of which is described in depth in a chapter. These studies evaluate the impacts of SPARC on different parts of the teaching and application interactions. The two first studies focused on how humans could teach robots, and consequently required repeatable environments to compare humans' efficiency and experiences when teaching a robot. The last study was run in a school with a single human teaching a robot to interact with children over multiple sessions and explored if SPARC could be used to teach a robot to interact with humans. All the studies used SPARC in the type of interaction presented in Figure 1.1, i.e. a teacher wants a robot to complete a task (included but not limited to human interaction) and can control the robot's actions through an interface.

The first study (Chapter 4) explored if SPARC could be used to provide learning to a robot in a Wizard-of-Oz (WoZ) interaction and if this learning impacts the workload and performance of the teacher in the task. We took inspiration of Robot Assisted Therapy (RAT) and decided to replace the child interacting with the wizarded-robot by a second robot running a model of a child and presenting typical features observed in children (such as probabilistic behaviour, partial observability of state and absence of easily definable optimal action policy). This repeatable environment allowed us to evaluate in a controlled study the impact of SPARC on the teacher.

The second study (Chapter 5) compared SPARC to another method in Interactive Machine Learning (IML): Interactive Reinforcement Learning (IRL) in a replication of the virtual environment initially used to test IRL. The main difference between the two methods resides in the quantity of control provided to the teacher; unlike IRL, SPARC provides teachers with full control over the robot's actions. In this study, participants controlled a virtual robot on a computer and had to teach it how to solve a task.

Finally, the last study (Chapter 6) deployed SPARC in a real interaction with humans, to teach children about food chains. This study used exactly the paradigm described in Figure 1.1: a child interacting with a robot and a teacher using a tablet to control the robot's actions and teaching the robot how to interact efficiently with children.

1.3.3 Learning Algorithms

put NN in gls - fix capital letter^{ES} To enable robots to learn from humans, they need to be equipped with Machine Learning (ML), i.e. an algorithm statistically learning a mapping between inputs and outputs. Two main categories of ML are relevant this research: Supervised Learning (SL) and Reinforcement Learning (RL).

reorganise^{ES} SL aims to learn a mapping between inputs and outputs to automatically reproduce a desired known behaviour. It uses a dataset of labelled examples and optimises an algorithm to minimise the prediction error of labels (Russell & Norvig, 2016). This aim, reproducing a desired behaviour, is especially connected with the work carried out in this research. By learning to reproduce the teacher's policy, the robot should reach an efficient behaviour in the target application. Typical examples of SL used in this study are Artificial Neural Network (ANN) and nearest neighbours methods. ANN model loosely the way brains and neurons work by having a group of interconnected 'neurons'. By changing the connections between the neurons, the network learns to reproduce the desired values on the output nodes according to the inputs. On the other hand, nearest neighbours methods are instance based methods, they compare the distance in a feature space between a point to classify and the different instances stored in a dataset and select the value of a majority of nearest neighbours in that space.

Unlike SL which reproduces a known behaviour, RL aims at providing an agent with the capacity to discover the world it interacts with and learn from this interaction with the world (Sutton & Barto, 1998). The agent has access to a description of the state and

actions it can do, and depending of the action selected, the state will change and the agent will receive a reward. The goal of the agent is to find an optimal policy maximising a notion of cumulated reward. RL is also linked to the work presented in this thesis: by allowing robots to learn to interact in human environments, we would reach our goals of efficient human-robot interactions.

Due to the relevance of both fields to this research (enabling humans to teach robots to interact), algorithms from both categories have been used. The first study presented in Chapter 4 used a feed forward neural network learning to reproduce a teacher policy. The second study in Chapter 5 used RL to combine human guidance and environmental and human rewards to learn an efficient action policy. The last study presented in Chapter 6 used an instance based algorithm adapted from Nearest Neighbours to enable online quick and efficient learning. More details about each algorithms and their related work can be found in the associated chapters.

1.3.4 Data Analysis

Graphs presented throughout this thesis have been generated using the seaborn package for Python and matplotlib Waskom et al. (2017). Often, we used violin plots, a graphical representation featuring the kernel density estimation of the distribution potentially producing the data. Statistical analysis in Chapters 5 and 6 have been made using the Jasp software JASP Team (2018). Jasp offers a Bayesian counterpart to classic statistical test, making them more robust and allowing to observe the presence or absence of effect. As such, instead of a *p-value*, the Bayes factor B is reported and represents how much of the variance on the metric is explained by a parameter (if $B < 1/3$ there is no impact, if $B > 3$ the impact is strong, and if $1/3 < B < 3$ the results are inconclusive; Jeffreys 1998; Dienes 2011).

1.3.5 Terminology

Throughout this thesis, the terms ‘wizard’, ‘supervisor’, ‘user’, ‘expert’ and ‘teacher’ have been used interchangeably to represent the people in control of a robot’s action and teaching that robot an action policy. Similarly, we refers to the robot as ‘robot’, ‘agent’ or ‘learner’ depending of the situation.

1.4 Contributions

This research work contributed both scientifically (by creating and evaluating SPARC) and technically (by developing software to multiple projects) to the state of the art in HRI and especially in teaching robots to interact with humans. This section highlights the original contribution of this thesis and indicates the relevant chapters and published work.

1.4.1 Scientific Contributions

- Design of SPARC, a new interaction framework for teaching agents in a safe way. (Chapter 3; Senft et al. 2015a,b)
- Evaluation of SPARC in three studies. (Chapters 4, 5 and 6)
- Demonstration of the importance of control over the robot's action when teaching a robot to interact. (Chapter 5; Senft et al. 2016b, 2017a)
- Design of a lightweight algorithm to quickly learn from demonstration in complex environments. (Chapter 6; Senft et al. 2017b)
- Application of IML to safely teach robots social autonomy from in situ human supervision. (Chapter 6; Senft et al. 2018)

1.4.2 Technical Contributions

- Partial development of a cognitive architecture and two tools for the DREAM project (European FP7 project: 611391). (Esteban et al., 2017)
- Development of an autonomous robot controller to support cardiac rehabilitation in the Human-Robot Interaction Strategies for Rehabilitation based on Socially Assistive Robotics project (Royal Academy of Engineering: IAPP\1516\137). (Lara et al., 2017; Casas et al., 2018)
- Development of a wizard interface for the Freeplay-Sandbox¹. (Lemaignan et al., 2017)

1.5 Structure

¹<https://github.com/freeplay-sandbox>

Rephrase^{ES} The structure of this thesis is outlined below to provide an overview of the content and context for each chapter. A summary of key experimental findings are included at the start of each relevant chapter for ease of reference.

- This chapter provided an introduction to the general field of this research (robots learning to interact with and from humans), the research questions including the central *thesis*, the scope and the contributions of the work presented in later chapters.
- Chapter 2 provides a description of the different fields of social HRI and draws requirements for controllers of robots interacting with humans. In a second part, it analyses the current robot controllers used in HRI identifying that no current controller fits these requirements. Finally, it introduces IML and proposes to apply it to HRI as a way to validate the previously defined requirements.
- Chapter 3 proposes a new interaction framework, SPARC, as a way to apply IML to HRI while validating the three requirements proposed in Chapter 2. This chapter describes the principles behind SPARC and the expectations and limits this method could have.
- Chapter 4 presents results from a first study evaluating the impact of SPARC on the supervisor's workload and performance compared to WoZ. Results support the hypotheses, validating some of the motivations of SPARC (a learning robot would reduce the workload on a supervisor).
- Chapter 5 presents results from a second study comparing SPARC to IRL, another interaction framework from IML. The main difference between the two approaches lies in the amount of control the teacher has: with SPARC, the teacher can correct any action executed by the robot. Results from a 40 participants study support that this control improves the efficiency of the learning (improving the performance, reducing the time and the number of inputs required to teach as well as decreasing the risks taken during the teaching phase).
- Chapter 6 presents the first study where SPARC has been applied to a real world HRI, child tutoring. Results demonstrate that, while not impacting the learning gain of the session, a supervised robot elicit richer child behaviour compared to a passive robot. Furthermore, by learning using SPARC an autonomous robot

can reach policy similar to the teacher's one and achieve the same impact on the children. These results support SPARC as a teaching method allowing to transfer a social and technical action policy from human to a robot in a safe way and leading to efficient autonomous behaviour.

- Chapter 7 presents a discussion from the main findings from the previous chapters and presents limitations and future directions of research for SPARC.
- Chapter 8 concludes the thesis and presents a summary of the main contributions.

Chapter 2

Background

This chapter describes social Human-Robot Interaction (HRI) and presents related research in agent and robot control. The first section introduces the different fields of application of social HRI and draws from them requirements for controlling a robot interacting with humans (the robot should: only execute appropriate actions and have a high level of adaptivity and autonomy). The second section provides the current state of the art in robot control for HRI and analyses it through the requirements presented in the previous section. And finally, building on the lack of controller satisfying the requirements from Section 1, ^{ES}the third section presents Interactive Machine Learning (IML), an alternative method holding promises to teach agents how to interact and how it could be applied to HRI.

2.1 Social Human-Robot Interaction

2.1.1 Fields of Application

clean^{ES} Reviews of HRI and socially interactive robots have already been presented in Goodrich & Schultz (2007) and Fong et al. (2003). However, these reviews are starting to be dated, and did not have the same focus than this research. As mentioned in the introduction, this work is focused on social robots, robots perceived as social agents in a human centred environment. Depending of the context of interaction, these social robots will have been designed to interact socially with humans, or sometimes, the perception of sociality and agency will simply emerge from the interaction (Fincannon et al., 2004). As such, the following criteria on the interactions were used to select the subfields of HRI relevant to this research:

- Presence of an interaction between a robot and a human: both the human and the robot are influencing each other's behaviour.
- The human partner considers the robot as a social agent, responding socially to

the robot and potentially bonding with it.

We reorganised and edited Goodrich and Schultz's categories, to fit with the criteria presented above, resulting on five subfields involving social interactions between robots and humans:

- Socially Assistive Robotics (SAR)
- Education
- Search and Rescue, and Military
- Hospitality, Home and Entertainment
- Collaborative Robots in Industry

We updated each category with recent research and highlighted the social component of the interaction and its impact on the controller used for the robot.

Socially Assistive Robotics

Socially Assistive Robotics (SAR) is a term coined by Feil-Seifer & Mataric (2005) and refers to a robot providing assistance to human users through social interaction. This field has been defined by Tapus et al. (2007) as one of the grand challenges of robotics.

One of the main applications of SAR is care for the elderly. In the near future, the ageing of population will have large impacts on the world, and societies will have to find solutions to tackle this challenge. The United Nations' Department of Economic and Social Affairs (2017) reports that the “population aged 60 or over is growing faster than all younger age groups”. This unbalance of growth will decrease the support ratio (number of workers per retiree) forcing societies to find ways to provide care to an increasing number of people using a decreasing staff. Robots represent a unique opportunity to compensate for this lacking workforce potentially allowing elderly to stay at home rather than joining elderly care centres (Di Nuovo et al., 2014) or simply to support the nursing home staff (Wada et al., 2004).

The second main application of SAR is Robot Assisted Therapy (RAT). Robots might be used to provide therapies or to follow and support a patient during their rehabilitation to improve their health, their acceptance in society or recover better from an accident. In therapies, robots were first used as physical platforms to help patient in rehabilitation

therapy during the 80s (Harwin et al., 1988). During this period, robots were primally used as mechatronic tools helping humans to accomplish repetitive task. But in the late 90s, robots started to be used for their social capabilities. For example the AuRoRA Project (Dautenhahn, 1999) started in 1998 to explore the use of robot as therapeutic tools for children with Autism Spectrum Disorder (ASD). Since AuRoRA, many other projects, such as the DREAM project¹, have started all around the world to use robots to help patient with ASD (Diehl et al., 2012; Esteban et al., 2017).

RAT is not limited to ASD only, the use of robots is also explored in hospitals, for example to support children with diabetes (Belpaeme et al., 2012), to support elderly with dementia (Wada et al., 2005) and stroke recovering patients (Matarić et al., 2007) or to monitor and provide encouragement in cardiac rehabilitation therapies (Lara et al., 2017).

These examples demonstrate that already today, robots are interacting with sensible populations (the elderly or patients in therapy). This implies that robots' social behaviours need to be constantly correct to ensure that no harm will be caused to these populations. And due to the shortage of workforce, these robots need to be as autonomous as possible.

Education

Social robots are being used in education, supporting teachers to provide learning content to children, transforming the teaching process from passive learning to active learning (Linder et al., 2001). In education, robots can take multiple roles such as peer, tutor or tool (Mubin et al., 2013). It should be noted that Mubin et al. stress that the intentions of the robotic community is not to replace teachers by robots, but provide them with a new form of technological teaching-aid. Nevertheless, Verner et al. (2016) presented positive results from an early stage study using a tall humanoid robot to deliver a science lesson to children. The remaining of the section will describe more in details the roles of tutor and peer robots (the 'tool' role has been excluded due to the lack of social interaction between the robot and the students). still valid?ES

Robotics tutors providing tailored teaching content in 1 to 1 interaction. Individualised feedback has been shown to increase the performance of students (Cohen et al., 1982; Bloom, 1984). However, tutoring requires a larger trained staff and as such is

¹<https://www.dream2020.eu>

more costly than large classes supervised by a single teacher. For this reason, tutoring is seldom used in public education today. Tutoring is however often available through private teacher at additional cost for the parents, potentially increasing social inequalities (Bray, 2009). Robotic tutors could provide this powerful one to one tailored interaction to every student during school time, leading to higher learning gain for the children without dramatically increasing the workload on teachers or the price of education (Kanda et al., 2004; Leyzberg et al., 2012; Kennedy et al., 2016; Gordon et al., 2016). In addition to classroom uses, robots could also support children at home as they have been shown to elicit advantages over web or paper based instructions (Han et al., 2005).

Peer robots learning alongside the children. Unlike other types of agents in education, peer robots have the opportunity to fit a special role seldom present in education today: the role of care-receiver rather than care-giver (Tanaka & Matsuzoe, 2012). Peer learning has demonstrated benefits both for the helper and those helped in Human-Human Interaction (HHI) (Topping, 2005). In HRI, a peer robot does not mentor a child to teach them new concepts, but learns alongside or from them, supporting them during the process and encouraging these children to produce behaviours improving their own learning. For example, in the Co-Writer project (Hood et al., 2015), a child has to teach a robot how to write, and as the child demonstrates correct handwriting to the robot, they improve their own skills at drawing letters. Peer robots are able to leverage the concept of learning by teaching (Frager & Stern, 1970) and peer learning (Topping, 2005) in a way hardly matched by humans. The robot can take the role of a less knowledgeable agent with endless patience and encourage the student to perform repetitive tasks such as handwriting. In a similar position, an adult would not be a believable agent requiring learning and a younger student might not have the compliance and the patience to learn from another child.

To provide efficient tutoring or peer support, robots need to be able to personalise their behaviour to the children they are interacting with in order to maximise the children's learning gain. Additionally, as pointed by Kennedy et al. (2015), a robot too social could decrease the learning for the children compared to a less social robot, consequently the robot's social behaviours have to be carefully managed to ensure its effectiveness.

Search and Rescue, and Military

[have a look to goodrich^{ES}](#) Robots are already deployed in the real world, outside of

labs and used during search and rescue missions (Murphy et al., 2008). For instance, after a natural or artificial catastrophe, robots have been sent to analyse the damaged area and report or rescue the surviving victims of the incident. During these missions, robots have to interact socially with two kinds of human partners: the survivors and the rescue team. In both cases the social component of the interaction is key. The survivor is probably in a shocked state and the searching robot could be the first link they have with the external world after the accident (Murphy et al., 2008). In this case, a social response is expected from the robot and it has to be carefully controlled. On the other side, the rescue team monitoring the robots is under high pressure to act quickly and faces traumatic events too. Even if the robot does not display a social behaviour, rescuers interacting with it might develop some feeling toward the robots they are using during these tense moments (Fincannon et al., 2004).

Similar human behaviours (i.e. emotional bonding with a robot) have also been observed in the army (Singer, 2009). Robots have been deployed as teleoperated drones and ground units alongside soldiers to complete scouting task or cleaning minefields. By interacting with a robot for extensive periods, some soldiers developed feelings toward this robot they used in a daily basis: taking pictures with it and introducing it to their friends. These relationships have gone as far as soldier risking their own life to in order to save the robot used by their squad (Singer, 2009).

These examples in these two fields demonstrate that even in interaction where the robot is not supposed to interact socially with humans, its users might consider it as a social agent. Consequently, the sociability of the robot has to be taken into account when interacting in such stressful environments. Overlooking the importance of social relationships human will form can lead to dramatic consequences (e.g. soldiers taking risks for the robot). As such, during the interaction, the robot's behaviour needs to be constantly appropriate not to create misleading expectations and to ensure that the goal of the interaction will be met.

Hospitality, Home and Entertainment

Robots are also interacting with humans in hotels around the world; for example, the Relay robot (Savioke²) delivers amenities directly to the guests' rooms in more than

²<http://www.savioke.com/>

70 hotels in the US, Europe and Japan³. Whilst the social interaction is still minimal today, these robots interact everyday with humans and have been seen evoking social reactions from them⁴.

Since the late 90s, scientists explored how robots could guide visitors in museums and exhibitions (Thrun et al., 1999; Burgard et al., 1999). These researches continue today to explore how to improve the social interaction between tourists and these guide robots (Bennewitz et al., 2005). Similarly, researchers have designed and tested a robot as a receptionist in a hall at Carnegie Melon University (Gockley et al., 2005). Likewise, long term studies have explored how humans perceive and interact with robots in shops and shopping malls (Kanda et al., 2009) and how robots should behave with clients (Kanda et al., 2008).

Robots have also entered homes and family circles: from vacuum cleaners to companion passing by pet robots. A notable example is Aibo: twenty years ago, Sony created Aibo, a robotic dog to be used as pet in Japanese families and a new version was released in early 2018. An analysis of online discussions of owners published 6 years after Aibo's first introduction gives insights on the relationship that owners created with their robots (Friedman et al., 2003). For example 42% of the community members assigned intentionality to the robot, such as preferences, emotions or even feelings. Similar behaviours have also been observed when the robot is not as a pet, but even just a tool. For instance, Fink et al. (2013) reported that one of their participants was worried that their Roomba (a robotic vacuum cleaner) would feel lonely when they would be away on holiday. More recently, the Pepper robot has been sold as a social robotic companion to families in Japan⁵. However, as of early 2018, no study in English has reported results of the interactions with families or long term use and acceptance.

reread^{ES} Similarly to previous fields, robots' behaviour (social or not social) in hospitality or at home will impact humans in ways hardly predictable in advance. This reinforces the necessity for robot's action policies to remain appropriate in any step of the interaction. Additionally, these robots will face a wide range of users' expectations, and will have to react to different unanticipated behaviours. Robots needs to be able to adapt their

³<https://www.spectrum.ieee.org/view-from-the-valley/robotics/industrial-robots/ces-2018-delivery-robots-are-fulltime-employees-at-a-las-vegas-hotel>

⁴<https://www.fastcodesign.com/3057075/how-savioke-labs-built-a-robot-personality-in-5-days>

⁵<https://www.softbankrobotics.com/emea/en/robots/pepper>

behaviours to these different users. Finally, robots will also interact with the same people over long periods (Leite et al., 2013). And, to sustain engagement over such time scales, these robots' need to change their behaviour over time to overcome possible boredom due to the vanishement of the novelty effect in repeated interactions (Salter et al., 2004).

Collaborative Robots in Industry

In industry, robots used to be locked behind cages to prevent humans to interact with them and getting hurt. However, recently social robots, such as Baxter (Guizzo & Ackerman, 2012), have been designed to collaborate with humans; they share the same workspace and interact physically and socially with factory workers. However, to collaborate efficiently with humans, the bidirectional communication between the robot and the humans needs to be as clear as possible. In other words, to interact efficiently and safely with humans, robots need to make their intentions clear to humans surrounding them (Dragan et al., 2013) and reciprocally, they also need to interpret human social cue to infer their goals and intentions (Scheutz et al., 2007).

Beyond legibility and interpretation, another key challenge in Human-Robot Collaboration (HRC) is task assignment. If a goal has to be achieved by a human-robot team, the repartition of tasks should be carefully managed to optimise the end result in term of task performance, but also to ensure comfort for the human. Explicit and implicit rules and personal preferences describe the expected role and behaviours of each participant and have to be taken into account in HRC. As such, the task repartition system and other planners used in HRC should be aware of these social norms and follow them (Montreuil et al., 2007). For example, recent work done in the 3rd Hand project⁶ explored how a robot should support a human in a collaborative assembly task by adapting its behaviour to this human's personal preferences and how this adaptation improves the team's efficiency (Munzer et al., 2017).

An additional challenge faced by robots with the recent advances in Machine Learning (ML), and especially with the omnipresence of neural networks and deep learning, is Explainable Artificial Intelligence (XAI) (Wachter et al., 2017). As agents learning to interact will make mistakes and behave unexpectedly from time to time, they have to be able to provide explanations for these errors in a way understandable by humans. This challenge is especially visible in HRC where both humans and robots aim to collaborate

⁶<http://3rdhandrobot.eu/>

to complete a task together. Hayes & Shah (2017) propose to achieve transparency through policy explanation, by allowing robots to answer questions and explain their behaviour by self observation and logic deduction. This transparency aims at increasing trust between the agents involved in the interaction and improve the robot's efficiency.

As demonstrated in Munzer et al. (2017), intelligent systems involved in HRC should adapt their behaviour to their interaction partners, be aware of preferences and rules to follow to ensure that the robot's behaviour is always appropriate, efficient and safe for the humans involved in the interaction. Furthermore, their autonomy needs to encompass behaviour explanation, be able to explain the reasoning steps and justify each of their actions.

2.1.2 Requirements on Robots Interacting with Humans

The review in Section 2.1.1 demonstrated that robots are already interacting with vulnerable populations: young children, the elderly, people requiring healthcare or in a stressful situations (victims of catastrophes or soldiers for example). Additionally, people tend to create emotional bonding with these robots even if they are not interacting socially with their users. As such, the behaviour of robots interacting with humans need to be carefully controlled to manage humans' expectations and ensure their safety. In other words, robots need to constantly behave in socially acceptable manners, avoiding any confusing, inappropriate or dangerous behaviour. Failure to do so might prevent the interaction to fit its goal, potentially elicit offence, anger, frustration, distress or boredom or even lead to physical injuries.

These undesired behaviours may come from different origins: lack of sensory capabilities to identify necessary environmental features, lack of knowledge to interpret human behaviours appropriately, failure to convey intentions, impossibility to execute the required action or incorrect action policies. Due to the wide range of origins of these potential social faux-pas, this research focuses only on the last point, obtaining an appropriate action policy: assuming a set of inputs, finding a way to have the robot select an appropriate action. The other issues are either orthogonal and would lead to failure even with an 'optimal' action policy as external factors prevent the robot from solving the problem or could be handled by having a better action policy (e.g. a policy generalising more efficiently or selecting suboptimal actions when the optimal ones are not available).

Appropriate actions are highly dependent on the interaction context: they could aim to match or reduce users' expectations of a robot's behaviour or complete a specific task. Additionally, actions correct in a certain context might be inappropriate in another one. Nonetheless, the intention behind being *appropriate* here is that actions executed should be guaranteed not to present risks for the humans involved in the interaction (for example, preventing physical harm or mental distress), while helping the robot to move toward its goal and achieving its objectives.

Additionally, interactions with humans 'in the wild' (Belpaeme et al., 2012) do not happen in well defined environments or rigid laboratory setups. In the real world, robots have to interact in diverse environments, with a large number of different people, for extended periods of time or with initial incomplete or incorrect knowledge. As such, the action policy also needs to be adaptable to the context and users as well as evolve over time. In summary, robots also need to be adaptive, to react to changing environments, cover a larger field of application and improve their action policy over time.

Lastly, in many cases today, interactive robots are not autonomous but partially controlled by a human operator (Riek, 2012). We argue that to have a real and useful HRI, the robot needs to be as autonomous as possible. Robots are expected to be used in areas where the workforce is already in shortage (e.g. healthcare) and requiring humans to control these robots decreases widely their applicability. As a community, HRI should strive toward more autonomy for robots interacting with humans.

Based on these considerations, we define three properties to evaluate how suited robot controllers are to interact with humans. Each axis is associated to a principle the robot has to follow to sustain meaningful social interactions:

1. Appropriateness of actions - The robot should only execute appropriate actions.
2. Adaptivity - The robot should be adaptivity to its environment and in time.
3. Autonomy - The robot should be as autonomous as possible.

We will use these axes to analyse current robotic controller types in Section 2.2.

As HRI is a large field, other research axes are equally important, such as the complexity or the depth of the interaction, the constraints put on the environment, the ability of the robot to set its own goals, the dependence and knowledge of social rules or the

range of application of a robot to cite only a few. However, we did not address these axes in the current work as they are more influenced by the goal and the context of the specific human-robot interaction taking place than the action policy itself. Additionally, an appropriate, adaptive, and autonomous robot should be able to safely and autonomously learn to interact in deeper and more complex interactions and learn to extend its abilities beyond the ones it initially started with to increase its range of applications.

Appropriateness of Actions

As argued previously, much of social human-robot interaction takes place in stressful or sensitive environments, where humans have particular expectations about a robot's behaviour. Additionally, even in less critical situations, human-human interactions are subject to a large set of social norms and conventions resulting from precise expectations of the interacting partners (Sherif, 1936). And some of these expectations are also transferred to interactions with robots (Bartneck & Forlizzi, 2004).

We define appropriate actions, as actions taking into account the social side of the interaction, and producing a correct robot behaviour at the right time. This behaviours needs to be safe for surrounding humans and help the robot to reach its goal. Failing to produce these appropriate actions, for example by not matching the users' expectations, may have a negative impact on the interaction, potentially compromising future interactions if the human feel disrespected, confused or annoyed. Furthermore, failing to behave appropriately can even harm the people interacting with the robot: not reminding an elderly to take their medication, not taking into account the state of mind of survivors after a disaster or behaving inconsistently with children with ASD might lead to dramatic consequences. Robots require a way to ensure that all the actions they execute do not present risks to the humans involved in the interaction while moving the robot closer to its goal.

not sure if paragraph useful^{ES} However, being able to behave appropriately is a tremendous challenge: real interactions involve a large sensory space, with the people participating often being unpredictable or at least highly stochastic. In addition, social interactions are grounded by a large number of (often implicit) norms, with expectations being highly dependent on the interaction context (Sherif, 1936). As such, it seems unlikely that every possible case of interaction and reactions from the humans interacting with the robot could be anticipated beforehand (Dautenhahn, 2004). But regardless of

the complexity of the interaction, social robots need an action policy able to generate the appropriate reactions for the expected states and human behaviours. This action policy also needs to be able to manage uncertainty, selecting a correct action even when facing a sensory state not explicitly anticipated by the designers.

[check with Charlotte's comments - maladroit^{ES}](#) For the review in Section 2.2, the appropriateness of actions axis is a continuous spectrum characterising how much the system controlling the robot ensures that the robot acts in a safe and useful way for the users at any moment of the interaction. For example, a robot selecting its actions randomly would have a low appropriateness as no mechanism prevents the execution of unexpected or undesired actions. On the other hand, a robot continuously selecting the action a human expert would have selected would have a high appropriateness as domain experts know which action is the correct one in this application domain.

Adaptivity

As stated before, humans are complex, indeterministic and unpredictable agents, as such an optimal robot behaviour is not likely to be known in advance and programmable by hand (Dautenhahn, 2004; Argall et al., 2009). Specifically, end users will express behaviours not anticipated by the designers, the interaction environment is often not perfectly definable and the desired behaviour might also need to be customisable by or for the end user or evolve over time. While many studies in HRI use robots following a static script, to interact meaningfully outside of lab settings or scientific studies, robots need this flexibility to extend their range of application and improve their interactions with users. In other words, robots interacting with people need to be able to adapt their action policy to the environment and improve their behaviour over time. We use the term *adaptivity* to represent this ability to express a behaviour suited to different conditions and refine it over time.

We propose three components for this adaptivity. The basic one is the adaptivity to the environment, i.e. the generalisation of the behaviour (reacting accordingly to unseen inputs). The second one is personalisation and adaptation: being able to adapt a behaviour to the current user or context. Finally, the last component is the adaptivity in time which is in essence learning (the possibility to enrich and refine the action policy over time).

Generalisation: Robots are interacting in human centred environments which are complex and highly stochastic. These environments are often under specified and robot designers cannot explicitly anticipate every single possible human reactions or occurring events. Furthermore, the state representations often use large vectors with multiple possibilities for each values. As such, predefining a specific robot reaction for each state possibility or each possible human behaviour is not feasible. Consequently, robots should have an action policy able to generalise to unseen and unexpected situations and react appropriately to different environments.

Personalisation and adaptation: As robots are interacting with humans, they will encounter different type of environments, contexts of interactions and persons with different roles. For example a robot used as an assistant for elderly people will have to interact in the home of the owner, but also follow them in the street or in a supermarket. In these different interaction contexts, distinct behaviours will be expected from the robot. Similarly, different human beings might have distinct roles and the robot needs to adapt its action policy to the type of person it is interacting with. For instance, in education, an autonomous would have to interact both with the students and the teacher, and its behaviour needs to take into account the role of the people it is interacting with. Additionally, the robot needs to personalise its behaviour to the person it interacts with: in entertainment or search and rescue, none of the users are known beforehand but providing a personalised behaviour adapted to the context may significantly impact the outcomes of the interaction. In summary, robots need to be able to adapt their actions policy to the environment and context they interact in and personalise their behaviour to the different users and their status.

Learning: When deployed in the wild, robots will be expected to interact over extensive periods of time with the same user, e.g. companion robots for the elderly, military robots for a squad or robots used in RAT (Leite et al., 2013). With these long-term social interactions, a key aspect in the engagement and efficiency is the co-adaptation between the user and the robot. Learning allows the robot to tailor its behaviour to the current user and track the changes of preferences and desires occurring over long-term interaction. Additionally, providing a robot with learning enables it to be used by non-experts in robotics, granting them a way to design their own human-robot interactions, and making use of their expertise and knowledge to have the robot interacting as they desire. This

is crucial as many application of social robotics, such as RAT, happen in environment where non-technical people possess the domain expertise required to ensure that the robot is efficient. And, as stated by Amershi et al. (2014), learning reduces the requirements on expensive and time consuming rounds-trips between domain-experts and engineers and additionally decreases the risks of confusion between these different communities. Finally, this adaptivity in time allow the robot to learn from its errors and improve its action policy over time. Furthermore, this learning can enrich the robot's action policy to allow it to tackle new tasks beyond its initial role, increasing its application and use.

In summary, for this review, adaptivity is a continuous scale ranging from no adaptivity at all: the robot has a linear script that it follows in all the interactions, to high adaptivity: the robot can generalise to unforeseen situations, dynamically changes its action policy according to the context of interaction and its partners, learn new actions and tasks and improve its action policy over time.

Autonomy

Today, many experiments in HRI are conducted using a robot tele-operated by a human (Riek, 2012; Baxter et al., 2016), and whilst having a human controlling the robot presents many advantages (e.g. the human provides the knowledge and the adaptivity required to interact efficiently and has sensing and reasoning capabilities not yet available for robots), multiple reasons push us away from this type of interaction (Thill et al., 2012). First, relying solely on tele-operation is not suited for deploying robots in the real world. Human control does not scale to interact for long periods of time or in many places. Robots are also expected to interact in fields already lacking workforce (e.g. healthcare), so if robots need to be continuously controlled, the advantage of automation is highly reduced. Second, for research, using humans to control robots reduces the transferability of knowledge gain to the real world. The human-robot interaction tends to become “a human-human interaction mediated by a ‘mechanical puppet’ ” (Baxter et al., 2016), which decrease the relevance of the robot as an agent and as such how reduces the applicability of results to future interactions with fully autonomous robots. And finally, human control of a robot's actions introduces multiple biases in the robot's behaviour (Howley et al., 2014), and these biases from human operators will affect the robots' behaviour, decreasing the replicability of behaviours. For these reasons, among

many, we argue that a robot used in social HRI should be as autonomous as possible. A limited human supervision could support the robot and be used to improve its behaviour, but the robot should not rely on humans for its action selection during the main parts of the interaction.

To analyse the different robot controller's autonomy, we take inspiration from Beer et al. (2014). Beer et al. define three components of autonomy: sensory perception, analysis and action selection. Autonomy is organised following a spectrum of different levels from no autonomy at all: a human is totally controlling the robot (doing sensory perception, analysis and action selection) to a full autonomy: the robot senses and acts on its environment without relying on human inputs. Levels exist between these extremes where a human and a robot share perception, decision and/or action: for example the robot can request information from a supervisor or the supervisor can override the action or goal being executed (Sheridan & Verplank, 1978).

Interdependence of Factors

These three axes used for the review: appropriateness of action, adaptivity and autonomy are not independent. Especially, as a robot able to learn might be also able to improve its appropriateness of action and its autonomy as it refines its action policy. This impact of adaptivity on the two other axes is fundamental to increase the robot's fields of application, performance and usability. However, while a learning robot could eventually reach an optimal, perfect and autonomous action policy, the behaviour expressed by the robot in early stages of the learning, while the action policy is not appropriate yet, is critical. Even during this learning phase, the robot's behaviour needs to be safe and useful for humans interacting with it. As such, adaptivity is a key element for a robot controller to improve and reach a correct and autonomous policy, but a mechanism must ensure that at every step of the interaction the robot's behaviour is appropriate regardless of the learning progress.

2.2 Current Robot Controllers in HRI

The previous section presented three axes to evaluate a robot controller: the appropriateness of actions, the range of adaptivity and the level of autonomy. Based on these three axes, this section presents and analyses high level categories of robot control currently used in HRI to define a robot behaviour. For each category, we will present the corresponding approach, indicate representative works done and qualitatively rate it

on the three axes.

2.2.1 Scripted Behaviour

One of the simplest ways to have a robot interacting with a human is probably to have explicit fixed behaviours. In this case, the robot is fully autonomous and follows a script for action selection. Success in using this approach is dependent on having a well defined and predictable environment to have the interaction running smoothly. However, if the interaction modalities (possible range of behaviours and goals) are limited enough, a constant action policy can be sufficient to handle all (sensible) human actions.

This approach is followed in a large number of research in HRI: as many studies are human-centred, the focus is not in the complexity of the robot's behaviour but on how different humans would interact with and react to a robot displaying behaviour with defined and controlled specificities. This also allows researchers to compare conditions with controlled differences and analyse the impact of small variations of behaviour. Whilst this has advantages when exploring people's reactions to robots, this method can hardly be used to deploy robots to interact with humans on a daily basis. Real world applications take place in undefined and open environments where potential human behaviours are almost infinite. Additionally, a fixed robot behaviour might also create boredom in users once the novelty effect vanishes (Salter et al., 2004).

By essence, this type of controller has a no adaptivity as the robot is following a preprogrammed script, but is fully autonomous as no external human is required to control the robot; and when the application domain is highly specified, the behaviour can be mostly appropriate.

2.2.2 Adaptive Preprogrammed Behaviour

To go beyond a simple script, robots can also be programmed to react in predefined ways to expected human actions. By adaptive preprogrammed behaviour, we denote a behaviour programmed before the interaction, but explicitly (or implicitly) including ways to adjust the action policy in reaction to anticipated human behaviours. This preprogrammed adaptation takes two forms: either having a fixed number of variables impacted by the actions of the partner and guiding the action policy (for instance using homeostasis), or explicitly planning for specific behaviours to be produced if predefined conditions are met (for example using a finite state machine).

Homeostasis, the tendency to keep multiple elements at equilibrium, is constantly used by living systems to survive and is also a good example of the first case of preprogrammed adaptation used in social HRI. For instance, Breazeal (1998) used a set of drives (social, stimulation, security and fatigue) which are represented by a variable each and have to be kept within a predefined range to represent a ‘healthy’ situation. If these variables reach values outside the desired homeostatic range, the robot is either over or under-stimulated, this will affect the robot’s emotional status and it will display an emotion accordingly. This behaviour have been shown to be enough to maintain human interacting with the robot for relatively long periods of time spanning more than ten minutes. Homeostasis approaches have also been extended to robotic pets (Arkin et al., 2003) or RAT (Cao et al., 2017).

On the other hand, a case of planned adaptation is clearly presented in Leyzberg et al. (2014). Participants have to play a cognitive game, and a robot delivers predefined advises on strategies depending on the performance and the current lack of knowledge of the participant. With these anticipated human behaviours, the robot can provide personalised support as long as the participants behave within expectations.

Similarly to other behaviour-based methods used in robotic control (such as the subsumption architecture; Brooks 1986), due to the indirect description of behaviours, homeostasis-based methods are more robust in unconstrained environments than a purely scripted controller, while remaining totally autonomous. However the action policy is not adaptive in time and similarly, the fixed set of rules limits the adaptability to unexpected event. Furthermore, with this indirect description of actions, there is no guarantee against the robot acting in inconsistent way in specific cases which limits the appropriateness of actions. Similarly, planned adaptation provides adaptivity to the environment but only in highly limited cases expected by the designers. This limits the adaptability of such an approach as the robot does not learn and may face situations not expected by the designers, also reducing the maximum appropriateness of actions.

Both predefined adaptation and homeostasis-based methods score highly in autonomy and can have a moderate to high level of appropriateness, but the adaptivity is low as they can only adapt to the environment within predefined, anticipated and limited boundaries and the robot does not learn.

2.2.3 Wizard of Oz

Wizard-of-Oz (WoZ) is a specific case of tele-operation where the robot is not autonomous but at least partially controlled by an external human operator to create the illusion of autonomy in an interaction with a user. It outsources the difficulty of action selection and/or sensory interpretation to a human operator. This technique has emerged from the Human-Computer Interaction (HCI) field (Kelley, 1983) and is today common practice in HRI (Riek, 2012). Similar to scripted behaviours, Wizard-of-Oz (WoZ) is mostly used in human-centred studies to explore how humans react to robot and not as a realistic way to control robots in the wild. A second use of WoZ is to safely gather data to develop a robot controller from human demonstrations (cf. Section 2.2.4).

Even in WoZ, part of the robot's behaviour is autonomous, and combining this robot autonomy and human control can be done in multiple ways. Baxter et al. (2016) define two levels of WoZ related to the levels of autonomy presented by Beer et al. (2014) and that correspond to the level of human involvement in the action selection process. Cognitive WoZ aims to provide a robot with human-like cognition or deliberative capabilities; while in perceptual WoZ, the human only replaces sensory system and feeds information to the robot controller. Typically, perceptual WoZ replaces challenging features of the controller required for a study, but not relevant to the research question. One of such typical challenge is Natural Language Processing (NLP). Despite all the progress made in speech recognition, NLP is still a challenge in HRI, especially when interacting with children (Kennedy et al., 2017). And as some studies require a limited speech recognition element to test an hypothesis, using a human for that part of the interaction allows to run the study without having to solve complex technical challenges (for instance, see Cakmak et al. 2010).

This level of human control impacts the autonomy of a system: a robot relying on human only to do perception has a higher autonomy than a robot fully controlled by an operator. Similar to the different levels of autonomy presented earlier, systems can also combine human control and predefined autonomous behaviour in mixed systems. For example, Shiomi et al. (2008) propose a semi-autonomous informative robot being mainly autonomous, but with the ability to make explicit request to a human supervisor in predefined cases where the sensory input is not clear enough to make a decision.

With WoZ, the adaptivity and the appropriateness of actions are provided almost exclu-

sively by the human, so these characteristics are dependent of the human expertise but are generally high. However, due to the reliance on human supervision to control the robot, the autonomy is low. For semi-autonomous robots, the picture is more complex: as explained by Beer et al. (2014), the initiative, the human's role and the quantity of information and control shared influence the level of autonomy. For example, in Shiomi et al. (2008) the robot explicitly makes requests to the human, but the human cannot take the initiative to step in the interaction limiting the adaptivity (especially as the robot policy is fixed). And as the human only has limited control over the robot's behaviour, no mechanism prevents the robot to make undesired decision, leading to a higher autonomy, but a lower appropriateness of actions and adaptivity compared to classical WoZ.

2.2.4 Learning from Demonstration

As stated by numerous researchers, explicitly defining a complex behaviour and manually implementing it on a robot can take a prohibitive amount of time or could not be possible at all for complex behaviours (Argall et al., 2009; Billard et al., 2008; Dautenhahn, 2004). This statement applies equally well to manipulation tasks and social interaction. In both cases, humans have some knowledge or expertise that should be transferred to the robot. However in social robotics, experts in the application domain often do not have the technical knowledge to implement efficient behaviours on a robot, which results in numerous design iterations between the users and engineers to reach a consensus.

The field of Learning from Demonstration (LfD) aims to tackle these two challenges: implementing behaviours too complex to be specified in term of code and empowering end-users with limited technical knowledge to transfer an action policy to a robot. The learning process starts with a human demonstrating a correct behaviour (Argall et al., 2009), and then offline batch learning is applied to obtain an action policy for the robot. Later, if required, reinforcement learning can complement the demonstrations to reach a successful action policy (Billard et al., 2008). In LfD, the human-robot interaction is key, however in most of the cases this interaction is only in the learning process and the object of the learning is not social interaction with humans, but manipulation or locomotion tasks such as grasping and moving an object, using a racket to hit a ball or throwing tasks (Billard et al., 2008).

However, two approaches have applied LfD to teach robots a social policy to interact

with humans. The first one aims at learning directly from human-human interactions and analyse the human behaviours to replicate them on a robot. For example, Liu et al. (2014) present a data driven approach taking demonstrations from human-human interactions to gather relevant features defining human social behaviours. Liu et al. recorded motion and speech from about 180 interactions in a simulated shopping scenario and then clustered these behaviours into high-level actions and implemented them on the robot. During the interaction, the robot uses a variable-length Markov model predictor to estimate the probability of a human executing each actions and finally winner-take-all is applied to select the most probable action. According to the authors, the final performance of the robot was not perfect, but if this approach was scaled using a larger dataset gathered from more human-human interactions in the real world, the performance should improve and become closer to natural human behaviours.

In the second approach, the data is collected through a WoZ setup and aims to learn to replicate the wizard's action policy to reach an autonomous social behaviour. Knox et al. (2014) coined this approach "Learning from the Wizard (LfW)". The method starts with a purely WoZ control study to gather data, and then, an action policy is derived by applying machine learning on the collected data. However, this original paper did not present a description of which algorithm could be used or how, and did not evaluate of the approach, instead it only offered a reflection on the application of this idea. An implementation and evaluation is briefly discussed by the authors in Knox et al. (2016), but the lack of implementation details and results reduces the usability of the paper.

LfW is widely used in HCI (especially dialogue management; Rieser & Lemon 2008) and has also been implemented by other groups of researchers in robotics. For example, Sequeira et al. (2016) extended and tested this idea to a create a fully autonomous robot tutor. This method is composed of a series of steps:

1. Collect observations of a human teacher performing the task.
2. Define the different actions used by the teacher and the features used for the action selection.
3. Implement these actions and features on a robotic system.
4. Set up a restricted-perception WoZ experiment where an operator uses only the identified features to select actions for the robot.

5. Combine machine learning applied on the data and hand-coded rules to create an autonomous robot controller.
 6. Deploy the autonomous robot.
- (7. If required, add offline refinement steps to fine tune the robot's behaviour.)

Both Knox et al. (2014) and Sequeira et al. (2016) stress the importance of using similar features for the Wizard of Oz control to the ones available to the robot during the autonomous part. Although this decreases the performance in the first interaction, it allows more accurate learning overall due to the similarity of inputs for the robot and the human controlling it.

Clark-Turner & Begum (2018) aimed to bypass these limitations by using a deep Q-network (Mnih et al., 2015) to learn an Applied Behaviour Analysis policy for RAT. They recorded videos, microphone inputs and actions selected in a WoZ interaction with neurotypical participants to train the network with the raw inputs and the actions selected to obtain a controller able to deliver the therapeutic intervention. However, in their study, the autonomous robot required additional limited human input to inform the algorithm of the state of the therapy and only reached a behavioural intervention with an accuracy inferior to 70%. This means that even with additional human input the robot would provide inconsistent feedback at some points in the interaction. However, this study only used a limited amount of data, and using more training examples should lead to better results.

LfD methods are based on real interactions either between humans, or between humans and robots controlled by humans; and, with enough demonstrations the robot should be able to select appropriate actions. However, efficiency is limited by the type of inputs recorded, the capabilities of the learning algorithm and the quality of the demonstrations which limit the appropriateness of the action policy (as seen in Clark-Turner & Begum 2018). Furthermore, after the learning phase, the robot's behaviour is mostly static, without any additional learning provided. As such, while possessing a good generalisation capability, LfD do not possess the adaptivity in time once the robot is deployed. Sequeira et al. (2016) propose to add offline learning steps, but online learning would allow for smoother transitions and improvements of the behaviours. Finally, all these methods require the presence of humans in a first phase but the robots are fully autonomous later in the interaction, so the autonomy is low in the first phase and then total during

the main part of the interaction.

2.2.5 Planning

An alternative way to interact in complex environments is to use planning (Asada et al., 1986). The robot has access to a set of actions with preconditions and postconditions and a defined goal it needs to reach. To achieve this goal state, it follows the three planning steps: *sense*, *plan* and *act*. The first step, *sense*, consist on acquiring information about the current state of the environment. Then, based on the set of actions available and the goal, a *plan* is created. This plan is a trajectory in the world, a succession of action and states which, according to the defined pre and postconditions, will lead to the goal. Finally, the last step is to *act*, to execute the plan. The plan can be reevaluated at each time step or only if an encountered state differs from the expected one, in that case the robot updates its plan according to the new state of the environment and continues trying.

The efficiency of planning relies on having a precise and accurate set of pre and postconditions for each action. And as humans are complex and unpredictable, it is a serious challenge, if not impossible, to model them precisely. As such, planning have seen limited use for open social interactions with humans. However, due to the nature of planning, reaching a specific goal in a known environment, it has been applied successfully to HRC. Additionally, limiting the interaction to a joint task also simplifies the modelling of the human: the interaction is more constrained and the human behaviour should limit to a number of expected task-related actions. The Human Aware Task Planner (Alili et al., 2009) is an example of planning used to assign task between a robot and human in a HRC scenario. One specificity of this planner is the ability to take into account predefined social rules (such as reducing human idle time) when creating a plan to allocate tasks to the human-robot team. Including these social norms in the plan construction is expected to improve the user experience and maximise human compliance to the plan.

Planning performance depends heavily on the model of the environment the robot has access to. A precise and correct model ensures that the robot will autonomously select the appropriate action whilst an incorrect one would lead to non appropriate behaviours. Similarly, the adaptivity depends on the model the robot has access to and whether it can update it in real time. However, in many cases when interacting with humans, the

model is static, only covering the tasks the robot has to complete the different contexts and states it is expected to face and as such presents limited generalisation capabilities to unanticipated situations or non task-related human actions.

Planning has also been extended with learning, which then allows for more adaptive and personalised action policies. This type of learning planner has been mostly used in manipulation and navigation to obtain better trajectories (Jain et al., 2013; Beetz et al., 2004) but not exclusively. In HRI, Munzer et al. (2017) presented a planner adapting its decisions to human preferences in a HRC scenario. With this approach, the robot estimates the risk of each actions and depending of the risk value will execute them, propose them (and waits for approval before executing an action), or wait for a human decision. Between repetitions of the task, the robot will update its planner to fit more precisely to the human preferences and improve its action policy for the next iteration of the task. Munzer et al. adopted principles from LfD to planning to improve quickly and efficiently the performance of the robot. However, while planning is well suited for strictly defined and mostly deterministic tasks, many social human-robot interactions cannot be totally specified symbolically with clear actions and outcomes and as such the application of planning to social HRI is limited. Nevertheless, it does provide robots with an autonomous, partially adaptive and appropriate action policy.

2.2.6 Summary

Table 2.1 presents a summary of the different approaches currently used in social HRI with their advantages and drawbacks for application in HRI and their evaluation on each of the three axes. The two most promising types of control are LfD and planning, however, both of them have their drawbacks: LfD is applied offline to create a monolithic controller with limited adaptivity after being deployed, and planning's reliance on a model of the world limits its application in open-ended social HRI in the wild.

An ideal controller would learn how to interact by interacting, using demonstrations from an expert to obtain an initial reasonable action policy, but still improving itself after being deployed using reactions from the environment or feedback from a teacher. A supervised learning from interaction would be the approach with the most potential as this type of learning can validate the three requirements: appropriateness of actions, adaptivity and autonomy. By essence, this continuous online learning aims at providing open-ended adaptivity to the robot. Including a human with control over the robot's

Table 2.1: Comparison of robot controllers in HRI

Controller	Advantage	Drawbacks	Application in HRI	Appropriateness	Adaptivity	Autonomy
Fixed preprogrammed behaviour	Quick and easy to create Clear specified and repeatable behaviour	Limited to highly constrained interactions	Human-centred studies in highly constrained env.	Low	Null	Maximal
Adaptive preprogrammed behaviour	Relatively simple to program More robust and efficient than scripted behaviour	Only provide adaptability in limited anticipated context	Human-centred studies in constrained environments	Medium	Low	Maximal
Wizard of Oz	Use human expertise to select the best action	Require constant high workload from human Not scalable	Human-centred studies Highly critical HRI	Maximal	Maximal	Null/Low
Learning from Demonstration	Transfer knowledge from human to robot in the real application environment	Lack of learning once deployed	HRI case by case	High	Medium	High
Planning	Complex behaviours and adaptable to variations in the environment	Human are too complex to have clear set of conditions Limited application to social interaction	Complex defined environments HRC	Medium	High	Maximal

actions can also ensure that actions are appropriate. And finally, as the robot learns, accumulates datapoints and demonstrations from the teacher it improves its action policy, reducing the reliance and workload on the human to reach high levels of autonomy while conserving the constant appropriateness of actions and the adaptivity.

This type of interaction is similar to IML: learning from the interaction and using a human teacher to speed up the learning. As shown in the next section, researchers have explored how to learn interactively non-social action policy from interactions with humans (Scheutz et al., 2017; Cakmak et al., 2010), but as of April 2018, no controller exists in HRI applying IML to the challenge of learning social interaction with humans.

2.3 Interactive Machine Learning

In Section 2.1.2, we stated that to be adaptive enough, a robot should be able to learn. Consequently, robot controllers used in HRI should make use of Machine Learning (ML). ML corresponds to a field of Artificial Intelligence (AI) aiming at providing artificial agents with learning capabilities to improve their behaviour and reach high level performances in a large range of tasks. ML has two main trends referring to the synchronisation between the learning and the use of algorithm: offline and online learning.

In robotics, offline learning is a technique allowing the robot to change its action policy over time by updating it outside of the interaction (such as Learning from the Wizard in Section 2.2.4). Between or before the interactions, a learning algorithm is used on a dataset previously accumulated to create a new action policy.

On the other hand, online learning (such as Reinforcement Learning (RL); Sutton & Barto 1998) learns during the interaction. Rather than single monolithic definitions or updates of the behaviour, this constant refinement of the agent's action policy benefits from a high number of updates, allowing the robot to learn even during the first interaction with the environment and never stop improving its behaviour.

Interactive Machine Learning (IML), as coined by Fails & Olsen Jr (2003), is a type of online learning with two specificities:

- Use of an end-user expert in the learning process.
- Learn by multitude of consecutive small updates of behaviour.

These two characteristics differ greatly from classical offline learning, such as deep

learning (LeCun et al., 2015) which uses costly monolithic learning steps without human influence to define a static behaviour. On the other hand, IML is an iterative process where the behaviour is improved at each small steps, and where the end-user can provide feedback on the learner's performance during all these iterations. IML aims to learn faster, by continuously using the human expert to correct the errors made by the algorithm as they appear, provide additional useful information to the learner and improve the knowledge gained at each learning step.

Amershi et al. (2014) presents an introduction to IML by reviewing the work done and presenting classical approaches and challenges faced when using humans to support machine learning.

2.3.1 Goal

The main goal behind IML is to leverage the human knowledge during the learning process to speed it up, to extend the use of classifiers from static algorithms trained only once to evolving agents learning from humans and refining their policies over time. As explained in Fails & Olsen Jr (2003), classifiers would gain from using human knowledge to iterate quickly to reach a good solution and agents learning from the interaction would gain from using additional feedback from humans (Thomaz & Breazeal, 2008; Knox & Stone, 2009). IML aims to combine the advantages from both Supervised Learning (SL) and online learning and applies this new type of learner to classification or interaction tasks.

Furthermore, by allowing a human user to see the output of an algorithms and provide additional inputs, the learning has the potential to be faster and tailored to this human's desires. By using human expert knowledge and intuition, the system can achieve a better performance faster (Thomaz & Breazeal, 2008). Additionally, a key advantage of IML is also being able to empower end-users of robotic or learning systems. These users are often non-technical, but possess valuable knowledge about what the robot should do. IML provides an opportunity to allow these users to design the behaviour of their robot, to teach it to behave the way they desire.

These human inputs take three forms: labels for specific datapoints (cf. active learning; Section 2.3.2), feedback over actions (similarly to reward in RL; cf. Sections 2.3.3 and 2.3.4) or demonstrations to reproduce (cf. LfD - 2.3.5).

2.3.2 Active Learning

Active learning is a form of teaching used in education aiming to increase students' achievement by giving them a more active role in the learning process (Johnson et al., 1991). This approach has been transferred to machine learning, especially to classifiers, by allowing the learner to ask questions and query labels from an oracle for specific datapoints with high uncertainty (Settles, 2009). The typical application case is when unlabelled data are plentiful, but labels can be limited in numbers or costly to obtain. As such, a trade-off arises between the performance of the classifier and the quantity of queries made by the algorithm. Often, the oracle would be a human annotator with the ability to provide a correct label to any datapoint, but their use should be minimised for reasons of cost, time or annoyance.

Using an oracle to provide the label of specific points with high uncertainty should highlight missing features in the current classifier resulting in improvements both in term of accuracy and learning speed. However, this specific relation between the learner and the human teacher raises new questions such as:

- Which points should be selected for the query?
- How often the human should be queried?
- Who controls the interaction? (i.e. who has the initiative to trigger a query?)

Researchers have explored optimal strategies for dealing with this relation between the learner and the oracle. This research has been especially active in HRI with robots directly asking questions to human participants and exploring how the robot's queries could inform the teacher about the knowledge of the learner (Chao et al., 2010). In a follow up study, Cakmak et al. (2010) showed that most users preferred the robot to be proactive and involved in the learning process. On the other hand, they also wanted to be in control of the interaction, deciding when the robot could ask questions even if it imposed a higher workload on the teacher. However, authors proposed that when teaching a complex task requiring a high workload on the teacher, the robot would probably be expected or should be encouraged to take a more proactive stance requesting samples to take over some workload from the teacher.

Active learning, being able to select a specific sample for labelling, can dramatically improve the performance of the learning algorithm (Settles, 2009). However, when

interacting in the world, the learner is not in control of which sample can be submitted to an oracle to obtain a label. Datapoints are provided by the interaction and are influenced by the learner's actions and the environment reactions. For agents learning during the interaction, the active learning approach working for classifiers is not applicable, so other methods have been applied such as RL, learning from human feedback or LfD.

2.3.3 Reinforcement Learning

The main framework of learning applied to learning from interaction is Reinforcement Learning (RL). RL aims to solve the problem of finding the best action policy (i.e. a policy maximising a certain metric) by observing the environment reaction to the agent's action.

Concept

Young infants and adults learn by interacting with their environment, by producing actions and receiving a direct sensory motor feedback from their environment. By learning the impact of their actions, humans can learn how to achieve their goals. Similarly, the field of RL aims to empower agents by making them learn by interacting, using results from trials and errors and potentially delayed rewards to reach an optimal, or at least efficient, action policy (Sutton & Barto, 1998).

RL agents interact in a discretised version of the time, considering life as a sequence of states and actions. The simplest version of RL is modelled as a finite Markov Decision Process (MDP), a discrete environment defined by the five ensembles $(S, A, P_a(s, s'), R_a(s, s'), \gamma)$ (Howard, 1960), with:

- S : a finite set of states defining the agent and environment states.
- A : a finite set of actions available to the agent.
- $P_a(s, s')$: the probability of transition from state s to s' following action a .
- $R_a(s, s')$: the immediate reward following transition s to s' due to action a .
- γ : a discount factor applied to future rewards.

The goal of the RL agent is to find the optimal policy π_* (assigning an action from A to each state in S) maximising the discounted sum of future rewards. The agent is not aware of all the parameters of the model, but only observes the transitions between

states and the rewards provided by the environment and has to update its policy to maximise this cumulated reward. Different algorithms exist to reach this policy, but the main features present in all of them are the concepts of exploration and exploitation (Sutton & Barto, 1998).

Exploration reflects the idea of trying out new actions to learn more on the environment and potentially gain knowledge to improve the policy; whilst *exploitation* is the execution of the current best policy to maximise the current gain of rewards. All the algorithms have to balance these two features to reach an optimal action policy. One way to deal with this trade-off is to start with high probably of exploration, to rapidly collect knowledge on the environment and then decrease this probably to converge toward an efficient policy, using this knowledge to make better choices of actions.

The more complex the environment is, the longer the agent has to explore before converging to a good action policy. It is not uncommon to reach numbers such as millions of iterations before reaching an appropriate action policy (Sutton & Barto, 1998). And during this exploration phase, the agent's behaviour might seem erratic as the agent tries actions often randomly to observe how the environment is reacting.

Application to HRI

This approach presents many features relevant to HRI: it possesses the autonomy required for meaningful interactions with humans and provides the adaptivity desired for having a large impact. However, as explained in the previous section, traditional RL has two main issues: requirement of exploration to gather knowledge about the environment and large number of iterations before reaching an efficient action policy. Generally, RL copes with these issues by having the agent interacting in a simulated world. This allows the agent to explore safely in an environment where its actions have limited impact on the real world (only time and energy) and where the speed of the interaction can be highly increased to gather the required datapoints in a reasonable amount of time. However, no simulator of human beings exists today which would be accurate enough to learn an action policy applicable in the real world. Learning to interact with humans by interacting with them would have to take place in the physical world, with real humans, and this implies that these issues of time and random behaviours would have direct impact.

To gather informations about the environment, the agent needs to explore, trying out

random actions to learn how the humans respond to them and if the agent should repeat them later. When interacting with humans, executing random actions can have dramatic effect on the users, presenting risk of physical harm as robots are often stiff and strong or cause distress. This reliance on random exploration presents a clear violation of the first principle to interact with humans presented earlier ('Only execute appropriate actions').

Even if random behaviours were acceptable, humans are complex creatures, behaving stochastically, with personal preferences and desires. And as such, learning to interact with them from scratch would require large number of datapoints and as interactions with humans are slow (not many actions are executed per minute) the time required to reach an acceptable policy would be prohibitive.

Despite this real-world constraints, RL has been used in robotics (Kober et al., 2013), but mostly applied to manipulation, locomotion or navigation tasks. For the reasons stated above, as of early 2018, RL has never been used to autonomously learn social behaviours for HRI.

Opportunities

Despite the limitations presented in the previous section, changes can be made to RL to increase its applicability to HRI. Combining RL and IML can ensure that the behaviour is appropriate to interactions with humans even in the learning phase.

García & Fernández (2015) insist on *safe* RL, ways to ensure that even in the early stages of the interaction, when the agent is still learning about the world, its action policy still achieves a minimal acceptable performance. The authors present two ways to achieve this safety: either by using a mechanism to prevent the execution of non-safe actions or by providing the agent with enough initial knowledge to ensure that it is staying in a safe interaction zone. These two methods are not limited to RL but are also applicable to other machine learning techniques to make them safer (for instance LfD; Billard et al. 2008).

The first method (preventing the agent to execute undesired actions) can be implemented by explicitly preventing the agent to execute specific actions in predefined states or by having a list of safe actions (Alshiekh et al., 2017). Using this method, the anticipated cases of errors can be prevented. However it seems unlikely that every case could be specified in advance, so such a method might be not sufficient for applying RL to HRI.

The second method (providing enough initial knowledge) can be achieved by carefully engineering the features used by the algorithm or starting from a initial action policy to build upon. For example, Abbeel & Ng (2004) proposed to use human demonstrations in a fashion similar to LfD but to learn a reward function and an initial working action policy. This method, Inverse Reinforcement Learning, has been applied successfully to teach a flying behaviour to a robotic helicopter. Once the initial policy and a reward function are learned, RL is applied around the provided policy to explore and optimise the policy. That way, only small variations of the policy will happen and only around the demonstrated one. These small variations ensure that policies leading to incorrect behaviours are negatively reinforced and avoided before creating issues (such as crashing in the case of the robotic helicopter).

Whilst being promising and having been applied for agents in human environments (such as for personalised advertisement - Theocharous et al. 2015) these approaches have not been used to learn social behaviours or to have robot interacting with humans.

2.3.4 Human as a Source of Feedback on Actions

When an agent is learning in a RL fashion and improves its behaviour by receiving rewards from the environment, an intuitive way to steer the agent's behaviour in the desired direction faster is to use human rewards. This approach is an adaptation of 'shaping': tuning a animal's behaviour by providing rewards (Bouton, 2007). In ML, using rewards from a human to bias and improve the learning presents multiple advantages which will be presented throughout this section. One notable advantage is the simplicity of the interface and its generalisability to any type of problem. As the teacher only needs a way to provide a scalar or a binary evaluation of an action to steer the learning, only a simple one-way interface is required. However, this simplicity of interaction is associated with a limited efficiency and a complexity of interpretation: the issues of how to interpret human rewards and how to combine them with environmental ones if existent are an active research field today (Knox & Stone, 2010).

When used on their own, human rewards enable an agent to learn an action policy even in the absence of any environmental rewards, which is specially interesting robotics as a clear reward function applicable to HRI or robotics in general can be complex to define. Early work in that field came from Isbell et al. (2006) who designed an agent to interact with a community in the LambdaMOO text based environment. Cobot, the agent, had a

statistical graph of users and their relations and executed actions in the environment. Users of LambdaMOO could either reinforce positively or negatively Cobot's action by providing rewards. While the interaction between the agent and the users was limited, Isbell et al. presented the first agent to learn social interactions with humans in an online complex and social environment.

While the goal of Cobot was to create an entity interacting with humans, Knox & Stone (2009) explored how humans could actively teach an agent an action policy in the absence of environmental rewards using TAMER (Training an Agent Manually via Evaluative Reinforcement). With this approach, the agent uses a supervised learner to model the human reward function and then takes the action that would receive the highest reward from the model.

However, unlike environmental rewards, human rewards are subjective evaluations of an agent's behaviour. As such by knowing humans tendencies and intentions when providing rewards, an agent is able to obtain more information from these human rewards than by treating them the same way as environmental ones. Many researchers explored how to obtain more information from human reward. For instance, Advice (Griffith et al., 2013) models how trustworthy the teacher is and as such how much importance the learner should give to their rewards. For example, rewards from inconsistent teachers will be reduced as the agent knows the source is not reliable. Alternatively, Loftin et al. (2016) explored how to infer the strategy used by the teacher in the reward delivery. Similar behaviours from different teachers might have different meaning: not rewarding an action might reflect an implicit acknowledgement of the correctness of an action or the active refusal to provide a positive reward (indicating the incorrectness of an action). By modelling this intention, the real meaning of rewards can be inferred and used to further improve the learning. Another relevant feature explored by this community is the dependence in time of the human reward policy. While reward functions are generally constant in time with RL, with humans they might vary according to the current performance of the agent. For example, a suboptimal policy could receive positive feedback early on, when it compares positively to the average behaviour; while receiving negative feedback later on, when the average agent's performance is better. MacGlashan et al. (2017) proposed COACH (Convergent Actor-Critic by Humans) to model how humans adapt their rewarding scheme in function of the agent's performance and deal with this non-stationary reward function. Similarly to other factors biasing

human rewarding strategies, this dependence of the reward function to the current agent's policy should be taken into account to maximise the knowledge gained from human rewards.

Even when environmental rewards are present, human rewards still have opportunities to improve the learning: they can enrich a sparse reward function, guide the robot faster to an optimal policy or correct incomplete or incorrect environmental rewards. Knox & Stone (2010) explore nine different ways to combine these two types of rewards and the impacts on the learning of each methods. From this analysis, they explain how to select an approach according to the specificities of the environment and the reward function.

Teachers can also use rewards to communicate other information to the learner. For example, Thomaz & Breazeal (2008) aimed to explore how humans would use feedback to teach a robot how to solve a task in a virtual environment. They used Interactive Reinforcement Learning (IRL) as a way to directly combine environmental rewards and human ones. However, during early studies, Thomaz and Breazeal discovered that participants tried to use rewards to convey intentions, informing the robot which part of the environment it should interact with. The next study involved two communication channels, a reward one to provide feedback on the actions and a guidance channel to provide information about the action the robot should execute. This guidance has been actively decided to be ambiguous; participants could not explicitly control the robot, but just bias the exploration, and adding this second channel improved the performance of participants. This study presented a first attempt to combine environmental rewards, human ones and human guidance to teach an agent an action policy and demonstrated the importance of giving additional ways for the teacher to impact the robot's behaviour.

While not being applied to robotics but mostly to learning non-social interactions, these implementations of IML provide important research describing how robots could be taught to interact with humans. These human rewards are especially interesting when the environmental reward function is sparsely defined or non-existent, providing a way to teach robots in any environments. However, humans do not simply evaluate an agent's actions, they adopt teaching strategies influencing their way of rewarding and want to provide guidance, hints or commands to help the agent to learn better and faster. In summary, human teachers desire to go beyond simply evaluating what the agent is doing, they want to provide advices or commands about how it should behave.

2.3.5 Interactive Learning from Demonstration

As presented in Argall et al. (2009) and Billard et al. (2008), LfD is majoritarily used in an offline learning fashion to learn a defined task without extending the action policy once the task is considered mastered. However, tasks such as social interaction are complex even for humans and probably will never be fully mastered for robots. As such (and as argued before), robots would highly profit from learning throughout all their life, not only once before being deployed, but learning new tasks and improving their skills as often as required (Dautenhahn, 2004).

With Interactive Learning from Demonstration (ILfD), an agent receives demonstrations not only once, but as often as required after being deployed. ILfD is related to Mixed Initiative Control (Adams et al., 2004) where an agent and a human share control on the agent's actions. The robot acts mostly autonomously, but in some cases (at the initiative of the human or the robot), the human takes over the robot control and make a demonstration that will be used by the robot to refine its action policy for the future.

One approach giving teachers a total initiative on the interaction is Dogged Learning (DL) (Grollman & Jenkins, 2007). With DL, an agent is autonomously interacting and a teacher has the power to override the agent behaviour at any time by selecting desired actions or outputs. Facing a potential difference between the algorithm's outputs and the teacher's ones, the robot executes the commands with highest confidence (often the human's one) and the learning component aims at reproducing the executed output. If the teacher does not provide any commands, the ones from the algorithm are used. DL does not provide the robot with the opportunity to request a demonstration, but instead, the robot can communicate its uncertainty to the teacher, indirectly asking for demonstrations.

Alternatively, Chernova & Veloso (2009) propose a method with a more complex interaction between the learner and the teacher. The Confidence Based Algorithm (CBA) is composed of two components: the Confident Execution (CE) and the Corrective Demonstration (CD). The CE enables the agent to act autonomously when its confidence in its action policy is high and on the other hand to actively request a demonstration when the confidence is low. The CD allows the teacher to provide a corrective demonstration when the agent executes an incorrect action, which provide more information to the agent than a classic negative reward. These two components aim to leverage the com-

plementary capabilities of the learner and the teacher. CBA has demonstrated efficient teaching in diverse scenario such as simple driving simulators or other classification tasks. But the effectiveness of this approach is bounded by the capacity of the learner to estimate this confidence to be able to request demonstrations and prevent incorrect behaviour to be executed. Another limit of such an approach is the impossibility for the teacher to correct undesired actions before they negatively impact world.

Both methods rely on the teacher being able to anticipate the robot's behaviour to provide demonstrations before an incorrect action is executed or before it impacts the agent and its environment. As such, the appropriateness of the robot controller is not at maximum as the teacher cannot ensure that no incorrect action will be executed during the learning, only that the robot would learn faster from its errors.

2.3.6 Importance of Control

Results from active learning, research using human to provide feedback and LfD have shown that human teachers take an active stance during the training of an agent and want multiple ways to influence the learner's behaviour (Amershi et al., 2014). Humans are not oracles, enjoying providing labels and evaluating an agent's actions, they desire to be in control of the learning and provide richer information to the agent. Kaochar et al. (2011) have shown than when given choice between different teaching methods, humans will never choose to limit themselves to use only feedback, but they want to teach using more modalities.

In addition to improving the teacher's experience in the teaching process, providing the humans with more control improves the learning (Thomaz & Breazeal, 2008; Chernova & Veloso, 2009). By allowing the teacher to demonstrate an action policy online, bias the action selection and preempt or correct undesired actions, the learner interacts mostly in useful states of the environment and with a correct action policy. This lead to faster learning and would improving the robot's performance highly in early stages of the learning. Another fundamental feature added by this human control over the robot's actions is safety. If a domain expert can prevent a robot interacting with humans to make errors and can ensure that all its actions are efficient, increasing greatly the quality of the interaction for the humans involved. This will further improve the applicability and use of the robot and would satisfy the two first principles: appropriateness of actions and adaptivity of the robot.

However providing the teacher with this control presents challenges for designing the interaction between the robot and its teacher. Unlike a simple scalar reward, being able to control the robot requires the teacher to be able to give commands or advice to the robot and to receive additional information about the learner beyond its observable behaviour. This enriched two-way communication might be complex to design, especially when the action space is bigger than a few actions or the learning mechanism not transparent. In addition to the communication interface, the time scales of the interaction are also key: to give the opportunity to the teacher to preempt undesired actions, the learner needs to communicate its intentions in a timely manner to the teacher which complexifies the relation between the learner and the teacher.

2.4 Summary

This chapter presented first an overview of fields of HRI where robots interact socially with humans. From these cases of application, we defined three principles a robot controller should follow. To interact efficiently with humans, the robot should:

1. Only execute appropriate actions.
2. Have a high level of adaptivity and learn.
3. Have a high level of autonomy.

Secondly, a review of current controllers for robots in HRI reported that no approach applied today in the field validates these principles. The review was extended to more general methods in ML with potential to satisfy these principles. IML shows promises for enabling a robot to learn online how to interact with humans, especially when the teacher is given control over the robot's behaviour and can demonstrate a correct action policy. However while humans have been used to teach robots behaviours or concepts, teaching them to interact with human in an interactive, online fashion has not been demonstrated in the field so far and no current method would satisfy all these requirements.

Chapter 3

Supervised Progressive Autonomous Robot Competencies

Key points:

- Proposition of a novel interaction framework to teach robots an action policy while interacting.
- A human teacher is in control of the robot's actions whilst the robot learns from this supervision.
- The teacher can select actions to be executed by the robot.
- The robot proposes actions about to be executed to the teacher.
- The teacher provides feedback on propositions (i.e. intentions) rather than executed actions; and can pre-empt actions.
- The robot's behaviour (under supervision) can be assumed to be optimal.
- The workload on the teacher decreases over time as the robot learns.

Parts of the work presented in this chapter have been published in Senft et al. (2015b) and Senft et al. (2017a). The final publications are available from Springer and Elsevier:

- http://dx.doi.org/10.1007/978-3-319-25554-5_60.
- <https://doi.org/10.1016/j.patrec.2017.03.015>.

motivation title?^{ES} As presented in Chapter 2, robots would profit from being able to learn from human teachers how to interact with other humans. We propose to use Interactive Machine Learning (IML) to achieve this transfer of social and task knowledge from the human domain-expert to the robot. This would result in a faster and safer learning than slow iterative update of behaviours by engineering the action policy, learning from large quantities of data or learning by trials and errors as with Reinforcement Learning (RL).

However, as stated in this Section 2.3, IML has never been applied to teach robots to interact with humans. No current system provides the teacher with enough control over the robot's actions to validate the first principle presented in Section 2.1.2 ('Only execute appropriate actions'). Techniques relying solely on feedback from the teacher cannot prevent the robot to execute an incorrect action, but only reduce the chances of future errors by rewarding negatively incorrect actions after their execution (Senft et al., 2017a). And, with current techniques based on Learning from Demonstration (LfD) the teacher relinquishes its control over the robot when not demonstrating, only reacting in hindsight after the learner makes mistakes and its erroneous actions have impacted the real world (Chernova & Veloso, 2009).

The problem tackled in this research is to provide a robot with an appropriate action policy, adaptive to different contexts and partners' behaviours and requiring a low workload on the teacher. As such, in Senft et al. (2015b), we introduced the Supervised Progressively Autonomous Robot Competencies (SPARC) framework of interaction. SPARC aims to allow end-users to safely and easily teach a robot an action policy applicable to social Human-Robot Interaction (HRI).

3.1 Frame

Similarly to other applications of IML, SPARC requires inputs from a teacher to learn an action policy to interact with the world. As framed in the introduction, in this framework, the robot interacts with two entities: the target and the teacher (as shown in Figure 3.1). This results into two intertwined interactions: the application interaction (task the robot learns to achieve) and the teaching interaction (relation with the teacher). In the generic case, the overall interaction is a triadic interaction (Teacher - Robot - Human target or Teacher - Robot - Environment); for instance, a teacher could teach a tutor robot to support child learning in an education task (as implemented in Chapter 6). But in specific cases, the application target is not a human but only part of the environment,

such as a robot at home learning from its user how to support them better.

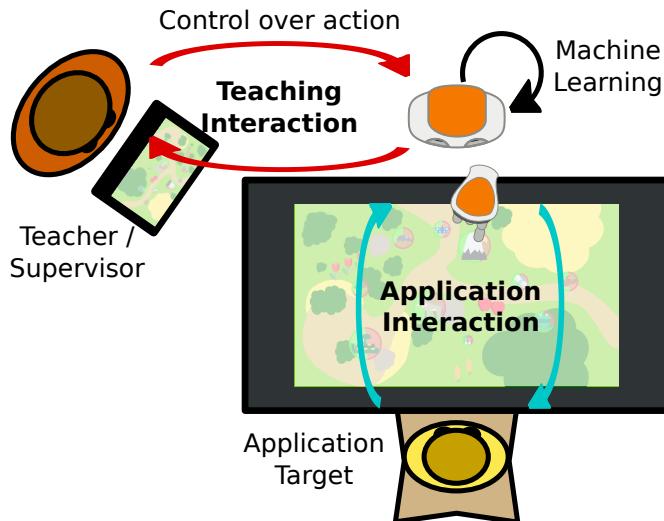


Figure 3.1: Frame of the interaction: a robot interacts with a target, suggests actions and receive commands and feedback from a teacher. Using machine learning, the robot improves its suggestions over time, to reach an appropriate action policy.

3.2 Principles

SPARC defines an interaction between a learner (virtual agent or robot) and a teacher following these principles:

- The learner has access to a representation of the state of the world and a set of actions.
- The teacher can select actions for the robot to execute.
- The learner can propose actions to the teacher before executing them (informing them about its intentions).
- The teacher can enforce or cancel actions proposed by the learner and actions non evaluated are implicitly validated and executed after a short delay.
- The learner uses Machine Learning (ML) to improve its action policy using the teacher's commands and feedback on propositions.

This type of interaction between the learner and the teacher is similar to the level 6 on the Sheridan scale of autonomy: "computer selects action, informs human in plenty of time to stop it" (Sheridan & Verplank, 1978); with the addition that the human has also the opportunity to select actions for the agent to execute. In this thesis, we will refer to this interaction as 'Supervised Autonomy': the robot interacts autonomously under

the supervision of a human who can ensure that the robot's behaviour is constantly appropriate.

This way of keeping a human in the learning loop, with the opportunity to override the agent actions, and the robot learning from these demonstrations is similar to Dogged Learning (Grollman & Jenkins, 2007). However, with SPARC, this ability to provide demonstrations is combined with the Supervised Autonomy. This results in a mixed control system where the teacher can select actions and have the robot execute them while the robot only proposes actions to the teacher. In response to this suggestion, the teacher has the choice between pre-empting the action or let it be executed. A learning algorithm on the robot's side uses the feedback and commands from the teacher to improve the correctness of the suggested actions until reaching an efficient action policy. This learning mechanism coupled with auto-execution of actions aims to decrease the requirement of interventions from the teacher over time, thus reducing the workload on the teacher as the robot learns. Additionally, keeping the human in the loop also gives them the opportunity to provide additional information to the algorithm speeding up the learning and to create a mental model of the learner. The diagram in Figure 3.2 and the flowchart in Figure 3.3 represent in a graphical way this interaction between the learner and the teacher.

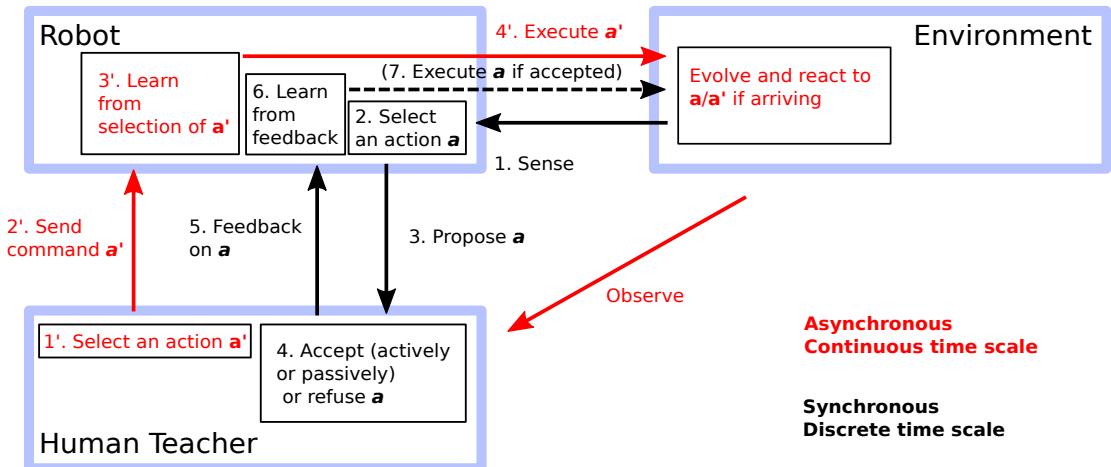


Figure 3.2: Diagram of interaction between the robot, the human teacher and the environment with SPARC: synchronously, the robot can propose actions to the teacher that evaluated (approved or cancelled). And asynchronously, the teacher can select actions to be executed.

Additionally, The main difference between SPARC and CBA (Chernova & Veloso, 2009) is that with SPARC, the robot communicates its intentions and the teacher has total control over the robot's action. With CBA and other classical IML, the teacher have to

wait for an action to impact the world before correcting it or providing negative feedback (Thomaz & Breazeal, 2008; Knox & Stone, 2009). However, using SPARC, the teacher is informed beforehand of the robot future actions and can pre-empt them before they impact the world. The agent learns to avoid actions with expected negative impacts without having to face the results of the execution of these undesired actions. This implies that the behaviour executed by the robot can be assumed to be optimal, making the interaction safer and potentially simplifying the learning mechanism.

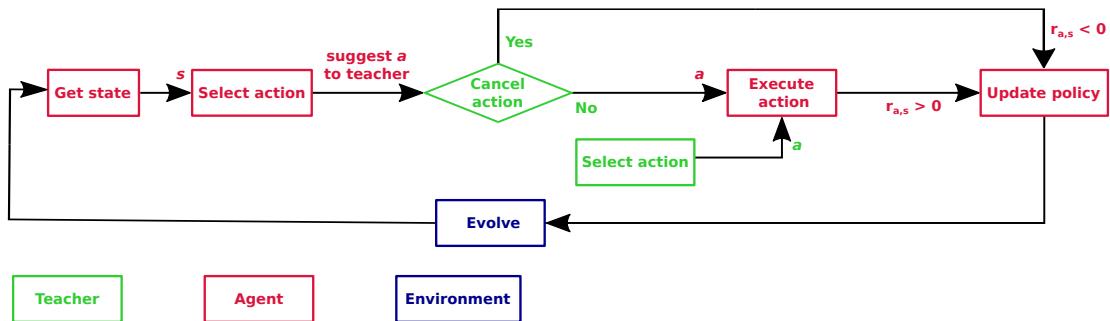


Figure 3.3: Flowchart of the action selection loop between the agent and the teacher.

This approach is comparable to predictive texting as seen on phone nowadays. The user can select the words proposed by the algorithms (or implicitly accept them by pressing the space bar) or write their own. The algorithm learns the user's preferences and habits and aims to suggest words more and more appropriate for the user. However, predictive texting aims mostly to correct users' errors and interact in a complex static environment. On the other hand, SPARC aims to replicate a teacher's action policy in continuous time, in a dynamic and interactive environment evolving both dependently and independently of the agent's actions.

Alternatively, SPARC can be seen as a way to provide proactivity to an agent. By observing interactions on longer time scales, such as an assistant robot at home, SPARC allows the robot to propose to help its user when the current state is similar to previous observation. This would compare to a passive case where each action executed by the robot has to be requested by the user or an autonomous robot interacting in the house without any transparency. By proposing actions to the teacher, the robot takes the initiative to support humans, while not imposing its presence. In human environments, executing actions (such as starting to play music, changing the lighting condition or cleaning the kitchen) without informing the surrounding humans could be perceived as rude or annoying if the timing is not right. On the other hand, this proactivity also needs to be kept in control as a robot proposing to help too often might be equally annoying.

3.3 Goal

SPARC aims to provide an interaction framework to teach robots an action policy possessing the following characteristics:

- Be usable by people without expertise in computer science.
- Allow fast policy learning from in-situ guidance.
- Require few or no human input for the robot to act in the world.
- Ensure a constantly appropriate robot behaviour.

Figure 3.4 presents an idealistic comparison of the expected workload, performance and autonomy of four methods: autonomous learning (e.g. RL; Sutton & Barto 1998), feedback based teaching (e.g. TAMER; Knox & Stone 2009), Wizard-of-Oz (WoZ) (Riek, 2012) and SPARC. Unlike other learning methods, by following the principles presented in Section 3.2, SPARC is expected to maintain a constant high performance even during early stages of learning. In later stages of the learning, the agent keeps improving its action policy, making its suggestions more accurate and allowing the auto-execution of actions to reduce the workload on the teacher.

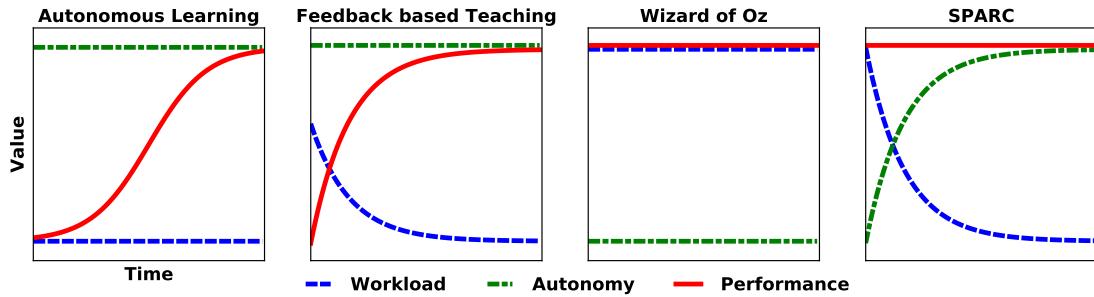


Figure 3.4: Idealistic evolution of workload, performance, and autonomy over time for autonomous learning, feedback-based teaching, WoZ and SPARC (arbitrary units).

tenses^{ES} Once the behaviour is deemed appropriate enough by the teacher, the agent is ready to be deployed to interact autonomously in the real world, if this outcome is desired. Alternatively, in contexts where a human expert still cannot be removed from the control loop, such as Robot Assisted Therapy (RAT), a supervisor could stay in control of the robot's actions by using the Supervised Autonomy. Similarly to the teaching phase, with this Supervised Autonomy, the robot would inform the supervisor of its actions and the human would only have to intervene in case of incorrect propositions. While still

requiring attention from the supervisor, this reduction of human actions to control the robots would reduce the workload on the supervisor. Furthermore, as the supervisor accumulates a better knowledge of the agent's behaviour, they can be especially careful in cases where the agent is prone to making errors. And as the control of the agent requires less effort from the supervisor, they can focus more closely on the application interaction rather than the teaching one.

3.4 Implications

3.4.1 Relation with Time

Similarly to other IML approaches, the requirement of a human in the action selection loop limits the time scale of interaction and this effect is an important consideration when applying SPARC to an interaction. With this type of IML, three time scales are coexisting: the robot's, the teacher's and the interaction's. The robot has an internal clock running probably multiple times per second, sensing the world and deciding if an action should be proposed. The human teacher has to be able to cancel proposed actions before their executions, so they need to be provided with a 'correction window' spanning more than one second to react to propositions. And finally, for some applications, actions are appropriate only during a short time, and if this amount of time (the validity window) is shorter than the correction window, action executed automatically would not be appropriate anymore, reducing the validity of SPARC.

As mentioned previously, depending of the application, actions might have to be executed in a time critical environment (such as driving) or less critical ones (such as an assistant robot at home). While being easily applicable to slow interactions, SPARC could still be applied to these time critical ones. For instance, if applied to autonomous driving, SPARC could display to the driver the planned trajectory with augmented reality and let the driver correct this trajectory if not appropriate. However, more critical elements, such as emergency breaking, would probably have to be done with a much shorter correction window so the car can break in time.

Additionally, the presence of this correction window reduces the rate of actions selection to 0.5 Hz or below, which might reduce the application of SPARC compared to other IML methods. However, this limitation of application is the price to pay to ensure the appropriateness of actions, and this effect can be mitigated by using higher level actions or by focusing on applications less critical in term of time.

Finally, the rate of selection of high level actions will be much lower than the rate of the robot’s action selection loop. At a human level, actions will be executed at a rate of few actions per minutes, while the robot’s processing runs at multiple hertz. This indicates that unlike classical RL methods, in most of the steps, the robot should not select any action. When interacting with humans, the learning algorithm and the state representation needs to take into account these differences of time scales to ensure that the robot’s behaviour is coherent and useful.

3.4.2 Difference with LfD

SPARC is an Interactive Learning from Demonstration (ILfD) method (cf Section 2.3.5) and as it uses human demonstrations of policies to learn, it presents many similarities with non-interactive LfD techniques (cf. Section 2.2.4). However, most of the applications of LfD (Argall et al., 2009; Billard et al., 2008) are focused on learning a manipulation skill in a mostly deterministic environment. LfD has seldom been used to teach an action policy to interact with humans (Liu et al., 2014; Sequeira et al., 2016; Munzer et al., 2017) and never in an online fashion. Munzer et al. proposed an interactive planner that would learn offline the current user’s preferences and desires, but two key differences exist between this approach and SPARC. The first one is the application domain. The learning planner is well suited to clearly defined environments (e.g. Human-Robot Collaboration (HRC)) where a similar task with clear steps has to be done multiple times. As such the learning can happen offline between the repetitions. SPARC is defined to be applicable to non-linear underspecified environments, with less constrained tasks, where the learning should happen online. Secondly, using a threshold, Munzer et al. define actions with low risk which are executed (and can be cancelled during the execution) and actions with higher risk which have to be validated first by the human. SPARC does not make this distinction, but proposes both types of actions to the teacher and will start executing them if no feedback is received. This removes the need for the human to explicitly approve correct proposed actions while ensuring that the human can cancel incorrect actions before their execution. This principle aims at reducing the number of required interventions from the human to teach and interact with the robot compared to methods such as the one presented by Munzer et al.

3.4.3 Interaction with Learning Algorithms

The principles of SPARC define it at the crossroads between Supervised Learning (SL) and RL. SPARC can be used in two ways: either to reproduce a teacher's policy in a supervised fashion or to help an agent discovering a useful action policy by using the teacher to bias the exploration, limiting the errors and only interacting in desired parts of the environment.

As such, SPARC only defines an interaction framework between a teacher and a learner and is agnostic to the learning mechanism: it can be combined with any algorithms used in SL or RL. This research presented in this thesis explored combinations with three types of algorithms: supervised learning using a feed-forward neural network (Chapter 4), reinforcement learning (Chapter 5), and supervised learning using an instance based algorithm (Chapter 6). However SPARC could be combined with a wide range of other algorithms or techniques such as planning.

Similarly to Inverse Reinforcement Learning (Abbeel & Ng, 2004) or other techniques combining RL and LfD (Billard et al., 2008), if used with a reward function, SPARC could go beyond the demonstrated action policy and achieve a performance higher than the demonstration. However this aspect has not been evaluated in this work.

3.5 Summary

This chapter introduced the Supervised Progressively Autonomous Robot Competencies (SPARC), a novel interaction framework to teach agents an action policy. This approach is suited to teach a robot to interact with humans as it validates the principles defined in Section 2.1.2 (appropriateness of action, adaptivity and autonomy). SPARC starts in a similar fashion to WoZ: the teacher selects actions at any time to be executed by the robot. Then, using a learning algorithm, the agent starts to propose actions to the teacher who can let them be executed after a short time or cancel them if not appropriate. This mechanism combining selections, suggestions and evaluations of actions ensures the appropriateness of actions as a human expert could have preempted any inappropriate action before their execution. This additionally provides the adaptivity as the teacher can extend the behaviour beyond the current action policy. Finally, the learning algorithm associated with the auto-executions of actions ensures that once the robot starts to learn, the human workload decreases; and, when an acceptable

3.5. SUMMARY

action policy is reached, the robot is ready to be deployed to interact autonomously if this outcome is desired.

Chapter 4

Study 1:

Comparison Between SPARC and WoZ

Key points:

- Design of an experiment to explore the influence of SPARC on the teacher's workload and task performance compared to an approach based on WoZ.
- Application target replaced by a robot to ensure repeatability of the target behaviour.
- Design of a robot model exhibiting probabilistic behaviour (simulating a child) with a non-trivial optimal interaction policy.
- Results from a within subject study involving 10 participants show that SPARC achieves a similar performance than WoZ while requiring a lower workload from the teacher.

Parts of the work presented in this chapter have been published in Senft et al. (2015b)¹.

The final publication is available from Springer via:

- http://dx.doi.org/10.1007/978-3-319-25554-5_60.

¹Note about technical contribution in this chapter: the author used software from the DREAM project for the touchscreen and the robot functionalities. The author contributed to the material used within the robot control and the Graphical User Interface. Algorithm used from the OPENCV neural network library.

4.1 Motivation

The Supervised Progressively Autonomous Robot Competencies (SPARC) has been designed to enable end-users without expertise in computer science to teach a robot an action policy while interacting in a sensitive environment, such as Human-Robot Interaction (HRI). By using machine learning and Supervised Autonomy, SPARC intends to allow a field expert to progressively transfer their knowledge to an autonomous agent without having to enforce each action manually. Additionally, as the agent is interacting in the target environment, displaying an appropriate action policy, the time spent to teach it is not lost but used to deliver the desired interaction even during the learning phase. For example, in the context of Robot Assisted Therapy (RAT), a therapist would teach the robot during a therapy session. And, as the therapist is in total control of the robot's action, the behaviour expressed by the robot always fits the desired goals for the therapy. This ensures that even the sessions used to teach the robot have a therapeutic value for the patient involved in the therapy.

SPARC, as a principle, allows to start a robotic application in a Wizard-of-Oz (WoZ) fashion and then move away from it as the robot gains autonomy. The aim of SPARC is twofold: maintaining a high level of performance in the target application while reducing the workload of the teacher over time. As the robot learns, the action policy is refined until reaching a point where the robot is autonomous or only necessitates minimal supervision to interact successfully.

As explained in Chapter 3, SPARC involves two interactions: the teaching interaction and the application one. As such, when the goal of the teaching is interacting with humans, the robot interacts simultaneously with at least two humans (the target(s) and the teacher). These two dependent interactions add complexity to the evaluation of the approach, especially as both humans are impacting each other.

The first step to evaluate SPARC was to focus on the teaching interaction, the relation between the robot and its teacher. To evaluate this aspect of the interaction, we decided to use the context of RAT for children with Autism Spectrum Disorder (ASD). However, as the presence of two humans decrease the repeatability of the test bench, we replaced the child involved in the therapy by a robot running a model of a child. The setup ends up with two robots interacting together: the *child-robot* completing a therapeutical task and the *wizarded-robot*, controlled by a participant, supporting the child-robot in its task

completion. Actions from the wizarded-robot impact the child-robot's behaviour and to achieve a high performance in the task, the child-robot needs to receive an efficient supporting policy from the wizarded-robot. As such, the child-robot's performance is used as a proxy to evaluate the performance of the participant in the supervision. This environment with a single human-robot interaction allows us to observe and evaluate the impact of SPARC on the teaching interaction.

4.2 Scope of the Study

The study presented in this chapter intends to evaluate if the learning component of SPARC allows participants to teach an efficient action policy for a robot interacting with humans. For repeatability concerns, the human-robot interaction target of the learning has been modelled by two robots interacting together. The control condition is a variation of WoZ, where participant still control a robot but without the learning component. By combining learning and Supervised Autonomy, SPARC aims to allow the teacher to maintain a high performance during the interaction while reducing the workload on the teacher over time.

To evaluate the validity of SPARC and the influence of such an approach, four hypotheses were devised:

H1 The child-robot's performance is a good proxy for the teacher's performance.

H2 When interacting with a new system, humans progressively build a personal strategy that they will use in subsequent interactions.

H3 Reducing the number of interventions required from a teacher reduces their perceived workload.

H4 Using SPARC allows the teacher to achieve similar performance than WoZ but with a lower workload.

H1 represents a validation of the model, ensuring that the child-robot performance represents the efficiency of the action policy applied by the teacher. H2 tests that human teachers are not static entities, they adapt their teaching target and their interaction strategy. H3 tests one of the motivations behind SPARC: does reducing the number of physical actions from a human to control a robot while requiring the teacher to monitor the robot suggestions lead to a lower workload. Finally, H4 is the main hypothesis, does

SPARC enables a robot to learn a useful action policy: reducing the teacher's workload while maintaining a high performance.

4.3 Methodology

4.3.1 Participants

The study involved 10 participants (7M/3F, age $M=29.3$, 21 to 44, $SD=4.8$ years). While SPARC is expected to be usable by anyone, regardless of their knowledge of computer sciences, this first study involved members of a robotic research group assuming the role of the robot supervisor. This decision is supported by the fact that in RAT scenarios, the wizard is typically a technically competent person with significant training controlling this robot for this therapy. As such, as the participants come from a population expected to assume this type role, the results of the study maintain their applicability to HRI.

4.3.2 Task

This study is based on a real scenario for RAT for children with ASD based on the Applied Behaviour Analysis therapy framework (Cooper et al., 2007). The aim of the therapy is to help a child to develop/practice their social skills. The child has to complete an emotion recognition task by playing a categorisation game with a robot on a mediating touchscreen device (Baxter et al., 2012). The robot can provide feedback and prompts to encourage the child and help them to classify emotions. In the task, images of faces or drawings are shown to the child on the touchscreen, and the child has to categorise them by moving them to one side of the screen or the other depending on whether the picture shown denotes happiness or sadness. In real therapies, the robot would be generally remote-controlled by an operator using the WoZ paradigm Riek (2012).

This study explores if SPARC can be used to teach the robot a correct action policy to support the child in this therapy scenario. As timing in human-robot interactions is complex, for simplification reasons, the interaction has been made discrete to have clear steps when the robot has to select an action. During these action steps, the selection of an action is decided by following the principles defining the Supervised Autonomy:

1. The robot suggests an action to the teacher.
2. The teacher can select an action for the robot to execute or let the proposed action be executed after a short delay.

3. The robot executes the selected action.
4. Both the robot and the teacher observe the outcome of the action until the next action selection step.

This study compares two conditions: SPARC, where the robot learns from the human selections and the WoZ condition where the robot is simply controlled by the participant. As mentioned before, in both conditions, actions can only be executed in predefined time windows dictated by the dynamics of the interaction. Additionally, a ‘wait’ action is present in the SPARC condition and presents an active choice for the participants. In a real WoZ scenario, participants would have to enforce every single action made by the robot, however, a ‘wait’ action in that context does not make sense. As such, in the WoZ condition, the robot proposes random actions, thus increasing the probability of having the teacher correcting the suggestion leading up to a setup similar to a real WoZ.

As mentioned earlier, the focus of the study being on the teaching interaction (the relation between the teacher and the robot), the second interaction (the application) has been kept constant by replacing the child by a robot. A minimal model of child behaviour is therefore used to stand in for a real child. A second robot is employed in the interaction to embody this child model: we term this robot the *child-robot* while the robot being directly supervised by the human teacher is the *wizarded-robot* (cf. Figure 4.1).

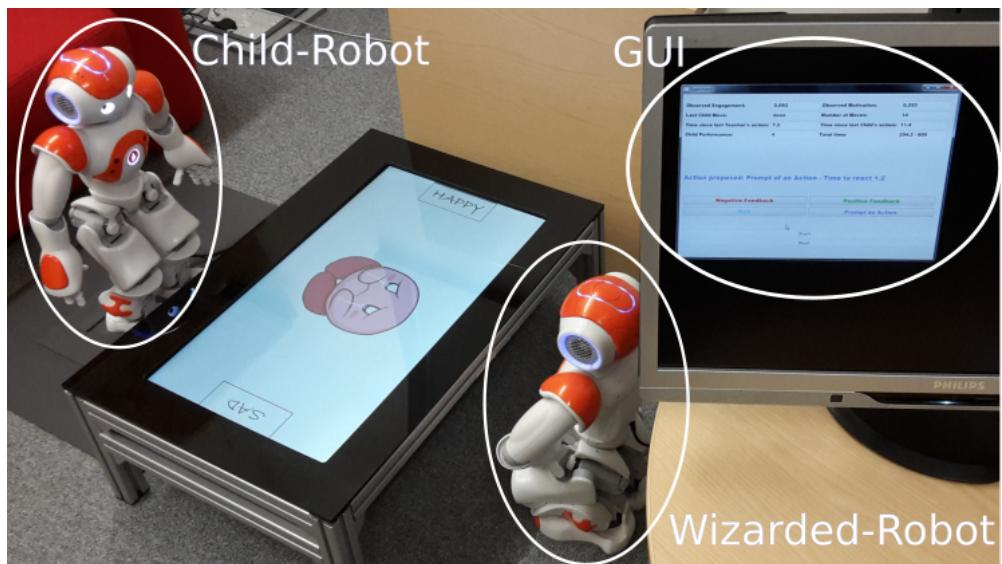


Figure 4.1: Setup used for the user study from the perspective of the human teacher. The child-robot (left) stands across the touchscreen (centre-left) from the wizarded-robot (centre-right). The teacher can oversee the actions of the wizarded-robot through the Graphical User Interface (GUI) and intervene if necessary (right).

4.3.3 Child Model

The purpose of the child model is not to realistically model a child (with or without autism), but to provide a means of expressing some characteristics of the behaviours we observed in interactions with children in a repeatable manner. The child-robot possesses an internal model encompassing an engagement level and a motivation level. Together these form the state of the child. The engagement represents the involvement of the child in the task, i.e. how often the child-robot will make categorisation moves. And the motivation relates to the seriousness of the child in solving task; in the model, the motivation gives the probability of success of each categorisation move.

These states are bound to the range [-1, 1] and influenced by the behaviour of the wizarded-robot. Values of 1 indicate that the child-robot's behaviour is positive, it is involved in the task. Values of -1 show that the child-robot is actively refusing to participate. And a 0 represents a neutral state where the child-robot is neither especially involved nor actively disengaged. To represent a tendency to return to a neutral state of mild engagement, both states asymptotically decay to zero with no actions from the wizarded-robot. These two states are not directly accessed by either the teacher or the wizarded-robot, but can be observed through behaviour expressed by the child-robot: low engagement will make the robot look away from the touchscreen, and the speed of the categorisation moves is related to the motivation (to which gaussian noise was added). There is thus incomplete/unreliable information available to both the wizarded-robot and the teacher.

As explained in Section 4.3.4, the wizarded-robot's action impact the child-robot state: congruent action will tend to increase engagement and motivation. However, if repeated, actions can lead to frustration for the child-robot. If a state is already high and an action from the wizarded-robot should increase it further, there is a chance that this level will sharply decrease. When this happens, the child-robot will indicate this frustration verbally (uttering one of eight predefined strings). This mechanism prevent the optimal strategy to be straightforward: always making actions aiming to increase motivation or engagement. The optimal strategy combines feedback actions and waiting ones to maintain the state values high but prevent them from overshooting. This non-trivial optimal action policy approximates better a real human-robot interaction scenario requiring a more complex strategy to be expressed by the robot.

4.3.4 Wizarded-Robot Control

The wizarded-robot is controlled through a GUI (shown in Figure 4.2) and has access to the variables defining the state of the interaction used by the learning algorithm:

- Observed engagement.
- Observed motivation.
- Type of last categorisation made by the child-robot (good/bad/done).

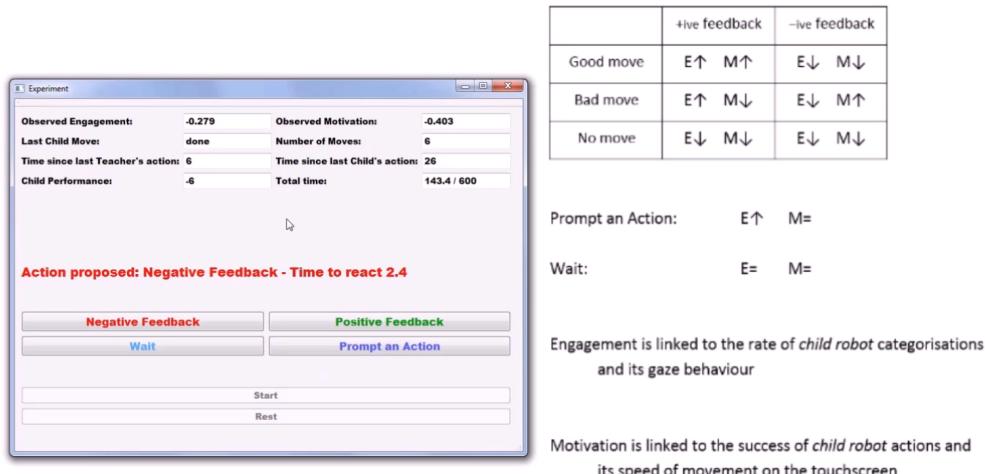


Figure 4.2: Screenshot of the interface used by the participants, the GUI on the left allows to control the robot and a summary of the actions' impact is displayed on the right.

Additionally, other metrics are displayed to the teacher but not used by the algorithm:

- Number of categorisations made by the child-robot.
- Time since teacher's last action.
- Time since child's last action.
- Child's performance.
- Total time elapsed.

The wizarded-robot has a set of four actions it can execute, each represented by a button on the GUI:

- **Prompt an Action:** Encourage the child-robot to do an action.
- **Positive Feedback:** Congratulate the child-robot on making a good classification.

- **Negative Feedback:** Supportive feedback for an incorrect classification.
- **Wait:** Do nothing for this action opportunity, wait for the next one.

The impact of actions on the child-robot depends on the internal state and the type of the last child-robot move: good, bad, or done (meaning that feedback has already been given for the last move and supplementary feedback is not necessary). A *prompt* increases the engagement, a *wait* has no effect on the child-robot's state, and the impact of positive and negative feedback depends on the previous child-robot move. Congruous feedback (positive feedback for correct moves; negative feedback for incorrect moves) results in an increase in motivation, but incongruous feedback can decrease both the motivation and the engagement of the child-robot. The teacher therefore has to use congruous feedback and prompts.

However, as mentioned in Section 4.3.3, if the engagement or the motivation exceeds a threshold, their value can decrease abruptly to simulate the child-robot being frustrated. This implies that the optimal action policy consist on providing congruous feedback and prompts, but also requires wait actions to prevent the child-robot from becoming frustrated and maintain its state-values close to the threshold without exceeding it. A 'good' strategy keeping the engagement and motivation high leads to an increase in performance of the child-robot in the categorisation task.

As introduced previously, to simplify the algorithm part, the interaction has been discretised, the teacher cannot select actions for the wizarded-robot at any time. Actions can only be executed at specific times triggered by the wizarded-robot: two seconds after each child-robot categorisation or if nothing happened for five seconds since the last wizarded-robot's action. When these selection windows are hit, the wizarded-robot proposes an action to the teacher by displaying the action's name and a countdown before execution. The teacher can only select an action in reaction to a proposition from the wizarded-robot; alternatively, if the teacher does nothing in the three seconds following the suggestion, the action proposed by the wizarded-robot is executed. This mechanism allows the teacher to passively accept a suggestion or actively intervene by selecting a different action and forcing the wizarded-robot to execute it.

4.3.5 Learning Algorithm

In the SPARC condition, the robot learns to reproduce the action policy displayed by the teacher. For this study, the algorithm used for learning is a Multi-Layer Perceptron (MLP): with five input nodes: one for the observed motivation, one for the observed engagement and three binary (+1/-1) inputs for the type of the previous move: good, bad, or done. The hidden layer had six nodes and the output layer four: one for each action. The suggested action is selected applying a Winner-Take-All strategy on the value of the output node and then displayed on the GUI before execution. The network is trained with back propagation: after each new decision from the teacher a new training point is added with the selected action node having +1 while the others are set to -1. The network is fully retrained with all the previous state-action pairs and the new one between each selection step.

This learning algorithm, MLP, is not optimal for a real time interaction as the online learning should happen quickly between learning iterations. However, as the length of interaction (and so the number of datapoints) is limited, the network can be retrained between two consecutive uses. Finally, the desired learning behaviour being purely supervised learning, this type of algorithm has been deemed suitable for this study.

4.3.6 Interaction Protocol

The study compared two conditions: a learning robot adapting its propositions to its user (the SPARC condition) and a non-learning robot constantly proposing random actions (the WoZ condition). The child-robot controller was kept constant in both conditions, while the state is reset between interactions. The design was a within subjects comparison with balancing of order: each participant interacted with both conditions, and the order of interaction have been balanced between participants to control for any ordering effects. In the order S-W the participants first interact with the learning wizarded-robot in the SPARC condition, and then with the non-learning one in the WoZ condition; and in the order W-S, this interaction order is inverted (starting with WoZ then SPARC). Participants were randomly assigned to one of the two orders.

The interactions took place on a university campus in a dedicated experiment room. Both robots were Aldebaran Nao, one of which had a label indicating that it was the child-robot. The robots faced each other with a touchscreen between them. The participant, assuming the role of the teacher, sat at a desk to the side of the wizarded-robot, with

a screen and a mouse to interact with the wizarded-robot (fig. 4.1). Participants were able to see the screen and the child-robot.

A document explaining the interaction scenario was provided to participants with a demographic questionnaire. After the information was read, a 30s video presenting the GUI in use was shown to participants to familiarise them with the interface, without biasing them towards any particular control strategy. Then participants clicked a button to start the first interaction which lasted for 10 minutes. The experimenter was sat in the room outside of the participants' field of view. After the end of the first interaction, a post-interaction questionnaire was administered. Similarly, in the second part of the experiment, the participants interacted with the other condition and completed a second post-interaction questionnaire. Finally, a post-experiment questionnaire asked participants to explicitly compare the two conditions. All questionnaires and information sheet are available online².

4.3.7 Metrics

Two types of metrics have been recorded for this study: interaction data representing objective behaviours and performance of the participants and subjective data through questionnaires.

Interaction Data

The state of the child-robot and the interaction values were logged at each step of the interaction (at 5Hz). All of the human actions were recorded: acceptance of the wizarded-robot's suggestion, auto-execution and selection of another action (intervention). The states of the child-robot (motivation, engagement and performance) were also recorded at this step.

The first metric is the performance achieved by participants in each interaction. As the policy applied by the participants cannot be evaluated directly, the performance of the child-robot in the task (number of correct categorisations minus number of incorrect categorisations) is used as a proxy for the participant performance. H1 evaluates if this approximation is valid by analysing the relation between the performance of the child-robot and the value of its inner states. If a correlation is found, it would demonstrate that a good supervision policy (managing to keep the engagement and the motivation of the child-robot high) leads to a high performance. As such, this child-robot performance

²<https://emmanuel-senft.github.io/experiment-woz.html>

represents how efficient the action policy executed by the wizarded-robot was when controlled by a participant.

The second important metric is the intervention ratio: the number of times a user chooses a different action than the one proposed by the wizarded-robot, divided by the total number of executed actions. This metric represents how often in average a user had to correct the robot and could be related to the workload the user had to face to control the robot.

Questionnaire Data

Participants answered four questionnaires: a demographic one before the interaction, two post-interaction ones where they were asked to evaluate the last interaction with the robots and a post-experiment questionnaire where they had to compare the two conditions. All the rating questionnaires used seven item Likert scale. For clarity for participants, in the questionnaires the wizarded-robot is named ‘teacher-robot’.

Post-Interaction questions:

- The child-robot learned during the interaction.
- The performance of the child-robot improved in response to the teacher-robot’s actions.
- The teacher-robot is capable of making appropriate action decisions in future interactions without supervision.
- The teacher-robot always suggested an incorrect or inappropriate actions.
- By the end of the interaction, my workload was very light.
- What did you pay most attention during the interaction? (child-robot, touchscreen, GUI, other).

Post-experiment questions:

- There was a clear difference in behaviour between the two teacher-robots.
- There was a clear difference in behaviour between the two child-robots.
- Which teacher-robot was better able to perform the task? (first, second).
- Which teacher-robot did you prefer supervising? (first, second).

4.4 Results

4.4.1 Interaction Data

Figure 4.3 presents the aggregated results (collapsed between orders) for the performance and the final intervention ratio for both conditions. While the number of participants are not sufficient to perform statistical comparison, overall interaction results seem to show that both conditions lead to similar performance (SPARC: 32.6 (95% CI [27.89,37.31]) - WoZ: 31.4 (95% CI [25.9,36.9])) while the SPARC condition required less interventions (intervention ratio: SPARC: 0.38 (95% CI [0.29,0.47]) - WoZ: 0.59 (95% CI [0.52,0.67])).

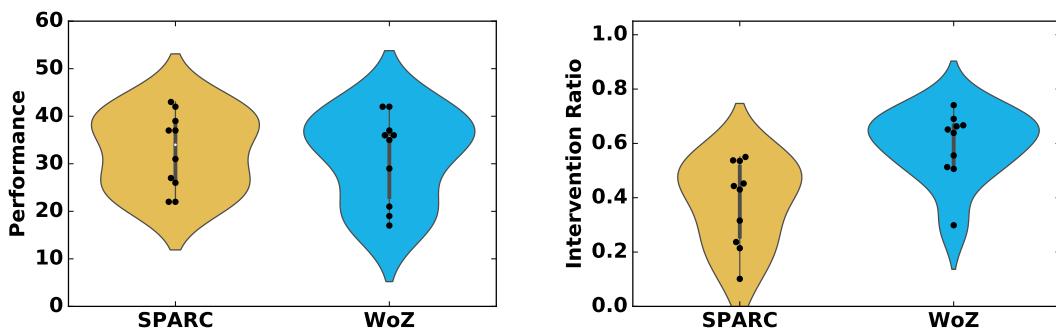


Figure 4.3: Aggregated comparison of performance and final intervention ratio for both conditions. Dots represent individual datapoint ($N=10$ per condition) and shaded area the probability distribution most likely to lead to these points.

Figure 4.4 presents the evolution of intervention ratio for each condition and orders. During the first interaction, participants discovered the interface and how to interact with it, which resulted in a high variation intervention ratio in the first 20 steps (each time the wizarded-robot proposes an action). However in the second phase of the interaction, when participants had developed their teaching policy, there is a tendency for SPARC to require a lower number of intervention than WoZ. This effect is higher in the second interaction, where as soon as 5 steps, the two conditions differentiate without overlap of the 95% CI of the mean. This would indicate that the two conditions differ in term of required interventions.

For both the performance and the intervention ratio, a strong ordering effect was observed. Figure 4.5 and Table 4.1 present the performance and final intervention ratio separated by condition and order. In both orders, the performance in the second interaction is higher performance as the participants were used to the system and developed an efficient interaction policy. On the other hand, the performance between

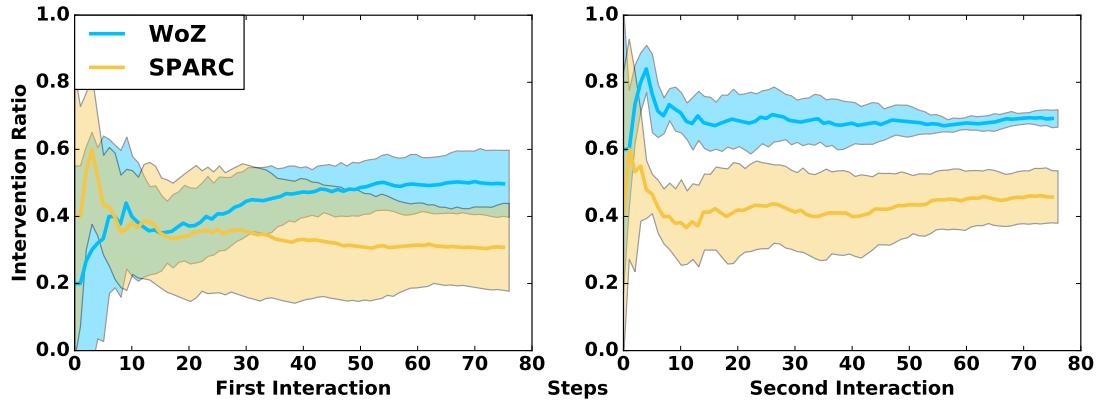


Figure 4.4: Evolution of intervention ratio over time for both conditions and both orders.
Shaded area represents the 95% CI.

condition for the same interaction number is similar (in both their first and second interactions, the condition of interaction did not impact the performance). However, for both orders, when comparing between condition for the same interaction number, the intervention ratio is lower when using SPARC compared to WoZ. This indicates that when the wizarded-robot learned using SPARC, a similar performance is attained as with WoZ, but the number of interventions required to achieve this performance is lower.

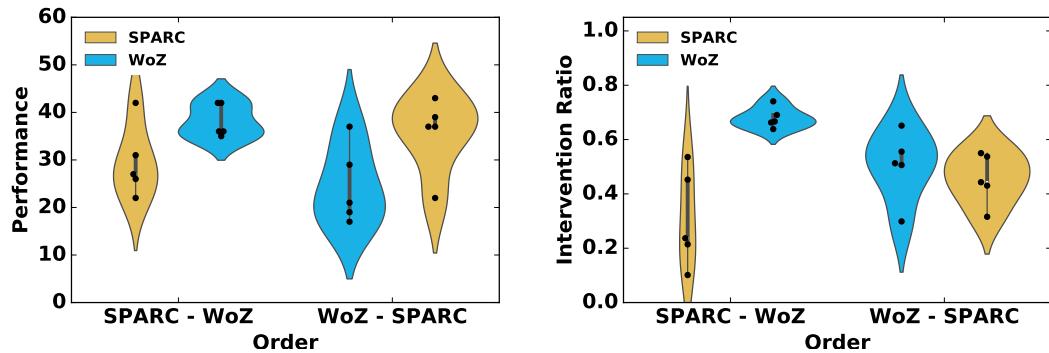


Figure 4.5: Performance achieved and final intervention ratio separated by order and condition. For each order, the left part presents the metric in the first interaction (with one condition) and the right part the performance in the second interaction (with the other condition).

Additionally, a strong positive correlation (Pearson's $r=0.79$) was found between the average child-robot motivation and engagement and its performance which shows that the performance achieved by the child-robot represents the capacity of the teacher to keep both engagement and motivation high.

4.4.2 Questionnaire Data

The post-interaction questionnaires evaluated the participant's perception of the child-robot's learning and performance, the quality of suggestions made by the wizarded-robot,

Table 4.1: Average performance and intervention ratio separated by condition and order.

	Order S-W		Order W-S	
	SPARC (int 1)	WoZ (int 2)	WoZ (int 1)	SPARC (int 2)
Performance M	29.6	38.2	24.6	35.6
95% CI	[23.6,35.6]	[35.5,40.9]	[18.1,31.1]	[29.3,41.9]
Intervention Ratio M	0.31	0.68	0.5	0.46
95% CI	[0.17,0.45]	[0.65,0.71]	[0.4,0.61]	[0.38,0.53]

and the experienced workload. All responses used seven point Likert scales.

Table 4.2 presents separated results for the questions asked in the post-interaction questionnaires, with more details for the questions exhibiting differences in Figure 4.6.

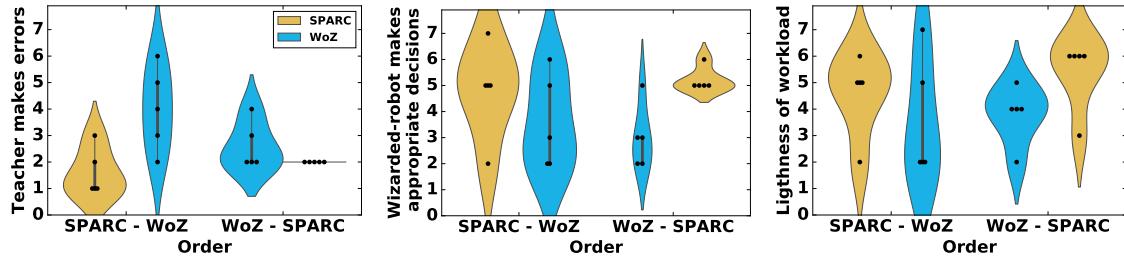


Figure 4.6: Questionnaires results on robot making errors, making appropriate decisions and on lightness of workload.

Across the four possible interactions, the rating of the child-robot's learning was similar ($M=5.25$, 95% CI [4.8, 5.7]). As the child-robot was using the same interaction model in all four conditions, this result is expected. There is a slight tendency to rate the child's performance as being higher in the WoZ condition but the error margin is too high to conclude anything.

Participants rated the wizarded-robot as more suited to operate unsupervised with SPARC than with WoZ (95% Confidence Interval of the Difference of the Mean (CIDM) for S-W ordering [-0.2, 2.6], CIDM for the W-S ordering [1.6, 2.8]).

Similarly, a trend was found showing that the wizarded-robot with SPARC is perceived as making fewer errors than with WoZ (CIDM for S-W ordering [1.3, 3.4], CIDM for the W-S ordering [0.1, 1.1]).

The participants tended to rate the workload as lighter when interacting with SPARC, and this effect is much more prominent when the participants interacted with the WoZ

Table 4.2: Average reporting on questionnaires separated by condition and order.

	Order S-W		Order W-S	
	SPARC (int 1)	WoZ (int 2)	WoZ (int 1)	SPARC (int 2)
Child learns M	5.2	5.2	5.2	5.4
95% CI	[3.7,6.7]	[3.8,6.6]	[4.2,6.2]	[4.7,6.1]
Child's performance M	4.6	5.0	5.0	4.4
95% CI	[3.4,5.8]	[3.3,6.8]	[4.0,6.0]	[3.7,5.1]
Wizarded-robot makes errors M	1.6	4.0	2.6	2.0
95% CI	[0.9,2.3]	[2.8,5.2]	[1.9,3.3]	[2.0,2.0]
Wizarded-robot makes appropriate decisions M 95% CI	4.8	3.6	3.0	5.2
	[3.4,6.2]	[2.2,5.0]	[2.0,4.0]	[4.9,5.6]
Lightness of workload M	4.6	3.6	3.8	5.4
95% CI	[3.4,5.8]	[1.8,5.4]	[2.9,4.7]	[4.4,6.5]

first (CIDM for S-W ordering [-0.6, 2.6], CIDM for the W-S ordering [0.7, 2.5]).

Most of the difference of mean interval exclude 0 or include it marginally, which would indicate tendency of difference, but due to the low number of participants, no statistical tests are applicable and as such no significance can be demonstrated.

4.5 Discussion

Strong support for H1 (a good teacher leads to a better child performance) was found, a correlation between the average value of states (engagement and motivation) and the final performance for all of the 10 participants was observed ($r=0.79$). This validity check confirms that the performance of the child robot reflects the performance of the teacher in this task: supervising the wizarded-robot to execute an efficient action policy maximising the inner state of the child-robot. Additionally, the model of the child robot exhibited the desired behaviour: allowing a wide range of performances without one obvious optimal action policy.

The results also provide support for H2 (teachers create personal strategies): all the participants performed better in the second interaction than in the first one. This suggests that participants developed a strategy when interacting with the system in the first interaction, and were able to use it to increase their performance in the second interaction. Looking in more detail at the interaction logs, different strategies for the wizarded-robot can be observed. For instance, the ratio of waiting action compared to

other supportive actions varied between participants.

H3 (reducing the number of interventions reduces the perceived workload) is partially supported: the results show a trend for participants to rate the workload as lighter when interacting with the SPARC, and another trend between using SPARC and the intervention ratio. However, when computing the correlation between the intervention ratio and the reported workload, a strong effect can only be observed in the second interaction ($\rho = -.622$). In the first interaction, the main cause of the workload is probably the discovery of the system and how to interact with it rather than the requirement to manually select actions for the robot. Nevertheless, regardless of the order of the interactions, SPARC consistently received higher ratings for lightness of workload and required fewer interventions to be controlled which indicates that using SPARC could decrease workload on robot's supervisor compared to WoZ.

Finally, H4 (using learning maintains similar performance, but decreases the workload) is supported: interacting with a learning robot in the SPARC condition results in a similar performance than interacting with a non-learning robot in the WoZ condition, whilst requiring fewer active interventions from the supervisor and a lower workload to control. Reducing the workload on the robot operator has real world utility, for example, in the context of RAT, it might free time for the supervisor to allow them to focus on other aspects of the intervention, such as analysing the child's behaviour rather than solely controlling the robot.

It should be noted that the actual learning algorithm used in this study is only of incidental importance, and that certain features of the supervisor's strategies may be better approximated with alternative methods – of importance for the present work is the presence of learning at all. Other algorithms and ways to handle time have been used in the following studies presented in Chapters 5 and 6.

4.6 Summary

Using a suggestion/intervention system, SPARC allowed online learning for interactive scenarios, thus increasing autonomy and reducing the demands on the supervisor. Results showed that the learning component of SPARC allowed participants to achieve a similar performance as interacting with a non-learning robot, but requiring fewer interventions to attain this result. This suggests that while both conditions allowed the participants to reach a good performance, with SPARC, the presence of learning

shifts part of the burden of selecting actions onto the wizarded-robot rather than on the human. Using SPARC, the robot partially learnt an interaction policy which decreases the requirement on the teacher to physically enforce each robot's actions. This indicates that a learning robot could reduce the workload on the operator freeing them to do more valuable tasks and that SPARC could be an efficient interaction framework to operate this learning. In addition to providing a robot with autonomy, this reduction of workload has real world implications, in the context of RAT, it could allow the therapist to focus more on the child than on the robot, with improved therapeutic outcomes as potential result.

Chapter 5

Study 2:

Importance of Control Over the Learner

Key points:

- Design of an experiment comparing SPARC and another IML method: IRL.
- The application domain is a replication of the world used in early studies evaluating IRL.
- IRL uses partial guidance to the robot and explicit rewarding of the robot's action to teach it a policy.
- SPARC uses full control over the robot's action, implicit rewards and evaluation of intentions rather than actions.
- Results from a mixed design study involving 40 naive participants show that SPARC achieves a better performance and an easier and faster teaching than IRL.

Parts of the work presented in this chapter have been published verbatim in Senft et al. (2017a)¹. The final publication is available from Elsevier via

- <https://doi.org/10.1016/j.patrec.2017.03.015>.

¹Note about technical contribution in this chapter: the author reimplemented every part of the system using Qt.

5.1 Motivation

Previous work in Interactive Machine Learning (IML) showed that humans want to teach robots not only with feedback on its actions but also by communicating the robot what it should do (Thomaz & Breazeal, 2008). However, in most research where agents are taught policies using human guidance, the teacher is given little or no control over the agent's actions and has to observe the agent executing an action even when knowing that this action is incorrect (cf. Section 2.3.4). This chapter explores how these IML approaches could be improved by applying the principles of Supervised Progressively Autonomous Robot Competencies (SPARC) defined in Chapter 3. This chapter also presents experimental results demonstrating how these principles influence the learning process, the agent performance and the user experience and how these results compare to other traditional IML approaches.

The study presented in Chapter 4 explored how SPARC could be used with Supervised Learning, to replicate a teacher's action policy. However, some of the most promising features of IML arise when combined with Reinforcement Learning (RL) as it might allow an agent to learn beyond the demonstrations (Abbeel & Ng, 2004). As such, this chapter proposes a way to apply the principles underlying SPARC to classical feedback based RL and evaluates how this human control over the robot's actions impacts the learning. This chapter presents results from a study involving 40 participants comparing the teaching efficiency and user experience of SPARC to Interactive Reinforcement Learning (IRL), another IML approach offering less control but having been validated in previous studies (Thomaz & Breazeal, 2008).

5.2 Scope of the Study

5.2.1 Interactive Reinforcement Learning

IRL implements the principles presented in Thomaz & Breazeal (2008): a human supervises and teaches an agent to interact autonomously in an environment. This teaching is achieved by providing guidance and positive or negative feedback on the last action executed by a robot. In this study, the algorithm controlling the robot combines this human feedback with environmental ones to form a reward used to update a Q-table. This Q-table assign a Q-value (interest of taking an action) to every state-action pair and is used to select the next action. Three additions to the standard interaction mechanism

have been proposed and implemented by Thomaz and Breazeal and are used in this study as well: guidance, communication by the robot and an undo mechanism (Thomaz & Breazeal, 2008).

The guidance channel emerged from the results of a pilot study where participants assigned rewards to objects to indicate that the robot should do something with them. With the guidance channel, teachers can direct the attention of the robot toward certain items in the environment, informing the robot that it should use them in its next action. This guidance behaviour offers partial control over the robot's actions restricting the executable options, but cannot be used to explicitly set the robot's behaviour.

Additionally, the robot communicates uncertainty by directing its gaze toward different parts of the environment with equally high probability of being used next. The aim of this communication of uncertainty is to provide transparency about the robot's internal state, for example indicating when the robot is unsure about its next action and that guidance should be provided.

Finally, the undo mechanism aims at providing a way for the teacher 'cancel' the robot's action, to bring it back to relevant part of the world, in order to speed up the teaching. After receiving a negative reward, the robot tries to cancel the effect of the previous action on the environment (if possible), resulting in an undo behaviour. As shown in Thomaz & Breazeal (2008) (hereafter the 'original study' or 'original paper'), these three additions improve the robot's performance on the task and the user experience.

In summary, Teachers have two ways to transmit information to the robot: a reward channel (providing a numerical evaluation of the last action) and a guidance channel (directing the robot's attention toward parts of the state to restrict the exploration).

5.2.2 SPARC

SPARC uses a single type of input from the human similar to the guidance in IRL but no reward channel. However with SPARC, the guidance channel directly controls the actions of the robot. The robot communicates all of its intentions (i.e the action it plans to execute next) to its teacher by looking at a part of the environment. Following the principles proposed in Section 3.2, the teacher can either not intervene, letting the robot execute the suggested action or step in and force the robot to execute an alternative action. This combination of suggestions and corrections gives the teacher full control over the actions executed by the robot. This also makes the rewards redundant.

Rather than requiring the human to explicitly provide rewards, a positive reward is directly assigned to each action executed by the robot as it has been either enforced or passively approved by the teacher.

5.2.3 Differences Between IRL and SPARC

Unlike IRL, SPARC offers the user full control over the actions executed by the robot. SPARC changes the learning paradigm from learning from the human's evaluation of actions' impacts to learning from the human's knowledge and the *expected* impact of actions. An expert in the task domain evaluates the appropriateness of actions before their execution and can guide the robot to act in a safe and useful manner. This implies that the robot does not rely on observing the negative effects of an action to learn to avoid it (as in IRL), but rather it learns what the best action is for each state. Even in a non-deterministic environment such as human-robot interactions, some actions can be expected to have a negative consequence. And the human teacher should be able to stop the robot from ever executing them, preventing the robot from causing harm to itself or its social or physical environment.

Another noticeable difference is the type of information the robot communicates with the user: in IRL, the robot communicates its uncertainty about an action and with SPARC its unambiguous intention to execute an action. Similarly, the communication from the user to the robot differs between the two approaches. In SPARC the user can offer the whole action space as commands to the robot, which removes the need for explicit rewards, while in IRL, the teacher can guide the robot toward a subset of the action space and has to manually provide feedback to evaluate the robot's decisions. A result is that the quantity of information provided by the user to the robot is similar for both IRL and SPARC.

5.2.4 Hypotheses

Three hypotheses have been tested in the study:

H1 *Effectiveness and efficiency with non-experts.* IRL and SPARC will have differences in performance, speed, number of inputs used, mental effort on the teacher and the number of errors during the teaching phase when used by non-experts. We predict that for each metric, SPARC will lead to better results.

H2 *Safety with experts.* SPARC can be used by expert users (knowledgeable in

the interaction process) to teach an action policy safely, quickly and efficiently, achieving better results than other IML methods lacking control.

H3 *Control*. Teachers prefer a method in which they can have more control over the robot's actions.

5.3 Methodology

5.3.1 Participants

A total of 40 participants (age $M=25.6$, $SD=10.09$; 24F/16M) were recruited using a tool provided by the University of Plymouth to reach a mixed population of students and non-student members of the local community². At the start of the experiment, all participants gave written informed consent, were told of the option to withdraw at any point and completed a demographic questionnaire. Participants were mostly not knowledgeable in machine learning and robotics (average familiarity with machine learning $M=1.8$, $SD=1.14$; familiarity with social robots $M=1.45$, $SD=0.75$ - Likert scale ranging from 1: not at all familiar to 5: extremely familiar). The study lasted around one hour and followed a 2x2x3 mixed design where participants interacted with both conditions three times. To avoid ordering effects, the order of interaction was counterbalanced between two groups: group 1 interacting with IRL then SPARC and the interaction order is inverted for group 2 (see also Figure 5.2). Participants were distributed randomly between the two groups whilst balancing gender and age. All participants received remuneration at the standard U.K. living wage rate, pro rata.

In addition to naive non-expert users, an expert user (the author) interacted five times with each system following a strictly optimal strategy for both conditions. These results from the expert are used to evaluate H2 and show the optimal characteristics of each system (IRL and SPARC) when used by trained experts in robot interaction, such as therapists in the context of assistive robotics.

5.3.2 Task

The task used in this study is the same as Thomaz & Breazeal (2008): "Sophie's kitchen", a simulated environment presented on a computer where a virtual robot has to learn how to bake a cake in a kitchen. As the source code was not available, the task was reimplemented to stay as close as possible to the description in the paper and the

²<https://uopsop.sona-systems.com/Default.aspx?ReturnUrl=%2f>

online version of the task³.

The scenario is the following: a robot, Sophie, is in a kitchen with three different locations (shelf, table and oven) and five objects (flour, tray, eggs, spoon and bowl) (see Figure 5.1a). The participant has to teach Sophie to bake a cake by guiding it through a sequence of steps while giving enough feedback so the robot learns a correct series of actions leading to the completion of the task. There are six crucial steps to achieve a successful result:

1. Put the bowl on the table (Figure 5.1b).
2. Add one ingredient to the bowl (flour or eggs).
3. Add the second ingredient (Figure 5.1c).
4. Mix the ingredients with the spoon to obtain batter (Figure 5.1d).
5. Pour the batter in the tray (Figure 5.1e).
6. Put the tray in the oven (Figure 5.1f).

The environment is a deterministic Markov Decision Process (MDP), defined by a state, a set of actions (move left, move right, pick up, drop and use), a deterministic transition function and an environmental reward function. The environment includes end states, corresponding to a success or a failure, which reset the simulation to the initial state and provide a reward (+1 for success and -1 for failure). All the other states corresponding to intermediate steps have a reward of -0.04 to penalise long sequences. Different action policies can lead to success, but many actions end in a failure state, for example putting the spoon in the oven. This environment includes a large number of possible states (more than 10,000), success and failure states and a sparse environmental reward function. These elements increase the value of having a teacher present to support the learning. As argued by Thomaz and Breazeal in the original paper, this environment provides a good setup to evaluate methods of teaching a robot.

5.3.3 Implementation

Two conditions were constructed to compare the IRL and SPARC approaches to this task. The underlying learning mechanism is identical in both conditions. The only

³<http://www.cc.gatech.edu/~athomaz/sophie/WebsiteDeployment/>

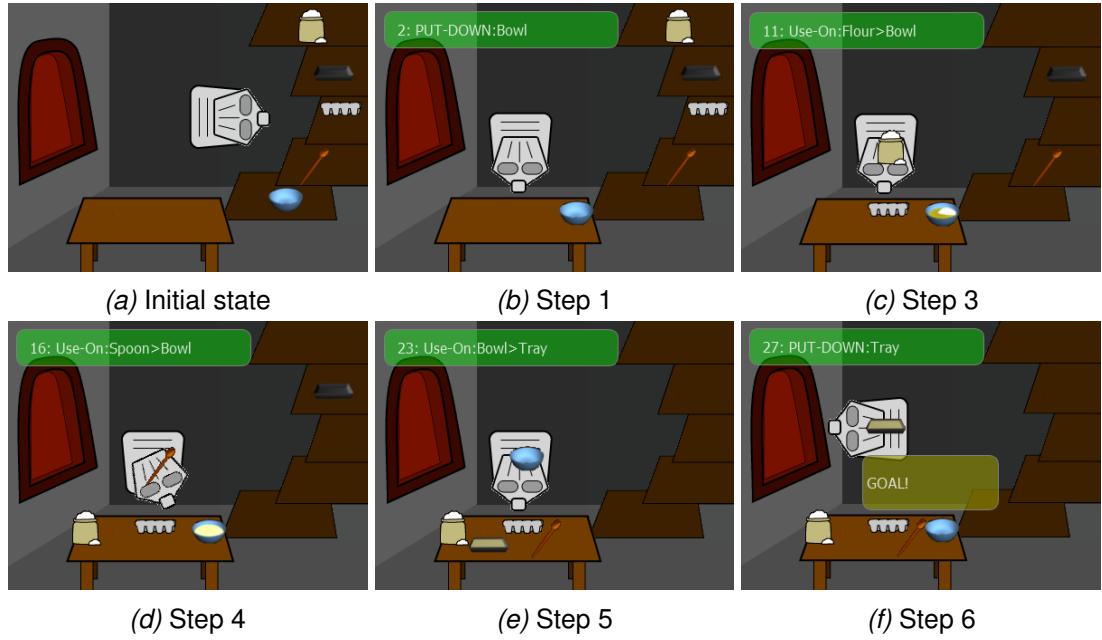


Figure 5.1: Presentation of different steps in the environment. (a) initial state, (b) step 1: bowl on the table, (c) step 3: both ingredients in the bowl, (d) step 4: ingredients mixed to obtain batter, (e) step 5: batter poured in the tray and (f) step 6 (success): tray with batter put in the oven. (Step 2: one ingredient in the bowl has been omitted for clarity, two different ingredient could be put in the bowl to reach this state)

differences lie in the manner of interaction (inputs to and from the algorithm) and the amount of control over the robot's actions. With IRL teachers have to explicitly provide rewards and have a partial control over the action selection, while with SPARC rewards are implicit and the control over actions is total.

The learning algorithm (see Algorithm 1 and 2) is a variation on Q-learning, without reward propagation⁴. This guarantees that any learning by the robot is due to the human's teaching, and as such provides a lower bound for the robot's performance. By using Q-learning, the robot's testing performance would be higher. Similarly to the original study, the algorithm uses a learning rate $\alpha = 0.3$ and a discount factor $\gamma = 0.75$.

As shown in Table 5.1, another difference between the conditions is that with SPARC, the algorithm learns immediately after executing an action (and only with positive rewards). On the other hand, IRL learns about an action just before executing the next one, based on a positive or negative evaluation received between the actions.

Interactive Reinforcement Learning

We have implemented IRL following the principles presented in Thomaz & Breazeal (2008). The user can use the left mouse-click to display a slider providing rewards.

⁴In Q learning the update function is $Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha(r_t + \gamma \max_a Q(s_{t+1}, a)) - Q(s_t, a_t))$

Table 5.1: Simplified outline of algorithms used for both condition.

Algorithm 1: SPARC	Algorithm 2: IRL
while learning do $a_t = \underset{a}{\operatorname{argmax}} Q[s_t, a]$ look at object or location used in a_t while waiting for command (2 seconds) do if received command then $a_t = \text{received command}$ $r_t = 0.5$ else $r_t = 0.25$ Act in the world: execute a_t , transition to s_{t+1} $r_t = r_t + r_{\text{environment}}$ Learn: $Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha(r_t + \gamma \underset{a}{\operatorname{max}} Q(s_t, a) - Q(s_t, a_t))$	while learning do $A_{t+1} = [a^1 \dots a^n], n \text{ actions with high } Q[s_{t+1}, a^i]$ while waiting for guidance and reward on a_t (2 seconds) do if $n > 1$ then indicate confusion if received reward r'_t then $r_t = r_t + r'_t$ if receiving guidance then if guidance acceptable then $a_{t+1} = \text{guidance}$ Learn: $Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha(r_t + \gamma \underset{a}{\operatorname{max}} Q(s_t, a) - Q(s_t, a_t))$ Act in the world: execute a_{t+1} , transition to s_{t+2} $r_{t+1} = r_{\text{environment}}$

Guidance is implemented by right-clicking on objects to direct the robot's attention toward a specific object. Guidance can only be provided for objects the robot is facing, otherwise right-clicking has no effect. Following a guidance message, the robot will execute the candidate action involving the object. The action space is not entirely covered by this guidance mechanism: for example, it does not cover moving from one location to another. This guidance gives a partial opportunity to the user to limit the exploration for the current step, without preventing the robot to explore in further steps.

Some modifications to the original study were required due to the lack of implementation details in the original paper, one of them being the use of a purely greedy policy instead of using softmax. As, the presence of human rewards and guidance limits the importance of autonomous exploration, the greediness of the algorithm should assist the learning by preventing the robot from exploring outside of the guided policy.

It should be noted that the presence of the human in the learning process alters deeply the concept of convergence. By providing rewards, the teacher can manually force the robot's policy to converge or diverge.

SPARC

SPARC uses the gaze of the robot toward objects or locations to indicate to the teacher which action the robot is suggesting. Similarly to the guidance in IRL, the teacher can use the right click of the mouse on objects to send a ‘command’ to the robot and have it execute the action associated to this object in the current state. However, in this condition, this communication has been extended to also cover locations. With SPARC, the command covers the whole action space: at every time step, the teacher can specify, if desired, the next action to be executed by the robot. Similarly to the guidance, this command can be used on objects only if the robot is facing them. If a robot’s suggested action is not corrected, a positive reward of 0.25 is automatically received (as it has the implicit approval from the teacher). If the teacher selects another action, a reward of 0.5 is given to the selected action (the corrected action is not rewarded). That way, actions actively selected are more reinforced than the ones accepted passively and participants still have access to a wider range of rewards with IRL. This system allows for the use of reinforcement learning with implicit reward assignation, aiming to simplify the teaching interaction.

5.3.4 Interaction Protocol

Participants were divided into two groups and interacted with both IRL and SPARC, with the order of presentation being counterbalanced between groups (see Figure 5.2). Participants in group 1 interacted with IRL first for three sessions and then with SPARC for the three remaining sessions; and the interaction order was inverted for participants in group 2.

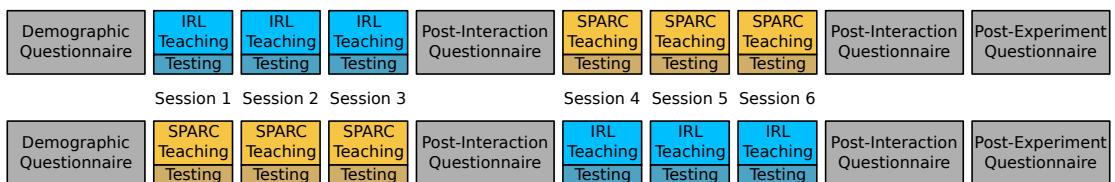


Figure 5.2: A representation of the timeline experienced by participants according to the order they were in. The top row corresponds to group 1 and bottom row to group 2.

After welcoming participants and before interacting with a system, participants completed a demographic questionnaire and received two information sheets. The first one explained the task (describing the environment and how to bake the cake) and the second one described the system they would interact with (IRL or SPARC).

After reading the sheets, participants interacted for three sessions with the system they were assigned to. Each session started with a teaching phase where the participants could interact with the robot to teach it to complete the task. The teaching phase was composed of a number of episodes, corresponding each to a trajectory from the initial state to an end state (success or failure) after which the environment was returned to the initial state. Similarly to the experiment by Thomaz and Breazeal, participants could decide to terminate the teaching phase whenever they desired by clicking on a button labelled ‘Sophie is ready’. But the teaching phase was automatically terminated after 25 minutes to impose an upper time-limit on the study.

After the teaching phase, the robot ran a testing phase where the participant’s inputs, other than a force stop, were disabled. The test stopped as soon as an ending state was reached or the participant forced a stop (e.g. if an infinite loop occurs). This testing phase’s aim is to evaluate the participants’ performance in the teaching task. The interaction with each system involved three repeated independent sessions with their own teaching and testing phases. This aims to observe how the interactions evolved as participants get used to interact with a system.

After participants completed their three sessions with the first system, they were asked to complete a first post-interaction questionnaire. Then they received the information sheet for the second system, interacted with it for three sessions and completed a second post-interaction questionnaire.

At the end of the experiment, participants completed a last questionnaire, the post-experiment questionnaire, received the financial compensation and were explained the goal of the study. All information sheets and questionnaires can be found online⁵ and the questionnaires are described in Section 5.3.5.

5.3.5 Metrics

Interaction Metrics

We collected four metrics during the teaching phase (teaching performance, teaching time, number of failures and number of inputs provided) and one during the testing phase (the testing performance). All interaction metrics were collected three times per conditions, once for each session. As not all participants reached a success during the testing phases, we used the six key steps defined in Section 5.3.2 as a way to

⁵<https://emmanuel-senft.github.io/experiment-irl.html>

evaluate the performance ranging from 0 (no step has been completed) to 6 (the task was successfully completed) during the testing phase. For example a testing where the robot puts both ingredients in the bowl but reaches a failure state before mixing them would have a performance of 3.

The testing performance represents the success of participants in teaching the robot to complete the task. On the other hand, the teaching performance corresponds to the highest step reached by participants in the teaching phase and represents a teaching method's ease of guiding the robot. The teaching time is the duration of the teaching phase, ranging from 0 to 25 minutes. The number of failures is the number of times a participant reached a failure state during the teaching phase. It can be related to the risks involved by the teaching; a safe teaching process should lead to a low number of failures, while a risky one would have a high number of failure. The number of inputs corresponds to the number of commands, guidances or feedback inputs used in a teaching session. Similarly to the teaching time, the number of inputs can be seen as the quantity of efforts invested in the teaching process.

Questionnaires

The post-interaction and post-experiment questionnaires provide additional introspective information to compare with the quantitative data from the interaction. Two principal metrics are gathered: the workload on participants and the perception of the robot.

Workload is an important factor when teaching robots. As roboticists, our task is to minimise the workload for the robot's user and to make the interaction as smooth and efficient as possible. Multiple definitions for workload exist and various measures can be found in the literature (e.g. Wierwille & Connor 1983; Moray 2013). Due to its widespread use in human factors research (Hart, 2006) and clear definition and evaluation criteria, we used the NASA-Task Load Index (TLX) (Hart & Staveland, 1988). Following the methodology proposed to administer NASA-TLX, we averaged the values from all 6 scales (mental, physical and temporal demand, performance, effort and frustration) ranging from 0 (low workload) to 20 (high workload) to obtain a single workload value per participant for each interaction. This assessment is made during the post-interaction questionnaires. This results in two measures of workload per participant, one for each condition.

Finally, the participants' perception of the robot was also evaluated in the post-interaction

and post-experiment questionnaires using rating questions (measured on a 5 item Likert scale), binary questions (where participants had to select one of the two system), and open questions on the preference of system and the naturalness of the interaction.

5.4 Results

Most of the results collected in the study were non-normally distributed. Both ceiling and floor effects can be observed depending on the conditions and the metrics. For instance, for the teaching time, some participants preferred to interact much longer than others, resulting in skewed data. Likewise for the testing performance: often participants either reached a successful end state or did not hit any of the sub-goals of the task in the testing phase ending often in two clusters of participants: one at a performance of 6 and one at 0. Similarly, some participants who interacted a long time with the system did not complete any step, while others could achieve good results in a limited time. Due to the data being not normally distributed and the absence of possible transformation making them normal, Bayesian statistics were conducted using the JASP software (JASP Team, 2018). Three types of test have been used: mixed ANOVA for omnibus comparisons between conditions for the first and the second interaction (between participants), independent t-test for post-hoc comparisons between participants and paired samples t-test for post-hoc comparisons within participants. All tests have been performed using their Bayesian counterpart, which also removed the need for doing a correction on post-hoc tests such as Bonferroni. As such, no p-value is reported, but a B factor representing how much of the variance on the metric is explained by a parameter (if $B < 1/3$ there is no impact, if $B > 3$ the impact is strong, and if $1/3 < B < 3$ the results are inconclusive; Jeffreys 1998; Dienes 2011).

For each interaction metric, two mixed ANOVA between participants were calculated to explore the impact of the conditions on the metric. The first ANOVA is applied to the first interaction (session 1,2 and 3) and compares participants in group 1 interacting with IRL and participants in group 2 interacting with SPARC. The second ANOVA is related to the second interaction (sessions 4, 5 and 6) and compares participants in group 1 interacting with SPARC and those in group 2 interacting with IRL. If required, additional post test were made within participants for the three sessions corresponding to each interaction to measure if successive interactions with a same system impact the metric.

5.4.1 Interaction Data

Five objective metrics (teaching performance, testing performance, teaching time, number of inputs provided and number of failures) have been used to assess the efficiency of IRL and SPARC.

Teaching Performance

Figure 5.3 presents the maximum performance reached by participants during the teaching phase, i.e how far in the steps they brought the robot during the teaching phase. It relates to the ease of guiding the robot through the task using a method. If a method does not allow a teacher to direct the robot's behaviour, the robot will have issues reaching useful states which will lead to a poor teaching performance. On the other hand, methods allowing the teacher to steer the robot to the desired parts of the environment should achieve a high teaching performance. The teaching performance is also an upper bound for the testing performance as, due to the risk of failures or loop in the environment, the performance in the testing phase cannot (or has dramatically low probability to) achieve a higher performance than in the teaching phase.

In the first three sessions participants interacted with either IRL or SPARC and swapped for the remaining three sessions. The bayesian mixed ANOVA shows difference between conditions (and between participants) when interacting with the first system (participant in group 1 interacting with IRL and those in group 2 with IRL) and this effect is also present in the second interaction (first interaction: $B_1 = 2881$ - second interaction $B_2 = 76.2$). According to the medians shown in Table 5.2 and the graphs in Figure 5.3, for both interaction, participants using SPARC achieved a higher teaching performance than the ones using IRL. The session number (the repetition of additional sessions with the same system - within participants) had no impact on the teaching performance (first interaction: $B_1 = 0.089$ - second interaction $B_2 = 0.105$) which means that with additional interaction with a system participants did not reach a higher or lower teaching performance.

Table 5.2: Median performance in the teaching phase. Noted that between session 3 and 4 participants change system.

	\tilde{X}_1	\tilde{X}_2	\tilde{X}_3	\tilde{X}_4	\tilde{X}_5	\tilde{X}_6
IRL	3.0	3.5	3.0	3.5	2.5	3.0
SPARC	6.0	6.0	6.0	6.0	6.0	6.0

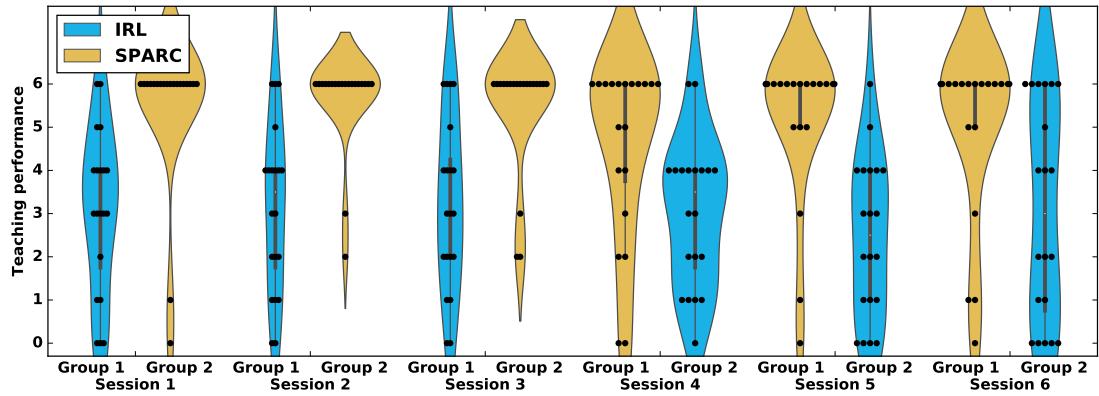


Figure 5.3: Comparison of the teaching performance for the six sessions (the left columns presents the data of participants in group 1 and the right ones those in group 2). The colours are swapped between session 3 and 4 to represent swapping of conditions. A 6 in teaching performance shows that the participant reached at least one success during the teaching phase. The vertical grey lines represent minimal barplots of the data and the shaded areas the probability distribution most likely to produce these results.

This higher teaching performance for SPARC provides partial support for H1 and its prediction: 'SPARC will be more effective and efficient than IRL when used by non-experts'.

Testing Performance

Figure 5.4 presents the performance of the system during the testing phase, and represents how successful was the participants' teaching. The bayesian mixed ANOVA shows an effect of condition on the performance for both interactions ($B_1 = 8.8 \times 10^5$ and $B_2 = 7340$). The median performance scores in Table 5.3 show that a higher test performance was achieved when participants used SPARC compared to when they used IRL. The session number has no impact on the performance on the first interaction, but results are inconclusive for the impact of repetition on the second interaction ($B_1 = 0.084$ and $B_2 = 0.80$).

As shown in Table 5.3 and Figure 5.4, only a limited number of participants succeeded in teaching the robot to complete the task using IRL, this finding will be discussed in more details in section 5.6.

Table 5.3: Medians of the performance in the testing phase.

	\tilde{X}_1	\tilde{X}_2	\tilde{X}_3	\tilde{X}_4	\tilde{X}_5	\tilde{X}_6
IRL	0.0	0.0	1.0	0.0	0.0	0.0
SPARC	6.0	6.0	6.0	4.5	6.0	6.0

This higher testing performance for SPARC provides partial support for H1 and its

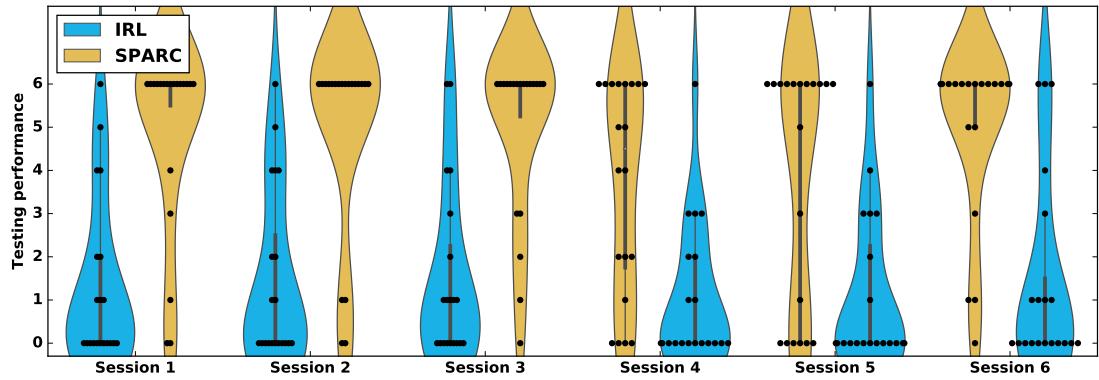


Figure 5.4: Comparison of the testing performance for the six sessions. A 6 in performance shows that the taught policy led to a success.

prediction.

Teaching Time

Figure 5.5 presents the time participants spent teaching. They could stop whenever they decided or the session would stop automatically after 25 minutes. The bayesian mixed ANOVA shows the important role of condition ($B_1 = 31.4$ and $B_2 = 679$) and session number on the time spent teaching ($B_1 = 8.3 \times 10^9$ and $B_2 = 3188$). Table 5.4 and additional post-hoc comparisons between the sessions in each interaction indicate that in the first interaction, the teaching time decreases between the first and the second session and then tends to stabilise between the second and the third sessions ($B_{12} = 4.4 \times 10^5$, $B_{13} = 2.6 \times 10^6$ and $B_{23} = 0.435$). A similar pattern occurs in the second interaction ($B_{45} = 850$, $B_{46} = 382$ and $B_{56} = 0.172$) with more support for a stabilisation of teaching time between session 5 and 6.

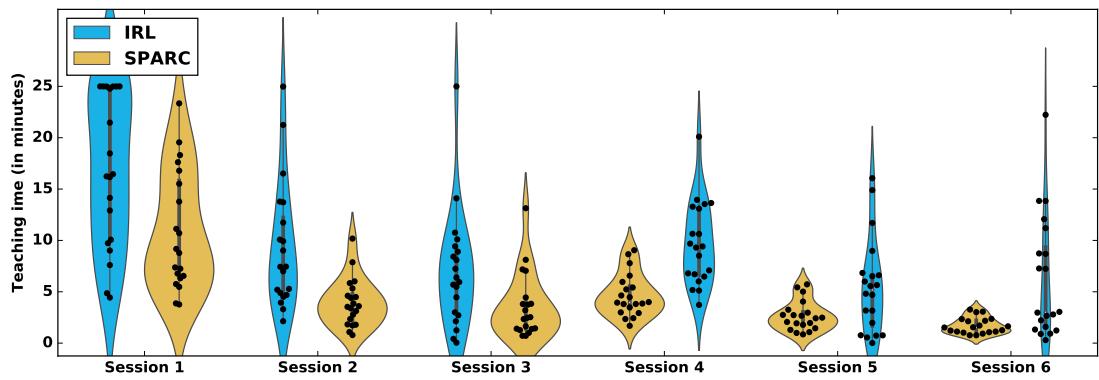


Figure 5.5: Comparison of the teaching time for the six sessions. At 25 minutes, the session stopped regardless of the participant stage in the teaching.

Combined with the consistent high performance of SPARC, this decrease of teaching time indicates that participants managed to learn an efficient way to use SPARC to

Table 5.4: Medians of the teaching time in each session (in minutes).

	\tilde{X}_1	\tilde{X}_2	\tilde{X}_3	\tilde{X}_4	\tilde{X}_5	\tilde{X}_6
IRL	16.34	7.43	6.16	9.36	5.18	3.0
SPARC	8.97	3.56	2.49	3.96	2.45	1.53

teach the robot a successful action policy. On the other hand, this similar decrease of teaching time and the lower performance with IRL could indicate that participants lost motivation to interact with IRL. As they did not find an efficient way to teach the robot with IRL, they dedicate less efforts to try in successive session. These interpretations provide partial support to H1 and its prediction.

Number of Inputs

Figure 5.6 presents the number of inputs the participants provided while teaching. The bayesian mixed ANOVA shows that in both interactions, the condition had an impact on the number of inputs provided ($B_1 = 27.4$ and $B_2 = 34.1$). On the other hand, the session number only had a clear impact for the first interaction, the results are inconclusive for the second interaction ($B_1 = 4.1 \times 10^5$ and $B_2 = 1.5$). Table 5.5 and additional post-hoc comparisons between sessions indicate that in the first interaction, the number of inputs used decreases between the first and second sessions and then tends to stabilise between the second and the third sessions ($B_{12} = 2707$, $B_{13} = 4.7 \times 10^4$ and $B_{23} = 0.410$). Similarly, for the second interaction, a difference tends to be observed between session 4 and 5 and session 4 and 6 while the number of inputs is similar between session 5 and 6 ($B_{45} = 2.6$, $B_{46} = 2.7$ and $B_{56} = 0.17$).

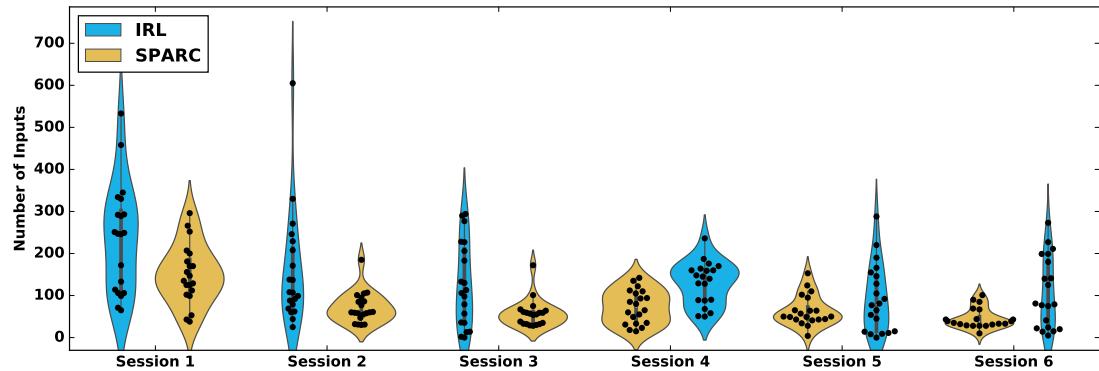


Figure 5.6: Comparison of the number of inputs provided by the participants for the six sessions.

Similarly to the teaching time, this reduction of inputs provided during the teaching, while maintaining a high performance for SPARC offers partial support for H1 and its

Table 5.5: Medians of the number of inputs in the testing phase.

	\tilde{X}_1	\tilde{X}_2	\tilde{X}_3	\tilde{X}_4	\tilde{X}_5	\tilde{X}_6
IRL	248.0	107.5	109.5	142.5	79.0	80.0
SPARC	141.0	60.0	56.0	72.5	50.0	37.0

prediction.

Number of Failures

Figure 5.7 presents the number of failure states participants encountered during the teaching phase. The bayesian mixed ANOVA shows that for both interactions, both the condition ($B_1 = 6.2 \times 10^4$ and $B_2 = 2.6 \times 10^4$) and session number ($B_1 = 1.5 \times 10^4$ and $B_2 = 11$) play an important role on the number of failures. Table 5.6 and additional post-hoc comparisons between sessions indicate that in the first interaction, the number of failures decreases between the first and the second session and then stabilises between the second and the third one ($B_{12} = 619$, $B_{13} = 1.7 \times 10^3$ and $B_{23} = 0.25$). Similar results can be observed in the second interaction ($B_{45} = 3.3$, $B_{46} = 7.5$ and $B_{56} = 0.2$).

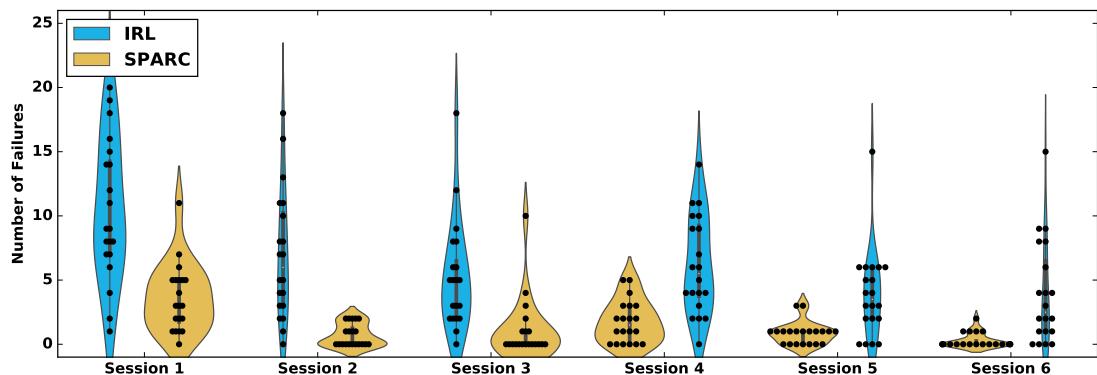


Figure 5.7: Comparison of the number of failures for the six sessions.

Table 5.6: Medians of the number of failures in the testing phase.

	\tilde{X}_1	\tilde{X}_2	\tilde{X}_3	\tilde{X}_4	\tilde{X}_5	\tilde{X}_6
IRL	9.0	6.0	5.0	5.5	3.5	2.5
SPARC	3.0	0.0	0.0	1.5	1.0	0.0

The fewer failures faced when using SPARC compared to IRL offers partial support to H1 and its prediction. Additionally, the low number of failures when using SPARC in the last sessions of both interaction (sessions 3 and 6) shows that participants became more efficient with SPARC, reaching successes without facing failures, which partially support H2: ‘SPARC can be used by expert users (knowledgeable in the interaction process) to teach an action policy safely, quickly and efficiently’.

5.4.2 Questionnaire Data

The main task of the post-interaction questionnaires was to assess the workload on participants when interacting with a condition using the NASA-TLX questionnaire. Figure 5.8 presents the workload for participants for each condition for both interactions (the average of the six ratings from 0 to 20 for each category). In the first interaction, participants using IRL reported an average workload of 12.9 ($SD = 2.33$), whereas the ones using SPARC reported 8.94 ($SD = 3.01$). In the second interaction, participants interacting with IRL had an average workload of 13.87 ($SD = 2.84$) and the ones using SPARC reported 7.44 ($SD = 3.41$). Bayesian independent t-test show a strong effect on the condition for both interactions ($B_1 = 462$ and $B_2 = 8.1 \times 10^4$) between participants. And bayesian paired t-test show a similar effect of the condition within participants for both orders (order 1: $B_{IRL-SPARC} = 1.7 \times 10^6$ - order 2: $B_{SPARC-IRL} = 1.1 \times 10^4$). Regardless of the comparison criteria (between or within subjects), participants reported a lower workload when interacting with SPARC than when interacting with IRL.

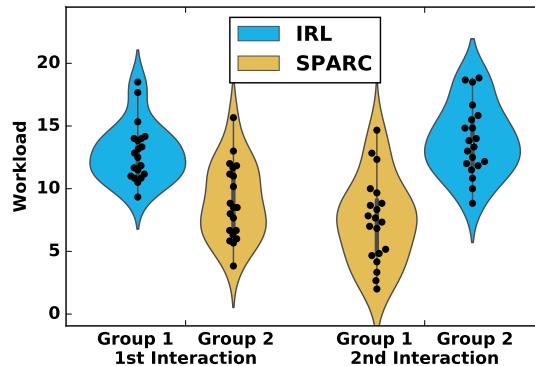


Figure 5.8: Average workload for each participants as measured by the NASA-TLX for each conditions in both interaction order.

This lower workload when using SPARC compared to IRL offers partial support for H1 and its predictions.

5.4.3 Expert

To evaluate the best case potential offered by SPARC and IRL, an expert in Human-Robot Interaction (HRI) knowing the detail of the algorithm and the interactions (the author) interacted five times with each system. For both systems, the expert followed a strictly optimal strategy. In the case of IRL the optimal strategy consisted on providing as much guidance as possible, rewarding positively correct actions and negatively incorrect ones. For SPARC the optimal strategy consisted on providing commands for every

single action to demonstrate an optimal trajectory to the robot. This shows the expected behaviours in optimal conditions, the best metrics achievable. Results of the interactions are presented in Table 5.7. In both cases, the expert successfully taught the robot (as indicated by a performance of 6 during the teaching and the test), which indicates that both systems can be used to teach a robot an action policy. However as demonstrated by a bayesian independent t-test, the time required to teach the robot with IRL is higher than with SPARC ($B = 7102$).

Table 5.7: Results of an expert interacting 5 times with each system following an optimal strategy. When the variance is 0, Bayes Factor cannot be computed.

	IRL $M(SD)$	SPARC $M(SD)$	<i>B</i> factor
Performance	6 (0)	6 (0)	NA
Time (minutes)	4.5 (0.67)	0.60 (0.03)	7102
Inputs	115.6 (8.4)	28 (0)	NA
Number of Failures	3.2 (0.84)	0 (0)	NA

Additionally, when using IRL, even an expert cannot prevent the robot from reaching failure states during the teaching due to the lack of control over the robot's action. Conversely, when interacting with SPARC, due to the full control and clear communication, the teacher can ensure that only desired actions are executed. So with sufficient knowledge of the interaction possibilities, an expert can teach the robot to behave safely without having to explore and reach undesired states using SPARC. This has real world applications in HRI, as random exploration is often impossible or undesirable when interacting with humans. SPARC offers a way for the teacher to stop the robot from executing actions with negative consequences whilst still guiding the robot toward useful parts of the environment.

Similar results to these were observed with our non-expert participants: in their last session with SPARC, both groups had a median of 0 failures and a performance of 6. This indicates that more than half of the participants successfully taught the robot the task without ever hitting a failure state after gaining understanding of SPARC in their first and second interaction with it.

The absence of failures, the lower number of inputs and the shorter time required to teach with SPARC compared to IRL when used by an expert user provide support for H2.

5.5 Validation of the Hypotheses

5.5.1 Effectiveness and Efficiency with Non-Experts

The objective metrics show that despite spending a shorter time interacting with SPARC and using fewer inputs, participants reached a higher performance than with IRL and faced fewer failures during teaching. Additionally, when interacting with SPARC, the time participants took to teach the robot decreased to reach a plateau in the second and third sessions, without negatively affecting the performance. This indicates that after the first session, participants understood the interaction mechanism of SPARC and consistently managed to achieve a high performance whilst requiring less time to teach the robot the task. On the other hand, when interacting with IRL, participants' performance remained low over the sessions, and their teaching time decreases between session 1 and 2 but not further between session 2 and 3. This decrease of teaching combined with low performance might be due to a loss of motivation after session 1 where often participants did not succeed to teach the robot, reducing the desire to further interact in successive sessions. The results suggest that teaching the robot using SPARC allows the robot to achieve a higher performance than with IRL, in a shorter time, while requiring fewer inputs and making fewer errors when teaching. This conclusion is supported by subjective measures: the workload on the teacher is lower when using SPARC than when using IRL.

For these reasons, H1 and its prediction is ('Compared to IRL, SPARC can lead to higher performance, whilst being faster, requiring fewer inputs and less mental effort from the teacher and minimising the number of errors during the teaching when used by non-experts.') is supported.

5.5.2 Safety with Experts

As presented in Section 5.4.3, when interacting with SPARC, an expert can reach a success easily and safely (requiring a low number of inputs and a short time and without facing a single failure). This effect is also observed after some training for the naive participants: most of them reached a success without encountering any failures in their last session with SPARC.

However, when interacting with IRL, even the expert applying a strictly optimal policy cannot prevent the robot reaching failures states. This effect is due to the lack of control

of feedback-based IML methods. As teachers only rate the actions of the agent, they cannot prevent the learners from making errors. They can only negatively reward these errors to reduce their chance of being selected in the future. While the guidance allows to partially mitigate this effect, the presence of actions not covered by this guidance limits the its efficiency during the teaching.

This difference shows support for H2 ('SPARC can be used by expert users to teach an action policy safely, quickly and efficiently, achieving better results other IML methods lacking control'). This also demonstrates how the principles presented in Chapter 3 provide control to the teacher over the robot's actions and by extend improve the teaching. Consequently, the principles underlying SPARC ensure that even in the early stages of teaching (when the robot's action policy is not mature to correctly select actions without supervision), the action policy of the robot is appropriate, which is not the case of most other IML methods (as demonstrated by the number of failures when teaching with IRL).

5.5.3 Control

One of the main differences between the two methods is the way in which the concept of teaching is approached. With IRL an exploratory individual learning approach is followed: the robot has the freedom to explore, whilst receiving feedback on its actions and limited guidance about what action to pursue next from a teacher. This social aspect of the teaching: with hints and guidance, partial control over the robot actions and bidirectional communication is inspired by the way humans teach. While not every member of the population is knowledgeable about Machine Learning (ML), they are experienced with social learning (Thomaz & Breazeal, 2008). This similarity between how humans teach robots and other humans has also been supported by behaviours displayed by participants in the original study. Participants gave motivational rewards to the robot, just as one would do to keep a child motivated during learning, despite the absence of effect or use in classical reinforcement learning (Thomaz & Breazeal, 2008).

On the other hand, SPARC promotes a more direct teaching process: the supervisor explicitly tells the robot what to do and expects it to obey and learn. The robot is not totally considered as a social agent from the supervisor's point of view, but rather as a tool having to learn an action policy. This does not mean that the robot cannot be social: the supervisor can teach the robot in a non-social way how to interact socially

in a non-social way. This approach is more task oriented, and we argue that it better fits many applications of HRI when the interaction with the teacher does not have to be social. For example, in Socially Assistive Robotics (SAR), the task (such as interaction with a child with Autism Spectrum Disorder (ASD)) is more important than the social relationship between the robot and its supervisor (a therapist for example) and as such the relevance of the social side of the interaction between the teacher and the robot is reduced.

The post-experiment questionnaire included the open question: ‘which robot did you prefer interacting with and why?’. Almost all the participants (38 out of 40) replied that they preferred interacting with SPARC. Half of all the participants used vocabulary related to the control over the robot’s actions (‘control’, ‘instruction’, ‘command’, ‘what to do’ or ‘what I want’) to justify their preferences without these words being used in the question. Furthermore, multiple participants reported being frustrated not to have total control over the robot’s actions with IRL, they would have preferred being able to control each of the robot’s actions.

To the question ‘which interaction was more natural?’, 10 participants rated IRL as being more natural, using justifications such as: ‘The robot thinks for itself’, ‘Some confusion in the [IRL] robot was obvious making it more natural’, ‘More like real learning’, ‘Because it was hard to control the robot’ or ‘People learn from their mistakes faster’. But despite these participants acknowledging that IRL is more ‘natural’, closer to human teaching, they still preferred teaching using SPARC. This suggests that when humans teach robots, they are focused on the outcome of the teaching, on the learner’s proficiency in the task. As mentioned previously, this might relate to the role of robots, they often interact in human-centred scenarios where they have to complete a task for their users. And, due to the absence of life-long learning for robots today, it is not worth investing time and energy to allow the robot to improve its learning process or explore on its own. These comments from the participants show support for H3 (‘Teachers prefer a method providing more control over the robot’s actions.’).

5.6 Discussion

Despite not being originally designed for use in combination with Reinforcement Learning, SPARC achieved good results in this study. This shows that principles presented in Chapter 3 are agnostic to the learning algorithm and promote an efficient teaching

interaction. Furthermore, SPARC achieves a higher performance, in a shorter time and facing less failures than IRL, whilst requiring a lower workload from the human teacher. And finally, when used by experts (designer or trained participants), SPARC demonstrates that teaching can be safe and quick: the full control over robot's action in the teacher's hands ensures that only desired actions will be executed. These results show an important feature of teaching robots to interact in human environments. As robots interact in task oriented, human-centred environments, human teachers need approaches with direct control and more focused on commands rather than letting the robot explore on its own and only evaluate its actions.

5.6.1 Comparison with Original Interactive Reinforcement Learning Study

Unlike the original experiments evaluating IRL (Thomaz & Breazeal, 2008), in this study, most of the participants did not succeed in teaching the robot the full cake baking sequence using feedback and guidance (the IRL condition). In Thomaz and Breazeal's study, the participants were knowledgeable in machine learning: when asked to rate their expertise in ML software and system (1=none, 7=very experienced), they reported an above average score ($M=3.7$, $SD=2.3$), but the population in the presented study was drawn from a more general public having little to no knowledge of machine learning ($M=1.8$, $SD=1.13$ - on a 5-item Likert scale). This can explain why a much larger number of participants did not achieve success with IRL in this study whereas Thomaz and Breazeal only reported 1 participant out of 13 failing the task. In our study, only 12.5% of the participants and the expert did manage to teach the robot using IRL.

As demonstrated by the teaching performance, most of the participants did not manage to reach a single success even during the teaching phase in the IRL condition. We identify the lack of control over the robot's actions as a limiting factor for the teaching, as participants did not manage to steer the robot to do correct actions, they could not reward them and teach the robot an efficient action policy. Additionally, the requirement of explicit feedback made the learning task more complex. Participants often did not reward an action after a guidance, assuming that informing the robot what it should do did not require an additional explicit reward. Teachers of robots need to have control over the robot's action and robots should also use implicit rewarding to ease the task for the teacher. For example, SPARC uses implicit rewarding by automatically providing a positive reward to actions selected by the teacher and also every action not corrected

by the teacher as it has been implicitly validated. This is consistent with Kaochar et al. (2011) who note that feedback is not well suited for teaching an action policy from scratch, but better for fine tuning. For teaching the basis of the action policy, they recommend using demonstrations, a method much closer to SPARC.

5.6.2 Advantages and Limitations of SPARC

In the implementation of SPARC for this study, the algorithm mostly reproduces actions selected by the teacher. One could argue that no learning algorithm is required, instead the actions could just be blindly reproduced by the robot. However, when combined with reinforcement learning, SPARC does provide advantages. As a state visited multiple times in an episode is considered as a single identical state for the learning algorithm, loops in the demonstrations can be removed for future executions of the action policy. Additionally, this provides the algorithm with a way to deal with variations in teaching. It allows the robot to reach a success from the initial state but also to continue the action policy from any state in the trajectory. And finally, due to the suggestion/correction mechanism, the teacher can let the robot act on its own only intervening when the robot is about to execute an incorrect action.

However SPARC also has limitations in the current implementation, related to the quality of the human supervised guidance. If the teacher allows an action to be executed by mistake (through inattention or by not responding in time), this action will be reinforced and will have to be corrected later on. This might lead to loops when successive actions are returning to a previous state (such as move left, then right). In that case, the teacher has to step in and manually guide the robot to break this cycle. Furthermore, due to the automatic execution of actions, the teacher has to be attentive at all times and ready to step in when a wrong action is suggested by the robot. This is a limitation as a lack of supervision can lead to undesired reinforcement of incorrect behaviours.

In this study, SPARC has been applied to a scenario where a clear strategy with optimal actions was present. The interaction also took place in a virtual environment with a discrete time and a limited number of states. Real human-robot interactions are stochastic, happen in real time and often there is no clear strategy known in advance, and as such present limited similarity with this study. However, in these real HRI, human experts in the application domain know what type of actions should be executed when, and which features of the environment they used for their decision. And, as

this knowledge might not be available to the robot's designers or could be complex to formalise in a set of rules a robot should follow, robots should be able to learn from a domain user in an interactive fashion. And this study presented a simple environment allowing us learn more about how humans could teach a robot using SPARC.

The limitations of this study (simulated deterministic world, limited number of state, discretisation of time and absence of interaction with humans) have been addressed in Chapter 6. In the study presented in that chapter, SPARC has been applied to a real-world social interaction with humans, possessing all the challenges typical to these interactions: complex non-deterministic world, with continuous time, real impact of actions and importance of the social factors in the interaction.

5.6.3 Lessons Learned on Designing Interactive Machine Learning for HRI

From observing participants interacting with both systems, we derived four recommendations for future designs of interactive learning robot that we also used to develop the study presented in Chapter 6.

Clarity of the Interface and Transparency

Algorithms used in machine learning often need precisely specified inputs and outputs and require an internal representation of the world and policies. These variables are often not accessible to a non expert: the weights of a neural network or the values in a Q-table are not easily interpretable, if at all. The inner workings of the machine learning algorithms are opaque, and people only have access to inputs and outputs of the black box that is machine learning. As such, care needs to go into making the input and output intuitive and readable. For example, in this study (following Thomaz and Breazeal's original study), the communication between the robot and the teacher occurred through the environment: using clicks on objects rather than a more classical Graphical User Interface (GUI) with buttons. This design decision had important consequences: as the interface is not explicit, participants first had to familiarise themselves with the interface, discover how to interpret the robot's behaviour, which actions are available for each state and learn the exact impact of the robot's actions. This lack of clarity led to a high number of failures and high teaching time during the first session in our study. So, we argue that to avoid this precarious discovery phase for the teachers, roboticists have to design interfaces taking into account results from the Human Factors community as advocated by Adams (2002), such as including the users in the design process or

finding intuitive ways to train teachers to use these interfaces.

Limits of Human Adaptability

Human-Robot Interaction today is facilitated by relying on people adapting to the interaction, often making use of anthropomorphisation (Złotowski et al., 2015). Roboticists use people's imagination and creativity to fill the gaps in the robot's behaviour. However, human adaptivity has its own limits: in our study, often participants adopted one particular way of interacting with the system and they held on to it for a large part of the interaction. For example, participants clicked on an object requiring two actions to interact with, assuming that the robot had planning capabilities which it did not. Or when the robot was blocked in some cycles (due to constant negative reward in and undo behaviour IRL or a loop created and not stopped with SPARC), participants kept on trying the same action to break the loop, without really exploring alternatives. For these reasons, if robots are to be used by a naive operator, they need mechanisms to detect these 'incorrect' uses, and either adapt to these suboptimal human inputs or at least inform the user that this type of input is not efficient and clarify what human behaviour is appropriate instead.

Importance of Keeping the Human in the Learning Loop

As argued in previous chapters, we think the presence of a human in the learning process is key. This human has the opportunity to provide important knowledge about the environment and allow the machine learning to deal with sensor errors or imperfect action policies. As in real world a robot's behaviour can hardly be perfect, keeping a human in the learning loop allows to continue improving the robot's behaviour even after an acceptable policy is reached. This is different to most of the Learning from Demonstration (LfD) approaches where the robot is left unsupervised to interact once an action policy is learned (Argall et al., 2009; Sequeira et al., 2016). This was one of the important points we considered when proposing SPARC: there is no distinction between a teaching and a testing phase, they are merged into a single phase, moving away smoothly from Wizard-of-Oz (WoZ) to Supervised Autonomy. The teacher can correct the robot when needed and let it act when it behaves correctly. In this study, participants used this feature of SPARC: many participants corrected SPARC only when required rather than forcing every action. For example, 37.5% of the participants even let the robot complete the task once without giving a single command before starting

the test to be sure that the robot was ready. This demonstrate that keeping the human in the learning loop is important to ensure that the robot’s behaviour stays appropriate; and this study demonstrated that SPARC allows human teachers to be actively involved in the teaching process without requiring important workload for them.

Keeping Teachers in Control

Most of the scenarios where a robot has to learn how to interact with humans are human-centred: the robot has to complete a task to help a human (such as SAR). In these scenarios, the goal of learning is to ensure that the robot can complete the task it has been assigned, not to provide the robot with tools to learn more efficiently in further interactions. Accordingly, participants in our study did not desire to have the robot exploring on its own and learn from its experience, they wanted to be able to direct the robot (see Section 5.5.3). In addition to reducing the effectiveness of the learning, a lack of control over the robot’s actions can lead to frustration and loss of motivation for the teacher as shown with the results of IRL in this study. This human control is especially critical when the robot is designed to interact with other people because undesired actions can have a dramatic impact, such as causing physical or mental harm for the interaction partners or bystanders. For these reasons, we argue that when designing an interactively learning robot for HRI in human-centred scenarios, it is critical to keep the human teacher in control.

However, this control does not mean that the robot cannot learn and become autonomous. We take a stronger inspiration from LfD, using human input more efficiently to guide the learning, speeding it up and making it safer, especially in the early stages of the learning. With SPARC the human is in control during all the interaction, but especially when the robot is prone to making exploratory mistakes, so that the teacher can prevent them before they occur. But once the action policy is appropriate enough, the teacher can leave the robot to interact mostly on its own, providing only limited supervision to refine the action policy.

5.7 Summary

As presented in Chapter 3, SPARC has been designed to allow naive humans to teach an action policy to a robot while maintaining an appropriate behaviour. This chapter presented a study where SPARC was combined with RL to teach a simulated robot to complete a baking task. SPARC used intentions communicated by the robot,

full control over the robot's behaviour and an implicit rewarding mechanism to allow participants teach the robot an action policy. A study involving 40 participants compared this approach with IRL, another IML approach using communication of uncertainty, partial control and explicit rewarding to teach the robot. When interacting with SPARC, participants took less time and fewer inputs to reach more successes, whilst facing fewer failures. Participants also reported a lighter workload when using SPARC than when interacting with IRL. This study, demonstrated that SPARC is usable by naive participants to successfully teach a robot an action policy quickly and safely.

Based on these results and our observations of the participants, we propose four guidelines to designing interactive learning robots: (1) the interface to control the robot should be intuitive, (2) the limits of human adaptability have to be taken into account (robots should detect deadlocks in human behaviours and adapt how they are controlled or inform the human about these incorrect behaviours), (3) the operator should be kept in the learning loop and (4) teachers should stay in control of the robot's behaviour when interacting in a sensitive environment (such as Robot Assisted Therapy (RAT)). The first two points can be seen to apply to all robot teaching methods, and should be addressed at the time of designing the interface. And, by definition, SPARC aims to address these last two points: maintaining the performance of an adaptive system by remaining under progressively decreasing supervision.

In summary, this chapter extended SPARC and compared it to other methods from the IML field. SPARC succeeded in its goal, allowing participants to teach easily and safely an action policy to a robot. Finally, insights from this study have been used to guide the design of study presented in Chapter 6, the final study of this research, which involves teaching a robot to interact with humans in real-world HRI.

Chapter 6

Study 3:

Application of SPARC to Tutoring

Key points:

- Design of an experiment to test SPARC in an educative application with children.
- Design and use of a new learning algorithm adapted from nearest neighbours to teach quickly and efficiently in an online fashion.
- Between participants study involving 75 children comparing 3 conditions: a passive robot, a supervised robot and an autonomous robot.
- Psychology PhD student teaching the supervised robot using SPARC.
- Similar children behaviours with the autonomous and supervised robot, and different with the passive robot.
- Demonstration of the applicability of SPARC to teach a robot online an action policy to interact with humans.

Parts of the work presented in this chapter have been published verbatim in Senft et al. (2017b) and Senft et al. (2018), additional publication are under review¹. The final publications are available from AAAI, EPFL via:

- <https://aaai.org/ocs/index.php/FSS/FSS17/paper/view/16011>.

¹Note about technical contribution in this chapter: the author extended code the freeplay sandbox, see <https://github.com/freeplay-sandbox/> and forks.

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- https://r41.epfl.ch/files/content/sites/r41/files/HRI2018/proceedings_2018/paper4.pdf.

6.1 Motivation

Chapters 4 and 5 tested the Supervised Progressively Autonomous Robot Competencies (SPARC) in interactions between robots or in a virtual world but not for human-robot interactions as it was intended to be used. As such, this Chapter addresses the thesis of this research and evaluates if SPARC can efficiently be used to teach a robot an interactive behaviour for real human-robot interactions. Human-Robot Interaction (HRI) in the wild typically occur in constrained but underspecified environments where social behaviours play an important role. This study takes place in the context of robot tutors for children in education. Tutoring is a framework widely used in HRI and providing opportunities for a rich and complex interaction between a child and a robot (Leyzberg et al., 2012; Kennedy et al., 2015). This scenario and the code are based on Lemaignan et al. (2017) but have been adapted to provide a new teaching task (teaching game and protocol), a knowledge test, a specific robot controller, a learning algorithm and an interface with the teacher supporting SPARC.

6.2 Scope of the Study

The main goal of this study was to explore the thesis proposed in this work: “A robot can learn to interact meaningfully with humans in an efficient and safe way by receiving supervision from a human teacher in control of the robot’s behaviour”. This thesis can be divided into two parts: “a robot can learn safely by receiving supervision from a human teacher” and “after learning, such a robot would have a meaningful interaction with humans”. To address these two statements, a study comparing three conditions was designed. In the control condition, the ‘passive’ condition, the robot is not interacting with the child during the learning task. This condition provides a benchmark against which the other conditions can be compared to evaluate the ‘meaningfulness’ and efficiency of the robot’s behaviour. In the second condition, the ‘supervised’ condition, the robot is being supervised and taught by a human teacher using SPARC. This condition is the one in which the robot learns, and can be used to evaluate the impact of the principles underlying SPARC when teaching a robot to interact with humans. Lastly, in the ‘autonomous’ condition, the robot applies the learnt policy to interact without supervision with the children. This condition aims at exploring how different the autonomous policy is from the supervised one, and evaluating if the teaching from the human was successful.

These conditions allow us to explore the statements presented above through three hypotheses:

- H1 The autonomous robot is able to interact socially and efficiently during the game sessions and maintain the child's engagement during the learning task.
- H2 An active robot (supervised or autonomous) supports child learning: learning gain in passive condition < learning gain in autonomous condition < learning gain in supervised condition.
- H3 Using SPARC, the workload on the supervisor decreases over time: the number of corrected actions and the number of actions selected by the teacher decrease with the progress in the sessions, while the number of correct actions increases.

6.3 Methodology

6.3.1 Participants

Children from five classrooms from two different schools in Plymouth were recruited to take part in the interaction. As both schools have an identical OFSTED evaluation (both school "require improvement"), all the children were combined into a single pool of participants. Full permission to take part in the study and be recorded on video was acquired for all the participants. In total, 119 children participated in the study, however not all of them have been included in the final results. Some participants took part in two pilot versions, with previous versions of the game or the protocol. For other participants, a breach in the protocol have prevented them to be included (such as freezing of the tablet due to an imperfect kernel version or refusing to continue the interaction). Additionally, children with special needs were encouraged to participate but were not included in the results. In the end, 25 participants per condition were included ($N=75$ in total; age: $M=9.4$, $SD=0.72$; 37F/38M). The remaining children in the classrooms interacted by pairs (and were not included in the evaluation) to accelerate the ending of the study, and free the room used in the school.

6.3.2 Setup of the study

Similarly to the study presented in Chapter 4, this study is based on the Sandtray paradigm (Baxter et al., 2012): a child interacts with a robot through a large touchscreen located between them and by interacting with the touchscreen and the robot, the child

is expected to gain knowledge or improve some skills. Additionally, a teacher can use a tablet to control and teach the robot in the ‘supervised’ conditions (cf. Figure 6.1). This type of potentially triadic interaction is typical of the interactions we considered when framing this research (cf. Figure 1.1). We desire an efficient behaviour for the robot in the application interaction (i.e. child tutoring) and a human teacher has knowledge about how the robot should behave and can transfer it to the robot *in situ* by using SPARC.



Figure 6.1: Setup used in the study: a child interacts with the robot tutor, with a large touchscreen sitting between them displaying the learning activity; a human teacher provides supervision to the robot through a tablet and monitors the robot learning.

By interacting with the robot and the sandtray, the child is expected to gain knowledge on a specific topic. For this study, the task is learning about food chains by exploring a specific food web (interconnections between multiple food chains) in an educative game. The child plays a game on the sandtray where they can move animals to discover the interactions between them. Learning is evaluated by a test before, after and between the sessions; and the robot guides the child through the study and can, depending of the condition, support them during the game.

6.3.3 Food Chain Game

The main learning activity to teach the child the food web is a game composed of ten animals and three types of plants. Animals have energy decreasing over time and they have to eat to stay healthy. Animals are not moving unless the child or the robot moves them and can eat or be eaten when entering in contact with another animal or a plant. The child has to feed the animals by moving them to their food to give them more energy and by feeding the animals, children can learn what the animals’ diet. Figure 6.2 presents an example of the game screen in the middle of a session.



Figure 6.2: Example of the game. Animals have energy in green and have to eat plants or other animals to survive. The child's task is to keep animals alive as long as possible.

6.3.4 Robot Behaviour

During the game, the robot can execute actions to provide hints and support to the child.

The robot has access to five types of actions:

- Movements: moving any animal to, toward or away from any items (animal or plant) - the robot points to an animal and moves it on the game while describing its action (e.g. "The eagle needs help getting close to the mouse").
- Drawing attention: the robot points an item and says a reminder to the child (e.g. "Don't forget the frog").
- Reminding rules: the robot says one of 5 sentences on the game (e.g. "Move the animals to feed them" or "Don't feed animals with a lot of energy").
- Congratulation: the robot provides congratulations (e.g. "Well done").
- Encouragement: the robot provides encouragement (e.g. "You can do it").

Considering all the possible combinations of actions and items, the total number of actions adds up 655. Additionally, to prevent the robot's behaviour to be repetitive and annoying, each utterance joining an action has multiple versions, and a random one not used recently is selected.

This set of actions has been selected to be generalisable to many type of scenario including a teaching activity on a screen. Furthermore, in this study, these actions represent different level of support, from general motivation and information on the game's goal to which animals the child should focus on or direct information about what an animal eats. This selection of actions aims to cover a large range of possible tutoring behaviours humans could use.

6.3.5 Wizard of Oz Application

In this study, the communication between the teacher and the robot occurs through the Wizard-of-Oz (WoZ) application, a Graphical User Interface (GUI) running on a tablet and allowing the teacher and the robot to communicate. This GUI represents the state of the game as the child sees it, but with additional button and functionalities to communicate both ways with the robot (see Figure 6.3). The teacher can use a combination of buttons and moving animals on the tablet to have the robot execute any possible action. For example, to move animals close to another item, the teacher can drag and release the animal's image to a position to request the robot to execute this movement. The robot controller will infer which action has been selected by the teacher by evaluating how the distances between animals change. Additionally, the teacher can select other animals or plants to clarify their action and give information about what features were relevant in the decision process. Similarly, the teacher can select an animal and press the 'Draw attention' button to have the robot point at the select animal and remind the child to use it. For instance, by clicking on the frog and the 'Draw attention' button, the robot will execute the *drawing attention to the frog*. This GUI design gives access to the teacher to the full 655 actions without requiring as many buttons.

Finally, the GUI is also used by the teacher to respond to the robot's propositions. Following the proposition of an action, a bubble describing the action will appear on top of the GUI, the corresponding items will be highlighted and if the action is a motion, an arrow will show the proposed motion. The teacher can react to the proposed action by pressing the 'Do it', 'Skip', 'Cancel' or 'Remove' buttons or let the action be executed. The action will be automatically executed after 2 seconds, during which the bubble will become greener to represent the passive acceptance of the action. The 'Do it' button executes the action straight-away, the 'Skip' button informs the algorithm that it

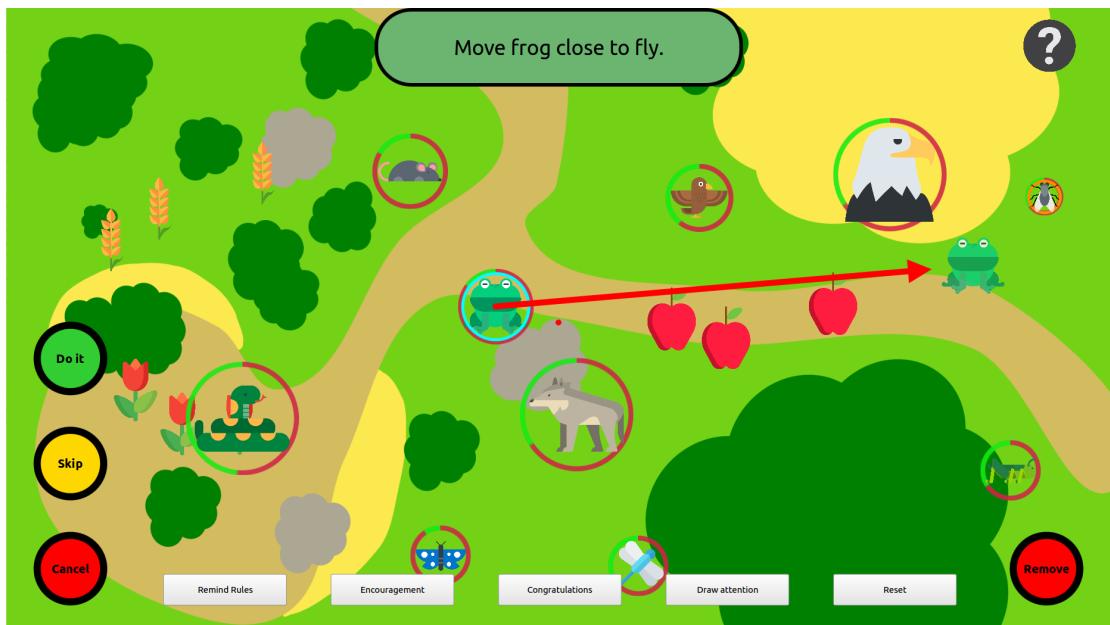


Figure 6.3: GUI used by the teacher to control the robot and respond to its suggestions. The game is in the same state as in Figure 6.2, and the robot proposes to move the frog close to the fly (text bubble, arrow, moving the shadow of the frog and highlight the frog and the fly).

should wait rather than doing the action, the ‘Cancel’ button assigns a negative reward to this action in that state and finally, the ‘Remove’ button looks for the closest previous instantiation of the action in memory and removes it, preventing this instance to be used later action selection.

6.3.6 Algorithm

The learning algorithm aims to reproduce the action policy by mapping an action (or no action) to each possible state. The state used in this study represents the situation of the game in a 210 dimensional vector, with value from 0 to 1. The dimensions include: distance between items, items’ energy, time since events (child and robot touching each animal, robot’s actions, interaction events: feeding an animal, death of an animal...), progression in the game sessions and child face direction (toward the robot, the screen or away). As mentioned before, the action space covers moving items in relation to other items, drawing attention to items, providing encouragements, congratulations and reminding the rules. In summary, the algorithm’s task is to map an action from the 655 (including a ‘wait’ action) to each possible combination on the 210-dimension state.

The actions and the state dimensions have been selected to be generic to many teaching tasks involving movable items: each item has a value assigned to it (here energy, but this could be changed in other scenario), and some movable items (here animals) can

be move to, toward or away from other items. Using these generic actions and this state definition, this implementation could be easily re-purposed to another teaching task.

The algorithm used for the learning is an adaptation of the one presented in Senft et al. (2017b). It is an instance based algorithm similar to the nearest-neighbours algorithm (Cover & Hart, 1967). However, two differences are notable compared to the initial algorithm. Firstly, instead of being defined on the full state space, instances are defined on a sliced version of the state. The intuition is that states needed to cover complex action policies require large number of dimensions, however for each single action, large parts of the state are irrelevant. For example, if a robot needs to pick-up a cup, the colour of the cup does not impact the optimal motion. In contrast, the colour matters if the robot has to answer the question: “which cup is on the left? The blue one or the red one?”. Consequently, the colour of the cup should be part of the state space, but should not be considered when selecting some of the actions. For this implementation, when selecting actions, the teacher can highlight features of the environment which *activates* specific dimensions of the state space which are used to store the instance in memory. By default, all the generic events (death, feeding, failed interaction) are *activated*. All the *non-activated* dimensions are left as wild-cards. Then, when comparing the current state to the saved instances, the distance is only computed on the *activated* dimensions of the stored instance. The second difference is that each instance saved has a reward assigned to it. For this study, if the teacher selects the action, the GUI assigns a reward of +1, and if the teacher cancels the action (following an incorrect suggestion from the algorithm) the reward is -1. When selecting an action, the algorithm looks through all the actions it has been using and for each action selects the closest instance to the current state and computes the expected reward as a multiplication of the distance by the reward. Then the algorithm selects the action with the highest expected reward and proposes it if the value is higher than an adaptive threshold.

The algorithm runs at 2Hz while we would expect actions to be selected every 5 to 20 seconds. So, unlike most of the discrete cases of action selections, in most of the steps no actions are required. To handle this difference of timescale, a waiting action has been added (through the ‘Skip’ button) and an adaptive threshold limits the propositions to actions with a high expected reward. Selecting an action can reduce the threshold, and cancelling or skipping an action can increase it. This aims to adapt the rate of action propositions to the desires of the teacher. A last mechanism filters propositions from

the algorithm not to transfer them to the teacher when an action is already proposed or the robot is currently acting. This filter also rewards negatively impossible actions (such as moving dead animals).

6.3.7 Study Design

The interaction protocol was as follows. Children were first introduced to the robot and the aim of the interaction and then had a first pre-test to evaluate their initial knowledge. Before starting the teaching game, children had to complete a tutorial where they were introduced to the mechanics of the game: animals have life and have to eat to survive and children can move animals to make them interact with other animals or plants and replenish their energy. After this short tutorial, they completed two sessions of the game where the robot could provide feedback and advices depending on the conditions they were in. Following these initial sessions of the game, children completed a mid-test before playing another 2 sessions of the game and a last post-test to conclude the study.

The study evaluated three conditions: the passive condition, supervised condition and autonomous condition. In all the conditions, the robot's behaviour during the introduction, tests, tutorial and conclusion was identical. The only change of behaviour happened during the games sessions. As the study design is between participants, children were each assigned to a condition, and in all the game session, the robot would be passive, supervised or autonomous.

In the *Passive* condition, the robot does not provide any advice nor feedback to the children during the game sessions. It only oscillates slightly to simulate a breathing motion and follows the child's face. In the *Supervised* condition, the robot is remotely supervised by an operator using SPARC. Finally, in the *Autonomous* condition, the robot applies the learnt policy and provides feedback and guidance to the child without human supervision.

In the study, the teacher was a psychology PhD student from the university, with limited knowledge in computing and machine learning. She has been instructed how to control the robot using the GUI, the effect of each buttons and how to perform each action. She was knowledgeable of the methodology used to run the study (but not the underlying implementation) and experimented controlling the robot in two interactions with the author interacting with the robot and one with a child before starting to supervise the robot for the supervised condition. No information about the learning algorithm or the

representation of the state and no feedback about optimal way of interacting or feedback on her action policy was provided before or during the supervision. As such, this robot teacher represents typical target populations for robotic applications: non-experts in machine learning or computing but with relevant domain knowledge such as teachers or psychologists.

In the *Autonomous* condition, the robot uses the suggestions from the algorithm and executes them with a probabilistic delay between 0 and 1.5 seconds based on the teacher's delay in answering the robot's propositions. This delay aims to give a pace and synchronisation of actions similar to the ones exhibited by the teacher when reacting to the robot's suggestion.

6.3.8 Metrics

To address the hypotheses presented in Section 6.2, we collected multiple metrics on both interactions (teaching and application). First, we recorded the actions executed by the robot in the supervised and autonomous conditions to characterise their action policies. Two groups of metrics have been collected to evaluate the application interaction: the learning metrics (corresponding to children's performance during the test) and the game metrics (corresponding to children's behaviour during the game). And finally, in the supervised condition, we recorded the origin of the action executed by the robot (teacher vs algorithm) and the outcome of the proposed actions (executed vs refused).

Policy Characterisation

During the game, the robot has access to 622 actions, which can be divided in seven categories: drawing attention, moving close, moving away, moving to, congratulation, encouragements and reminding rules. Due to this high number of actions, the largeness of the state space (210 dimension) and the complex interdependence between actions and states, totally defining a policy is impossible. Consequently, we decided to use the number of actions executed for each category per child to characterise the policy executed by the robot in the active conditions (supervised and autonomous). While not perfectly representing the action policy of each condition (e.g. the timing of actions is missing), this metric offers a proxy to compare these policies.

Learning Evaluation

The learning was evaluated through an open graph where children had to connect animals to their food. Figure 6.4 shows two examples of the test, with or without all the correct connections. Children were instructed to connect as many animals as possible. During the pre-test, the experimenter demonstrated how to connect animals by drawing an arrow from the frog to the fly, and then removing the arrow by pressing the *X* button. When children thought they were done, they could press the ‘Continue’ button, showing a screen asking confirmation to quit the test or allowing children to keep connecting animals. Additionally, the robot informed the child if not all the animals were connected to a food or that animals could eat many types of food if no more than one animal was connected to two items.

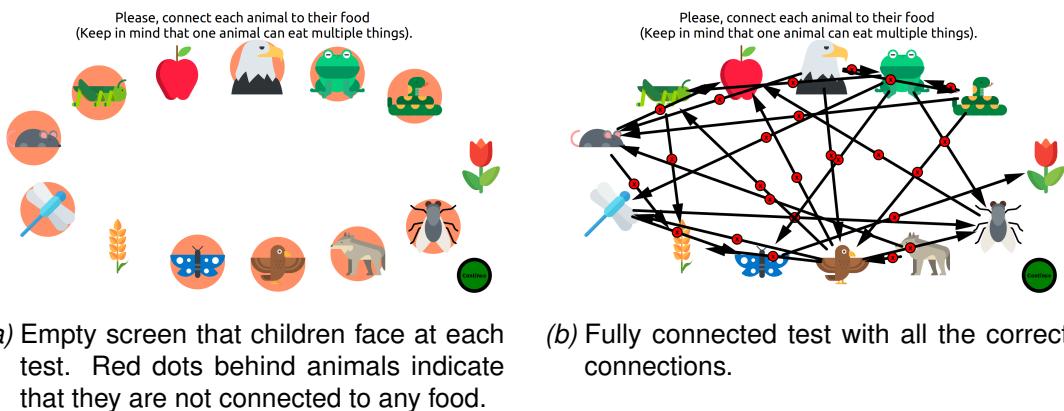


Figure 6.4: Test screen to evaluate children’s knowledge, empty starting screen (a) and fully connected and correct test (b).

They are in total 25 different correct connections and 95 possible incorrect ones. As the child can connect as many arrows as desired, the performance is defined as the number of correct arrows above chance (for the number of connected arrows on the test) divided by the maximum achievable performance to reach a score bounded to $[-1, 1]$. For example, if a child connects 5 good arrows and 3 bad, their performance would be:

$$P = \frac{\#good - (\#good + \#bad) \cdot \frac{\text{totalgood}}{\text{total}}}{\text{totalgood} - \text{totalgood} \cdot \frac{\text{totalgood}}{\text{total}}} = \frac{5 - (5 + 3) \cdot \frac{25}{25+95}}{25 - 25 \cdot \frac{25}{25+95}} = 0.168 \quad (6.1)$$

The three tests (pre, mid and post interaction) result in three performance measures. To account with initial differences of knowledge and the progressive difficulty to gain additional knowledge, we computed the learning gain as the difference between the

final and initial knowledge divided by the ‘progression margin’: the difference between the maximum achievable performance and the initial performance. This learning gain indicates how much of the missing knowledge the child managed to gain from the game.

Game Metrics

Different metrics have been gathered during the game sessions to characterise the children’s behaviours:

- **Number of different eating interactions:** number of unique feeding action type.
- **Points:** cumulated sum of animals’ energy over the game (typical range [550,1100]).
- **Interaction time:** Duration of game sessions, how long a game lasted until three animals ran out of energy (typical range [.5,3] minutes).

The number of different eating interactions informs on how many learning items the children have encountered in the games. A feeding interaction happens when an animal is moved to its food (or to a predator); and the number of different feeding interaction represents how many different correct connections the child been exposed to during the game (multiple feeding actions between the same animals would count only once). A game with a high number of different feeding represents a game where the child had the opportunity to learn many correct connections between animals. Consequently, by increasing this number, the children would be exposed to more learning items which should help them to perform better on the tests. Both the interaction time and the number of points reached in the game inform on the children’s success in the task: keeping the animals alive as long as possible.

Robot Learning

In the supervised condition, the robot executes actions selected or validated by the teacher, and by using SPARC, the robot can propose actions to the teacher. Faced with a proposition, the teacher has multiple ways to react. They can accept the action (by waiting for it to be executed, pressing ‘Do it’ or selecting the same action manually) or refuse it (by pressing the ‘Cancel’, ‘Skip’ or ‘Remove’ buttons). Actions can be divided in three categories: actions selected by the supervisor, robot’s good propositions and robot’s bad propositions. And the evolution of these categories represent how much the online component of the learning improves the quality of the robot’s suggestions and

reduces the workload on the teacher.

Some times the teacher cancelled actions and then selected them again, we called this effect the ‘reselection’. To obtain the final numbers of accepted and refused actions, we removed these reselection from the bad propositions and we added them to the good propositions as it represents cases where the teacher refused an action by accident.

6.4 Results

6.4.1 Comparison of Policy

Figure 6.5 presents the number of actions of each types executed by the teacher (in the supervised condition) and the autonomous robot. Both action policies present similarities: the action ‘Move away’ is almost never used, ‘Move to’ is never used, and the supportive feedback (‘Congratulation’ and ‘Encouragement’) are used more often than ‘Remind rules’ or ‘Drawing attention’. However, some dissimilarities are also present, for instance, the autonomous robot uses more encouragements than congratulations while the teacher did the opposite. The autonomous robot also reminded the rules more often and used the ‘Move close’ action less than the supervisor. These differences of actions are linked to the type of machine learning used; with instance based learning, some datapoints will be used in the action selection much more often than others, which explains this some biases. But these results show that the robot managed to learn a social and technical action policy presenting similarities with the one displayed by the teacher providing partial support for H1.

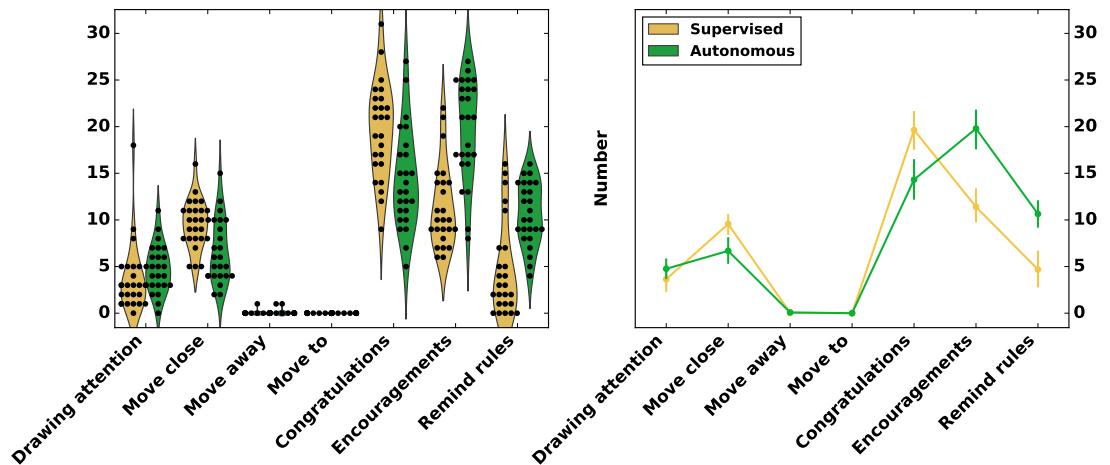


Figure 6.5: Comparison of actions executed for the autonomous and supervised condition. The left graph is a violin plot of the data, while the right presents the means and the 95% Confidence Intervals

6.4.2 Test Performance

Figure 6.6 shows the evolution of children's performance across the three tests. A Bayesian mixed-ANOVA show that in all conditions, children's performance increased across the tests ($B = 1.5 \times 10^{12}$), however the impact of the condition on the learning is inconclusive with a tendency to show no impact ($B = 0.539$). This indicates that by being involved in the task, every children learned and improved their performances on the test (by gaining in average 13% of the missing knowledge), but the robot behaviour during the game did not have an important impact on the children's learning gain (see Figure 6.7), invalidating H2.

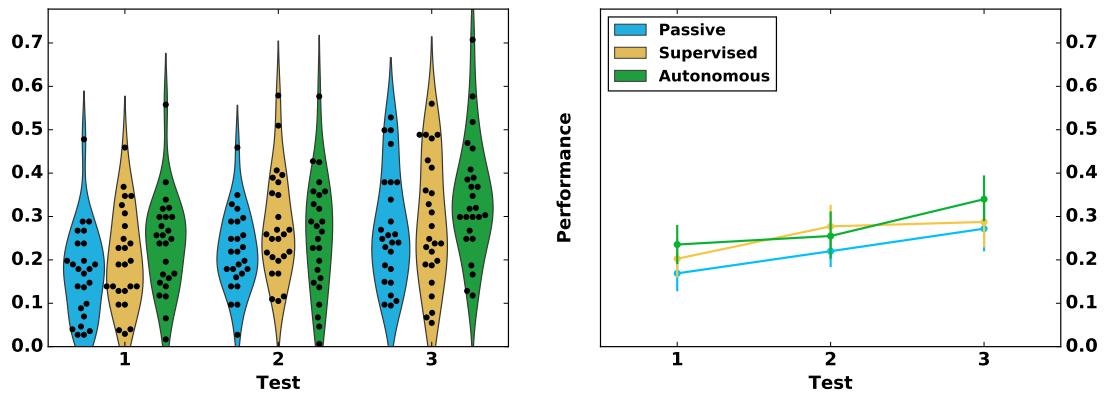


Figure 6.6: Children's performance for the three tests: pretest, midtest and posttest for the three conditions.

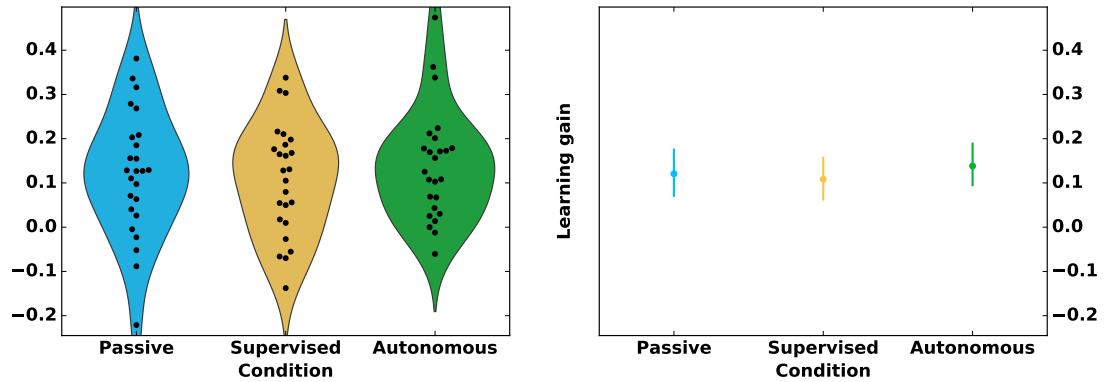


Figure 6.7: Children's normalised learning gain after interacting with the robot for the three conditions.

6.4.3 Game Metrics

Different eating behaviours Figure 6.8 shows the evolution of the number of different eating behaviours exhibited by the children across the four game sessions. A Bayesian mixed-ANOVA shows an impact of the condition on the number of different eating behaviours produced by the children in the game ($B = 6.1$). Post-hoc tests show

that there is no difference between the Supervised and the Autonomous conditions ($B = 0.154$), whilst differences are observed between the Supervised and the Passive condition ($B = 512$) and between the Autonomous and the Passive conditions ($B = 246$). This indicates that, compared to the Passive robot, the Supervised robot provided additional knowledge to the child during the game, allowing them to create more useful interactions between animals and their food, receiving more information from the game potentially helping them to learn. And the Autonomous robot managed to recreate autonomously this effect without the presence of a human providing input.

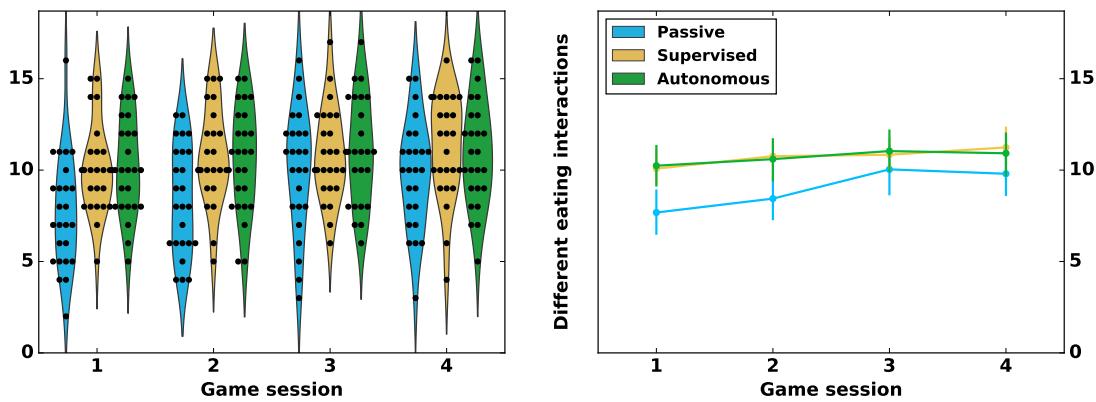


Figure 6.8: Number of different eating behaviour for the four games for the three conditions.

Points Figure 6.9 shows the evolution of the number of points achieved by the children across the four game sessions. A Bayesian mixed-ANOVA shows an impact of the condition on the number of points achieved by the children in the game ($B = 10.2$). Post-hoc tests show a strong difference between the Passive and the Supervised conditions ($B = 5.1 \times 10^4$) and differences between the Supervised and the Autonomous conditions ($B = 5.2$) and the Autonomous and the Passive condition ($B = 5.9$). This indicates that when the robot was supervised, it allowed children to achieve more points than a passive robot. And a similar effect is observed when the robot is autonomous, however the autonomous robot did not manage to reach the same efficiency as the supervised robot in helping the children to achieve a high score in the game.

Time Figure 6.10 shows the evolution of interaction time across the four game sessions. A Bayesian mixed-ANOVA shows inconclusive results on the impact of the condition on the interaction time in the game ($B = 1.1$). However, post-hoc tests show that there is no difference between the Supervised and the Autonomous conditions ($B = 0.287$), whilst differences are observed between the Supervised and the Passive

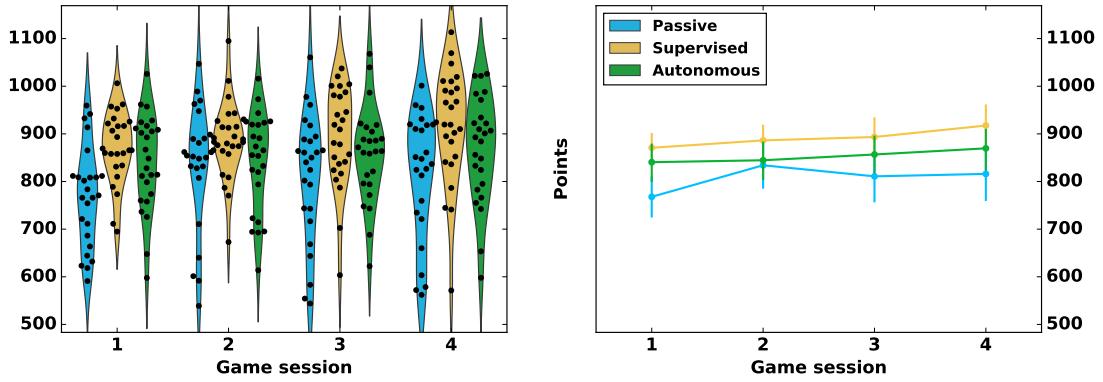


Figure 6.9: Points achieved by the children in each game session for the three conditions.

condition ($B = 118$) and a tendency of difference between the Autonomous and the Passive conditions ($B = 2.9$). This indicates that the Supervised robot allowed children to be better at the game, allowing them to maintain animal alive longer than a Passive robot. And the autonomous robot learned and applied a policy tending to replicate this effect and without exhibiting differences with the supervised one.

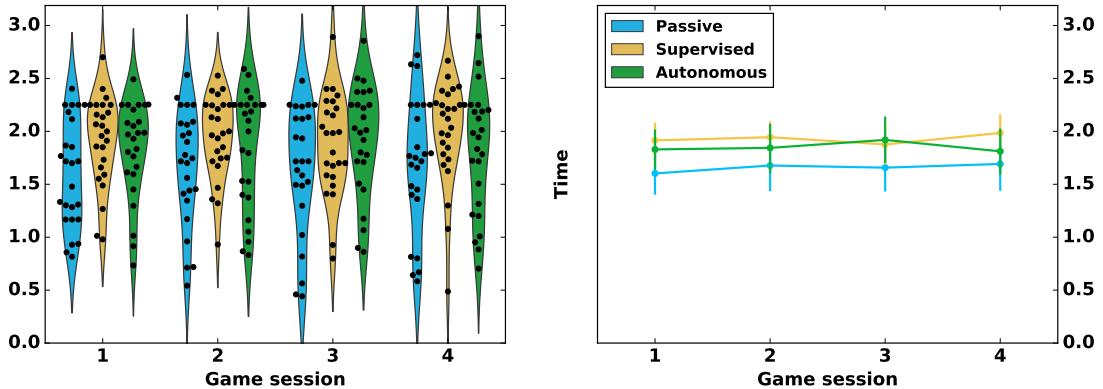


Figure 6.10: Interaction time for the four games for the three conditions.

Summary These game metrics show that the action policy executed by the autonomous robot allowed children to achieve similar results in the game than when the robot was supervised, and better results than when interacting with a passive robot. This provides support for H1 ("The autonomous robot is able to interact socially and efficiently during the game sessions and maintain the child's engagement during the learning task").

6.4.4 Teaching the Robot

Figure 6.11 presents the reaction of the teacher to the robot's suggestions across all the supervised sessions. In average the teacher accepted 22.3% of all the proposition of the robot, which represented 35% of all the actions executed by the robot and this

effect tended to be stable across the sessions.

In post-hoc discussion, the teacher reported three phases in her teaching:

- First sessions: she was not paying much attention to the suggestions, mostly trying to have the robot executing a correct action policy.
- Session 5 to around 16: she was paying more attention to the suggestions without giving them much credit.
- Last sessions: she started to trust the robot more but without ever trusting it totally.

I should add more about it... ES

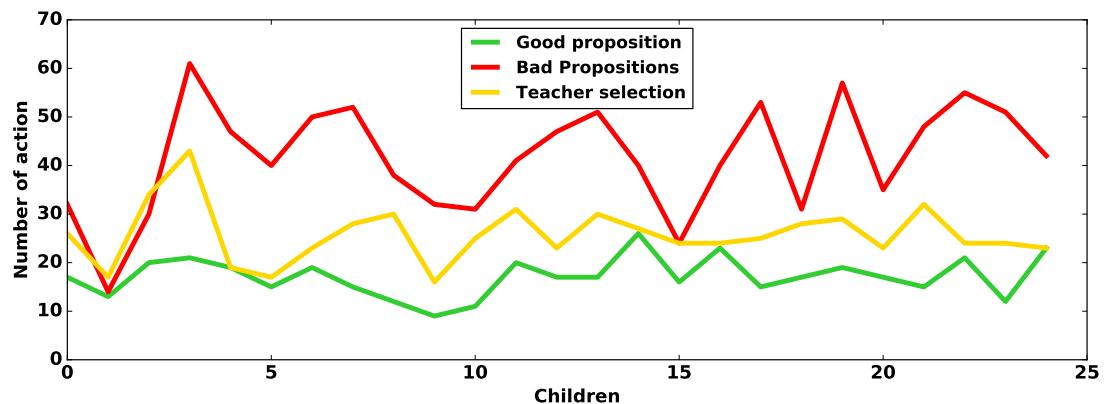


Figure 6.11: Summary of actions selection in the supervised condition: the ‘teacher selection’ label represents each time the teacher manually selected an action for the robot to execute.

The teacher did report a decrease of workload as she supervised the robot in more session. This is supported by behaviours such as typing her observations on a laptop, while gazing at the interface in multiple interactions (especially at the start of a session). However this decrease of workload seems to be due mostly to the teacher getting used to the interaction, and not to the online learning and the improvement of the suggested proposition, invalidating H3.

6.5 Discussion

6.5.1 Children Behaviours and Learning Gain

The active robot’s behaviours encouraged children to produce more ‘useful’ behaviours during the interaction. When interacting with the active robots, children encountered more situations with learning potential (such as the different eating behaviours). However, this additional exposure to learning items did not transform into an increase in

learning gain. In the three conditions, the children learned similarly; thereby not supporting H2. We identified two possible roots for this absence of transfer between positive game behaviours and performance in the test. The first one is that the game by itself, without the robot, encourages the children to explore. Children can learn solely from interacting with the game; consequently, the robot behaviour might distract children from their exploration. In that case two effects might cancel each other: on one hand the robot's behaviour provides additional knowledge to the child, but on the other hand active robots perturb their exploration of the game. This could result in the absence of effect of the robot's behaviour on the children's performance. The second possible origin would be in the test itself. The test only asked children to connect as many animals as possible, but children might have stopped connecting before showing all the knowledge. Accordingly, this way of testing children might not encourage them to demonstrate their exact knowledge. Having forced questions, for instance selecting randomly 20 connections and ask children if they are valid, might have provided a clearer evaluation of the children's knowledge.

6.5.2 Robot Learning

One of the motivation of SPARC is that it provides a way to smoothly move away from WoZ. By learning online the action policy, the number of actions selected or corrected by the teacher would decrease and the number of accepted suggestion would increase, hence reducing the teacher's workload. However, this expectation (and by extend H3) was not validated by this study's observations. The number of action accepted, refused and selected by the teacher stayed roughly identical throughout the interaction. One of the reasons identified was that the robot proposed a large number of actions (58% more than the total number of executed action). This indicates that the adaptive threshold selecting actions to be proposed was constantly too high. This high number of proposed actions partially explains the high number of actions refused by the teacher. As the robot tended to propose actions too often, the teacher reached a point in her supervision where she almost constantly refused the robot's propositions even in cases when they were correct. Another effect limiting the correctness of the proposition is the evolution of the teacher's policy. As the teacher progressed in the interactions, she started to evolve her action policy, adapt it to the child, using more and more different actions. As the algorithm could not predict actions not selected yet by the teacher, this lead to a requirement on the teacher to select new actions. Additionally, this limited the maximal

performance achievable by the algorithm. Toward the last interactions, the number of different actions used by teacher tended to converge, this indicates that the algorithm might have achieved better results in the following interactions.

This study also stands out on another point compared to classic problems using Machine Learning (ML). In this study, the agent (the robot) interacted in a continuous time, whereas generally agents in ML only exist in a discrete time. In discrete time, generally, an action has to be selected at each step, actions last one step, and optimal strategies can exist. However, when interaction in real time, actions take many steps and in most of the steps no action should be selected. Additionally, due to the continuous side of the time, actions are not valid at a specific step, but around that step. This imply that to reduce the teacher's number of selected actions, the algorithm does not have to select the same action as the teacher at each step, but needs to anticipate the teacher's actions, so that the teacher does not select them first. Such a requirement for the algorithm limits the visibility of results. The algorithm might selected correct actions around the time the teacher would select it, but if that proposition arrived a step after the teacher's selection, it would not be considered as a good proposition.

Nearest-neighbours is an algorithm sensitive to outliers [cite^{ES}](#), consequently, some instances in memory could be used too often, leading to an imbalance of policy (as observed when comparing the autonomous and supervised policy). One of the way to tackle this issue could be to the k nearest neighbours rather than only the closest one, this might have led to a more robust learning algorithm.

[limit of use of feature selection in the study^{ES}](#)

[difference of state feature accessible to the teacher and robot: temporality and verbality for example^{ES}](#)

[with more training data, and an algorithm addressing the fixable issues, the autonomous policy and the supervised ones should become closer and the workload on the teacher might decrease as the robot learns^{ES}](#)

In such complex tasks, humans are making use of a large number of undefined [ASK MADDIE^{ES}](#) 'states', especially temporal relations to select actions, and if the state definition the robot uses does not contains or cannot deal with these features, the learning will be limited.

While the autonomous behaviour is different from the taught one, it still presents many similarities in the distribution of actions executed by the robot and the children's reaction to this behaviour. More training data and a better learning algorithm should even smoothen this difference of behaviour between the supervised and the autonomous robot.

6.5.3 Importance of the Teacher

SPARC includes two distinct but simultaneous human-robot interactions. Thus, evaluating such interconnected interactions is a complex task: each human's behaviours will impact the other one. To explore a in a repeatable and comparable manner an interaction, the other one needs to be as constant as possible. However, humans are not constant and consequently evaluating these two interaction simultaneously is a challenge. By deciding to keep the same teacher for all the interaction, we only have a sample of one participant as a robot teacher. This could create some biases in the supervision, but as the teacher was not aware of the learning mechanism used for the robot and was not provided feedback on how to interact with the robot, these biases are limited. But, in essence, this is a case study of one participant teaching a robot. It would have been interesting to try distinct teachers and observe how their different behaviours would impact the learning process and the final policy. We would expect that the resulting autonomous should match the multiple teachers' policy. However due to the number of children required to train and test the robot, we could not explore this axis.

6.5.4 HRI are Human Centred

When a robot is supervised to interact with a human, and especially with a child, the main goal of the teacher is to ensure the experience for the child is optimal. Consequently, the teacher will be more focused on the child's behaviour than the robot learning. For instance, if an action would help the child but hinder the learning for a reason (for example an unusual child behaviour), the teacher will 'damage' the robot learning to improve the child experience. Teaching the robot will always be only a side activity or a by-product of the interaction.

Furthermore as children are different, and as the teacher adapts their policy to the specific child involved in the interaction, resulting not in one single policy applied to all the children but potentially to one per child. This is a challenge for ML as the complexity

of the task increases, the algorithm either have to learn a much larger action policy (covering all the different types of children) or learn a multitude of policies and be able to switch between them. Additionally, some of the feature used by the teacher to decide which type of policy to apply might not be available to the algorithm (for instance temporality or verbal utterance in our case). This implies that the algorithm might have different outputs for the same inputs, complexifying the learning process.

6.5.5 Opportunities

careful with overlap between this discussion and the final one^{ES}

Despite the limitations of this implementation of SPARC, this study demonstrated the first application of SPARC to real HRI. A robot learned to interact efficiently with humans from in-situ supervision. Would that be the first time?^{ES} The autonomous robot produced an action policy similar to the one demonstrated by the teacher in the supervision, and the effect on the children were similar too (improvement of game metrics compared to a passive robot). This supports H1: the autonomous has been able to interact socially with children and sustained engagement during the task (as demonstrated by the higher number of points and interaction time compared to the passive condition). This is an important contribution as the robot learned to interact in a complex task in real world, including large state and action spaces and where errors could have an important cost on the interaction, potentially leading to a child refusing to continue the interaction.

Furthermore, this achievement also used a teacher without knowledge in robotics or ML. This encourages the use of SPARC by a large part of the population and by extend increase the potential of people able to teach robots complex behaviours. This might help to reduce the entry bar of interaction with robots: if people do not need to know robotics or how to code to teach a robot a social behaviour, it may help to democratise the use of robots. While not have been explicitly demonstrated in this study, SPARC can also teach different behaviours using the same algorithm and state representation. Different teachers would teach the robots in dissimilar ways, therefore, the resulting autonomous behaviour would be different and would represent the teacher's policy. SPARC can be a way to allow non-expert in robotics to personalise their robot, to have it learn to behave in the way the each desire.

Even if the online learning did not reduce the teacher workload much through the interactions, SPARC possess two advantages compared to offline learning from WoZ

data using Learning from Demonstration (LfD) (Sequeira et al., 2016; Liu et al., 2014). Firstly, the learning algorithm has access to more datapoints: the teacher's selection but also their reaction to the algorithm propositions. Secondly, by receiving feedback about the algorithm's knowledge, the teacher can create a mental model of the robot and have an idea of how accurate its action policy is. Furthermore, by interacting with the learning algorithm, the teacher can start building a trust grounded by their experience with the learner, potentially knowing its strengths and weaknesses. And this teacher's knowledge of the learner states can ease the decision of deploying the robot to interact autonomously as the teacher experienced the policy and knows what to expect from the algorithm.

6.6 Summary

To conclude, this study proposed a new task for robot tutoring: a learning game to teach children about food webs, and most children involved in the study learned and improved their knowledge through the interaction. Additionally, for the first time in this research SPARC has been applied to teach a robot to interact with humans. By using a novel algorithm adapted from the nearest-neighbours designed to learning quickly in multidimensional states, the robot learned to produce a behaviour similar to the teacher's one. Furthermore, this teaching was performed by a user not expert in ML or robotics. While not leading to improvements in the children's learning gain, the behaviours from both the autonomous robot and the supervised one did improve the performance of the child in the game.

In summary, by this study we provided partial support for the main thesis of this research: "A robot can learn to interact meaningfully with humans in an efficient and safe way by receiving supervision from a human teacher in control of the robot's behaviour." And, while presenting limits in the current versions (for instance by not reducing the teacher's workload over time), SPARC succeeded in its goal to allow a user non-expert in computer science to safely teach a robot to interact with a human.

Chapter 7

Discussion

Chapter 2, put the light on the absence of robot controllers today providing adaptivity to a robot with a low workload from humans and while ensuring that the robot's behaviour is constantly appropriate. Based on this observation, Chapter 3 presented the Supervised Progressively Autonomous Robot Competencies (SPARC), an interactive teaching framework designed to allow robots to learn a social interactive behaviour by begin supervised by humans. Then Chapters 4, 5 and 6 evaluated this approach in three studies, the last of which evaluated SPARC in real Human-Robot Interaction (HRI) consisting of a learning activity involving 75 children. Combined together, these chapters sought support for the thesis of this research:

A robot can learn how to interact meaningfully with humans by receiving supervision from a human teacher in control of the robot's behaviour, this supervision will lead to an efficient, safe and low human-workload teaching and autonomous behaviour.

This chapter will combine the results from the different studies presented in this research to discuss the findings and will start by presenting the limitations of the approach proposed in this work, SPARC, and of its evaluation in the three studies. Ethical questions raised when humans teach robots to interact with humans will be discussed in Section 7.3.4, and Section 7.3 will presents the potential impacts of this research. Finally, the last section will propose axes where SPARC could be extended to increase its usability and application to HRI.

7.1 Limitations

7.1.1 Limitations of SPARC

SPARC, as presented in Chapter 3 presents several limitations restricting the range of domains it could be applied to.

The first of these limitations is the requirement of a human to supervise the robot, even once it has learned an action policy. As stated earlier, SPARC aims to move away from Wizard-of-Oz (WoZ) or other tele-operation method by learning an efficient action policy from the human commands. In its original framing, SPARC did not aim to create a fully autonomous agent behaving without supervision, but to smooth the teaching phase and the use phase in one single interaction using Supervised Autonomy. In this single phase, the workload on the supervisor would decrease as the robot learns while a high performance in the domain application would be maintained. However, Supervised Autonomy still requires a human involved in the supervision and as such presents limited applicability where robots are expected to fill gaps in human workforce or to reduce the requirements on humans.

Despite not being the original goal, and as demonstrated in Chapter 6, SPARC can still be applied to create a fully autonomous behaviour. In that case, the training process would be similar to Learning from Demonstration (LfD), with a training phase using SPARC and then the testing/deployment phase of the autonomous behaviour. However, by using SPARC two differences remain. During the training phase, instead of passively receiving commands from the teacher, the robot would proactively make suggestions to the teacher. As presented in Section 6.5.5 this aims at reducing the workload on the teacher during the training phase, would provide more datapoints for the learning and would inform the teacher about the state of robot's knowledge, potentially creating trust between the robot and its teacher. Furthermore, even after being deployed to interact autonomously, the teacher could still step in using SPARC to refine the action policy, or if a different behaviour has to be applied (e.g. if the robots interact with a child with special needs rather than a typical one), the teacher can take over using Supervised Autonomy to ensure a personalised for this specific interaction.

A second limitation of SPARC corresponds to the constant need for the human's attention. Throughout this research, we assumed that even if the robot behaviour may be mostly correct, the supervisor would be attentive to the robot suggestions and ready to correct them at any time. This assumption is similar to autonomous car using safety driver or the 'AutoPilot' of Tesla requiring constant human supervision^{ES1}. The agent is fully autonomous but may make mistakes and as such, a human needs to be ready to correct these errors before they impact the world. However, as demonstrated by the accidents in

¹ES: maybe not

2017 and early 2018 involving these supervised autonomous vehicles, this assumption is often violated, and a short moment of inattention may have dire consequence². By observing seemingly correct agent's behaviour, the human supervisor might start to overtrust the agent, missing the occasion to react in time to anticipable errors potentially leading to frustration or death in the case of autonomous vehicles [obvious but ref?ES](#). Some ways exist to potentially mitigate this limitation. For example, with Supervised Autonomy the agent informs in advance the supervisor about its actions, similarly a car could display the planned trajectory. This would provide the supervisor with more time to analyse the situation and potentially allowing them to react in time. Alternatively, the agent could communicate a lack of confidence in its actions or its interpretation of the environment, informing the supervisor that attention is specially required in that moment.

Similarly, as pointed already in Section 3.4.1, with SPARC, the presence of the correction window and the auto-execution of actions lead to several issues. To be applicable and make use of the auto-execution of actions as a way to reduce workload, the validity window of an action needs to be wider than its correction window. That way, actions approved passively are still valid when executed. To increase the application of SPARC to a wider range of application, the correction window has to be as narrow as possible. In contrast, the supervisor needs a correction window as wide as possible, to provide them with enough time to process the action and cancel it if required. Correction windows too narrow would put additional pressure on the supervisor to react in time. To cope with this additional time pressure, the supervisor might find ways to prevent the suggestions of actions or simply refuse each action proposed by the robot. This results in two effect having opposite requirements on the correction window. This need of a correction window wide enough to allow the teacher to react is probably one of the main limits of SPARC. Providing the teacher with enough time to correct undesired actions impacts the usability of SPARC. One way of mitigating it, could be to adapt the time window to the type of actions executed or to the algorithm's confidence in the validity of actions or allow the teacher the duration of this correction window. As such, specific actions with a short validity window (such as emergency breaking for autonomous vehicles) could be executed in time; and actions the robot is unsure about would be given more time to be corrected.

²As reported by media in early 2018

Another risk with SPARC is overloading the supervisor with suggested actions. If the supervisor has to correct more actions than it would have selected, the workload is not reduced but increased. While still providing useful information for the learning algorithm (and more than only the actions selected by the supervisor), this supplementary workload on the teacher is not desired. The algorithm needs to adapt the rate of suggestion to the pace of the interaction not to overload the teacher.

A last limit of SPARC is the interface between the learning algorithm and the teacher. Other Interactive Machine Learning (IML) methods using only feedback require a single scalar to evaluate actions and the communication needs to be only one way: from the teacher to the robot. On the other hand, to provide full control and accountability on the robot's actions, SPARC requires a way to inform the teacher about the robot intention and allow them to pre-empt actions. Furthermore, the teacher needs to be able demonstrate any action the robot should do, they require a way to transmit any action to the robot. As the robot may have access to hundreds of actions, assigning one button per action is not feasible, other ways of commanding the robot need to be found. Furthermore, as mentioned in Chapter 3, with SPARC the teacher can also provide additional information to the algorithm to speed up the learning. In summary, the interface between the robot and the teacher needs to provide the teacher with the robot's intention, allow the teacher to pre-empt actions, select any action and provide additional information to the learning algorithm. An interface providing all these features can easily be bloated and difficult to use by humans, increasing even more the required workload to control and teach the robot. For applying SPARC to complex environments, efforts need to be invested in the interface to make it intuitive and clear. For instance, in Chapter 6, the Graphical User Interface (GUI) used by the teacher represents the game, with some buttons for a sub part of the action set, but the majority of actions is inferred by the way the teacher move items on the screen and the items selected. An alternative way could be to use natural language. Humans are expert in using natural language to communicate and the open-endedness of this tool makes it suited for applications of SPARC where the teacher can speak and the time required to vocalise commands is not critical.

Need to be sure that all these limitations are mentioned in the corresponding parts^{ES}

7.2 Research Questions

RQ1 **What are the requirements of a robot controller to ensure a behaviour suited to HRI?**

Based on a review of the different fields of application of social HRI, we defined three requirements a robot controller should follow to ensure an efficient interaction. First and foremost, the robot's behaviour needs to be constantly appropriate: as robot often interact with vulnerable population, their behaviour needs to be constantly safe for the human interacting with the robot. Secondly, the robot should be adaptive, be able to generalise to unexpected situations, but also personalise its behaviour to the different humans it interacts with and be able to learn to improve and extend its action policy. Finally, the robot needs to be as autonomous as possible, or at least require a low human workload to interact in the world.

RQ2 **What interaction framework would allow a human to teach a robot while validating the requirements from RQ1?**

To validate the three principles expressed as answer RQ1, we proposed SPARC, a new teaching framework for robot which provides control over the robot's actions to a teacher and use this control to learn in a safe way, validating the first and second requirements. Secondly, by allowing the teacher to passively accept robot's proposition, we aim to decrease the workload on the teacher over time and progressively provide the robot with autonomy.

RQ3 **Could a robot decrease its supervisor's workload by learning from their supervision?**

Study 1 showed that providing a supervised robot with learning can reduce the workload on its supervisor. Furthermore, study 2 demonstrated that, compared to other methods, SPARC is an efficient way to enable a safe teaching and requires a comparatively low workload.

RQ4 **How providing the teacher with control over the learner's actions impacts the teaching process?**

Results from study 1 and 2 indicate that by informing the teacher in advance of its action, the robot ensures that its final behaviour will be correct. This implies that even in early phases of the learning, when the robot behaviour is not adequate yet, the teacher can prevent the robot's lack of knowledge to negatively impact the world. Furthermore, this control improve the teaching process by making it faster, safer, more efficient and lighter (as requiring a lower workload) than other methods lacking control.

RQ5 How teaching a robot to interact socially impacts the two humans involved in the overall triadic interaction? When being used to teach a robot to interact with a human, SPARC does allow the robot to constantly have an efficient behaviour (as demonstrated by the improvement of children's behaviours in the supervised condition in Chapter 6), but potentially might depending of the conditions increase the workload on the teacher compared to a classical WoZ. As the teacher needs to react to the robot's suggestions, they do have to monitor more autonomous agents.

RQ6 After receiving supervision from a human, could a robot behave autonomously in a social context? In Chapter 6, we used SPARC to teacher the robot in the supervised condition, and then deployed the robot to interact autonomously. During this autonomous interaction, the robot did apply a policy similar to the demonstrated one, and the impacts on the children's behaviour were close to. Consequently, in this study, the robot could behave socially in an autonomous fashion after having been supervised.

7.3 Impact

7.3.1 Teaching Robot to Interact with Humans

With SPARC we proposed a new way to teach robots to interact with humans. By following the principles presented in Section 3.2, a teacher can safely teach a robot an action policy suitable to interact with humans. This method provide a robot with an adaptive policy while ensuring the its behaviour is constantly appropriate. Furthermore, with the combination of proposition, correction and selection of actions, SPARC aims at reducing the workload on the teacher. Hence, this approach would be fit to control robots in HRI as it follows the requirements presented in Section 2.1.2. And, as demonstrated in Chapter 6, when applied to a real HRI, SPARC provided the robot with an efficient social action policy.

By demonstrating its applicability to teach robots to interact with humans from in-situ supervision, SPARC opens new opportunities to provide robots with action policy complex to define or not known in advance. Providing robot with the capability to learn to interact with human might allow robots to be deployed in new contexts where they are absent today.

7.3.2 Empowering Non-Experts in Robotics

By allowing end-users non-expert in robotics to teach a robot how to interact, SPARC provides an opportunity for anyone to personalise their robot. If combined with efficient interfaces and learning algorithms, approaches such as SPARC have the potential to democratise the use of robotics by allowing anyone to teach a robot to interact efficiently in a wide range of domains. Robot developers and designers can use this learning ability to deploy robots as *blank slate*, with just a way to perceive the world and act on it, and their behaviour could be defined by anyone. Users would start filling this blank slate with how they want their robot to behave, teaching their robot how to fulfil their personal needs.

7.3.3 Robots and Proactivity

Another way to interpret SPARC is a sa way to provide proactivity to a robot. By using Machine Learning (ML) and proposing to execute actions, the robot is actually taking the initiative to do an action without executing it straight-away. Proactive robot assistant would anticipate their user's needs and desires and would reduce their workload. By having the capability to learn new actions, or what action they should do, they would be adaptive companion able to solve a large quantity of tasks. Finally by informing the surrounding humans of their actions, such robots would only execute action deemed safe by their users.

7.3.4 Ethical Questions

Having robots interacting in human environment and being able to teach them to behave raise multiple ethical questions.

The first one concerns people's jobs. Throughout robots and machines history, many jobs have been automated and more are expected to disappear in the next years (Frey & Osborne, 2017). As such, deploying robots in social environments, such as education or care facilities, might lead teacher or social worker to fear for their jobs. However, in many of such social environments with no direct quantifiable return on investment, workforce is already lacking (e.g. nurses in the US; Nevidjon & Erickson 2001) and this shortage is expected to grow in the future. Consequently, robots provide an opportunity not to replace a workforce already in shortage of workers, but on the other end to support them in their job, making these jobs safer and more pleasant for the workers or

providing additional support for the clients or patients (Belpaeme et al., 2012)[not sure^{ES}](#).

However, the community as a whole needs to be aware of these fears and ensure by their work that robots have a positive impact on society.

The second question is privacy. As robots interact with the general population, and especially learn from and about them, issues concerning privacy arise. To have meaningful interaction with users, robots need to collect information about them, and the type of information collected, the storage and the use by third parties has to be carefully considered before deploying a robot. This effect is further increased when robots learn from humans, robots are not any more passively collecting data, but the interaction itself aims to gather more information about the user, about their preferences, their desires and their needs. Finally, this effect is amplified when interacting with vulnerable populations. As robots are expected to take an important role in education and care, humans interacting with them will tend to children or patient, and as they might not be able to ensure their privacy, this issue has to be considered beforehand. The question of sharing these information and this knowledge between robots and beyond, to the manufacturer or to the governments, needs to be addressed.

A last concern resides in the responsibility for actions executed by the robot. In a mixed-initiative interaction when both the autonomous agent and the human supervisor can impact the robot action policy, the responsibility of actions is complex to analyse. This effect is even increased when the robot can learn from its user. In that case, the role of the company or the entity distributing this robot and the role of the user have to be considered when looking for a legal entity accountable for the robot actions. To have this clearer accountability, Artificial Intelligence (AI) applied for robotics needs to be more transparent (Wachter et al., 2017).

7.4 Future Work

The work conducted in the thesis explored how robots could be taught to interact with humans and proposed a novel interaction framework, SPARC, to enable such a learning. However, SPARC could be extended in many ways and its principles applied to other applications.

7.4.1 Application Domains

Through this thesis, SPARC has only been applied to HRI in the context of tutor robots, to teach them to support child learning. However, the principles underlying SPARC could be applied to a much wider ranges of application in robotics and other AI. In robotics, SPARC would show promises in numerous fields of social HRI from assistant robot at home to collaborative robotics including robots in hospitality, military or industry. For example a robot could learn the preferences of a user and act as an embodied personal assistant, connected to devices in the house, calendar on the internet and supporting its users in routine tasks. Such a robot could learn to anticipate its user's need and propose to provide support proactively. In Human-Robot Collaboration (HRC), similarly to the work presented in Munzer et al. (2017), a robot could learn its partner preference, informing them of its actions and help them to complete the task faster. As explained in Feil-Seifer & Matarić (2005), IML approaches, and by extend SPARC, could be applied to classification tasks, maintaining the user informed about the state of the algorithm's knowledge and involving them in the learning process. For example, for semi-supervised image classification, the algorithm could automatically present a subset of classified images between learning steps to the user who could step in when a misclassification happen. In this case, where incorrect actions have limited impacts, the correction can happen in hindsight, as proposed in Chernova & Veloso (2009). Alternatively, the principles of SPARC could be also used to support agents using Reinforcement Learning (RL) in the real world. The supervisor could provide a safeguard preventing the agent to make errors, bringing it back to the correct parts of the environment or guiding the agent to relevant actions or features in complex environments.

7.4.2 Learning Beyond Imitation

rephrase^{ES} Another potential feature of SPARC, and other methods based on demonstrations, not evaluated in this research is reaching capabilities beyond the demonstrations. SPARC uses demonstrations and corrections from a human teacher to learn. By applying Supervised Learning (SL), the optimal outcome would be to match the teacher's performance. However, if the algorithm learn a value function or the teacher's goal, instead of reproducing the teacher policy, the agent could learn around the demonstrated policy and potentially become better than the teacher themselves. This capability

has been reached in Abbeel & Ng (2004), by using Inverse Reinforcement Learning. The agent learns a reward function from the human demonstrations and then, by applying RL around the demonstrated policy, the agent improves beyond the demonstrations and reaches super-human capabilities. Similarly to their methods, using the shared control provided by SPARC, a robot could interact under supervision, progressively proposing action to the supervisor. And the teacher could still direct the exploration, preventing the robot to reach dangerous parts of the world, while being open to better propositions than the ones expected. An example could be an agent learning a game such as under supervision, which could propose moves to a human player. That way, the agent could propose moves the human would not have thought about, and then the human could let them be tried or if they appear to risky, override them.

However, to reach these super-human behaviours, the agents requires a way to learn in addition to the human. The agent needs to have access to a second level learning, such as a reward function directly from the environment or learnt from the human demonstrations (such as with Inverse Reinforcement Learning). Alternatively, the agent could learn in simulation, only using the human supervision when acting in the real world to prevent potential mistakes.

7.4.3 Sustained Learning

In the two first studies presented in this research, the robot learn an action policy from a short term interaction (inferior to 25 minutes). In contrast, robots deployed to interact with humans on a daily basis will learn over much longer periods of time. This aspect, repeated learning, has been partial explored in Chapter 6, where the robot learns through 25 sessions. While progressing toward repeated learning, this study did not explore the challenges of life long learning (Thrun & Mitchell, 1995). For example, the STRANDS project Hawes et al. (2017), explores this challenge by deploying a learning robot for week-long continuous autonomous operation. In the current implementation, the temporal aspects of the interaction were taken into account only by being included in the state definition. However, to sustain continuous long term interaction, spanning multiple hours or days, the dependence in time of the action policy will have to be taken into account through other means. Additionally, the learning algorithm will have to scale to handle a constantly increasing number of datapoints (a feature not present with instance based learning).

Learning from humans but also when they are not here to teach^{ES}

7.4.4 Teacher Interface

Another axis to improve SPARC is the interface with the teacher. As mentioned in the previous section, one of the main limitation of SPARC is also what provide SPARC its strength: the inclusion of a human in the action selection process. Including this human and giving them the opportunity to pre-empt actions and select any actions come with limits the environments where SPARC is applicable. The robots needs to communicate its intentions and the human needs enough time to correct them before they impact negatively the environment or the humans interacting with the robot. Despite these limits in time —

However, the interface used by the teacher to control the robot could mitigate these limitations, and further could explore how to provide the best communication between the teacher and the robot. For example, in the case of a GUI in a tablet or a phone, the interface can combine buttons and a representation of the world where the robot could describe how it plans to act. Similarly, the teacher could use this representation of the world to select actions for the robot to execute (as used in Chapter 6). The type of GUI to control SPARC could use the knowledge obtained from designing application for phone for example. Alternatively, future work could explore how natural language could be used to control a robot using SPARC. Many challenges would have to be tackle such as natural language understanding, or creating a string to describe clearly yet concisely, actions the robot intend to execute. Despite this challenges, language possess the qualities required to communicate between a teacher and a robot: high bandwidth, familiarity for humans, open-endedness of description. As such using combining language and SPARC is a relevant direction of work...

7.4.5 Algorithms

In the future, SPARC should also be combine with richer learning algorithms. The three examples provided in this thesis represent only a small part of the algorithms SPARC can be combined with. More advanced ML would allow SPARC to learn faster and more efficiently, and ,as mentioned previously, potentially reach super-human performance in the task. However, as mentioned in Chapters 2 and 3, many challenges remains when using learning for HRI. The first one, the main one tackled by SPARC, is the high stakes of the interaction, incorrect errors might lead to disastrous consequences. In

addition, the data efficiency is fundamental: when interacting with humans, collecting information about human's reaction can be costly or take a large amount of time. As such, each datapoint should be used with high efficiency and the human included in the loop could provide additional knowledge to deal with this scarcity of data. Alternatively, the algorithm can combine data accumulated with different people to learn a more general policy. However, this lead to a transfer problem, assumptions and policy correct with one user might not be valid anymore for another. And doing this generalisation decreases the potential for personalisation that ML provide. One way to address this personalisation vs generalisation issue is to group people by similarity and learn to detect the group of a person and an action policy adapted to this group to reach a better action policy (Brunskill & Li, 2014). Alternatively, the robot could learn or already possess a general action policy and then use SPARC to refine it and adapt it to its user.

hierarchical learning^{ES}

7.5 Summary

I should probably state the things - difference with introduction^{ES}

This chapter started by presenting the main limitations identified for SPARC and how they could be address when designing an interaction involving SPARC. We then

Using robots in human environments and teaching them raise a number of ethical issues that were examined. Finally, we proposed directions to extend the efficiency and applicability of SPARC that could be addressed in future work.

mention that SPARC not magical tool solving every thing, but useful method applicable for a number of situations^{ES}

Chapter 8

Contribution and Conclusion

From James^{ES} This chapter seeks to provide an overview of the findings and topics covered in this thesis. The contributions to the field of social Human-Robot Interaction (HRI) are outlined and summarised. Following this, a conclusion is provided to briefly encapsulate the primary outcome of this work.

8.1 Summary

The main thesis presented by this work is the following one:

A robot can learn to interact meaningfully with humans in an efficient and safe way by receiving supervision from a human teacher in control of the robot's behaviour.

To explore this thesis and the research questions arising when addressing it, we first reviewed the field of application of social HRI. From this overview, we drew three requirements for a robot to interact efficiently in human-environments. The robot needs to constantly have an appropriate action policy, be adaptive and require a low workload from humans. Then we analysed the current controller for robots in HRI and identified the absence of a robot controller validating these requirements (cf. Chapter 2).

In Chapter 3 we aimed to address this lack of method validating this requirements by proposing a new approach, the Supervised Progressively Autonomous Robot Competencies (SPARC), to teach robots to interact and which would be applicable to HRI. SPARC aims to provide control over the robot's action to a human and use this supervision to learn online a correct action policy. To achieve this goal, SPARC is based on a set of principles allowing this teaching interaction to be efficient: the teacher can select actions for the robot, the robot can propose actions to the teacher, the teacher can pre-empt robot's propositions before an automatic execution and, finally, the robot learns from the teacher's selections and feedback to improve its action policy.

Once the method and the principles defining the interaction between the human teacher and the robot were set, we evaluated this approach in three studies with increasing ambition. Before testing SPARC in a real world interaction with humans (in Chapter 6), we needed to evaluate if the principles underlying SPARC could reduce the workload on the teacher and how the control over the robot's action impacts the teaching process, especially, is it sufficient to ensure a constant appropriate robot behaviour. The two first studies (Chapters 4 and 5) included humans only as teachers, but not as the target of the teaching. This allowed to gather initial information on SPARC in controlled and repeatable environments without having to tackle the challenges of interacting with humans in the real world.

The first study, presented in Chapter 4, evaluated the interaction between the supervisor and the robot in a controlled and repeatable environment inspired by Robot Assisted Therapy (RAT), where the child was replaced by a second robot simulating a child. The study showed that SPARC could allow a robot to learn, subsequently reducing the teacher's workload by decreasing the number of actions required from the teacher to control the robot.

Once SPARC demonstrated that it could allow a robot to learn and decreased the workload on the supervisor, we evaluated in Chapter 5 how the control provided to the teacher by SPARC could improve the learning process. To explore the impact of this teacher's control, we designed a second study comparing SPARC to Interactive Reinforcement Learning (IRL) an alternative approach used to teach robots, but providing the teacher with less control over the robot's action. Results showed that the control provided to the teacher help them to guide the robot to relevant parts of the environment, thus improving the teaching process and making it safer.

Since the two first study demonstrated the efficiency of SPARC to teach a robot to interact in virtual environments and ensured that the control provided by SPARC could ensure the appropriateness of the robot's actions, SPARC was ready to be evaluated in a real human-robot interaction. We decided to select the context of tutoring children in the wild as it is a classic application of HRI and encompasses many challenges faced by robots interacting with humans. This last study applied SPARC to teach a robot a social and a technical policy to support child learning. This study had three main goals. First, demonstrating the applicability of SPARC in teaching robots to interact socially with

humans, consequently addressing the thesis of this research. Secondly, exploring the impact during the teaching phase on the two humans involved in the triadic interaction. And finally, evaluating if, after having been taught by a human using SPARC, the robot could interact successfully with other humans in an autonomous manner. And results from this study demonstrated that during the teaching phase, the robot behaviour was efficient and appropriate to the interaction, but might require a relatively high workload from the teacher. And finally, when deployed autonomously, the robot could interact efficiently with children, leading to a similar policy than the teacher's and having similar effects on the children's behaviours.

8.2 Contributions

From James^{ES} This section will revisit the contributions outlined in the introduction (Chapter 1), with further expansion and explanation.

The main scientific contributions of this thesis are as follows:

- **Design of a new interaction framework for teaching agents in a safe way.**
One of the main contribution of this research is SPARC: a new interaction framework enabling robot to learn to interact with humans from in situ human supervision. This method is corner stone of this thesis and aims to allow robots to be adaptive, while constantly ensuring an appropriate robot action policy and potentially requiring a decreasing workload from humans.
- **Evaluation of SPARC in three studies.** Throughout this research, SPARC have been tested in three study, which were developed to explores different aspects of the human-robot interactions involved in SPARC and culminating to teaching a robot to interact with human in the wild.
- **Demonstration of the importance of control over the robot's action when teaching a robot to interact.** As demonstrated by the last two studies, giving the teacher control over the robot's action has consequent impacts: it makes the teaching process safer, quicker and more efficient and it also give the opportunity to reduce the workload on the teacher.
- **Design of a lightweight algorithm to quickly learn from demonstration in complex environments.** Learning to interact in complex environments, where the states can be defined by a large number of dimensions is a challenging task,

especially when the number of datapoints accessible to learn is low. By using a selective reduction of dimension decided by the teacher, this new algorithm allowed a robot to learn to interact in the complex environment that is child tutoring.

- **Application of Interactive Machine Learning (IML) to safely teach robots social autonomy from in situ human supervision.** Finally, the second main contribution of this research is a demonstration of online learning of interactive policy for HRI supported by human supervision. Similarly to agents using Reinforcement Learning (RL), by using SPARC a robot learned an action policy by interacting with humans from scratch.

probably need to clean last bit and highlight why it matters^{ES}

8.3 Conclusion

Providing a robot teacher with control can be a challenging task, but the rewards for doing so are consequent: the learning can be faster, more efficient and lightweight for the teacher. And most importantly, by preventing the robot's errors in early stage of the interaction, robots can be taught to interact in a wider range of situation where methods lacking control could not be applied.

from abstract^{ES} Throughout evaluating SPARC, this work contributes to extend our knowledge on how humans teach autonomous agents and the impacts of features of the teacher-robot interface on the teaching process. It is found here that a supervised robot learning from a human could reduce the workload required to express a useful robot behaviour. Furthermore, providing the teacher with the opportunity to control the robot's behaviour improves substantially the teaching process.

reopening

Glossary

Correction window The correction window is the time provided to a supervisor to correct an action before its execution. 129

Validity window The validity window is the duration of validity of an action, it represents how long an action is appropriate.. 129

Supervised Autonomy An agent acts autonomously in the world while being monitored by a human. The agent proposes actions which will be executed to the human who has the power to pre-empt them and to select actions to be executed by the agent at any time. 50, 53, 58–60, 100, 128, 129

Acronyms

AI Artificial Intelligence. 1, 7, 134, 135

ANN Artificial Neural Network. 7

ASD Autism Spectrum Disorder. 13, 20, 58, 60, 96

CIDM 95% Confidence Interval of the Difference of the Mean. 70, 71

DREAM Development of Robot-Enhanced Therapy for Children with Autism Spectrum Disorders (European FP7 project). 9, 57

GUI Graphical User Interface. 61, 63, 65–67, 99, 109–111, 130, 137

HCI Human-Computer Interaction. 26, 29

HHI Human-Human Interaction. 14

HRC Human-Robot Collaboration. 17, 18, 31, 33, 54, 135

HRI Human-Robot Interaction. 1–3, 5, 9–11, 14, 19, 21, 23–27, 31–33, 36, 38–40, 45, 48, 58, 60, 92, 93, 96, 98, 101, 102, 105, 124, 127, 131, 132, 135, 137, 139, 140, 142

ILfD Interactive Learning from Demonstration. 43, 54

IML Interactive Machine Learning. 6, 9–11, 32, 34, 35, 39, 42, 45, 48, 51, 53, 54, 75, 76, 79, 95, 102, 130, 135, 142

IRL Interactive Reinforcement Learning. 6, 10, 42, 75–81, 83, 86–88, 90–97, 100–102, 140

LfD Learning from Demonstration. 28, 30, 32, 34–36, 39, 42, 44, 48, 54, 55, 100, 101, 125, 128

LfW Learning from the Wizard. 29

MDP Markov Decision Process. 37, 80

ML Machine Learning. 1, 3, 7, 17, 34, 40, 45, 49, 95, 97, 122–125, 133, 137, 138

NLP Natural Language Processing. 27

RAT Robot Assisted Therapy. 6, 12, 13, 22, 26, 30, 52, 58, 60, 72, 73, 102, 140

RL Reinforcement Learning. 7, 8, 34–41, 48, 52, 54, 55, 76, 96, 101, 135, 136, 142

SAR Socially Assistive Robotics. 12, 96, 101

SL Supervised Learning. 7, 35, 55, 76, 135

SPARC Supervised Progressively Autonomous Robot Competencies. 6–10, 48–55, 57–61, 65, 68–70, 72, 73, 75–81, 83, 86–103, 105–107, 112, 115, 121, 123–125, 127–142

WoZ Wizard-of-Oz. 6, 10, 26, 27, 29, 30, 52, 55, 57–61, 65, 68–70, 72, 100, 109, 121, 124, 128, 132

XAI Explainable Artificial Intelligence. 17

Appendices

Appendix A

Contribution to the DREAM project

As part of DREAM, I have been involved in various meetings, developed tools to automate tasks and contributed to a significant part of the software developed during the project.

A.1 Software development

WP6, composed of Plymouth and VUB, was responsible to develop the cognitive controller of the robot. I developed mostly alone the deliberative, expression and actuation and naoInterface subsystems. I also converted scripts provided by the therapist into steps the robot can follow and programmed a robot behaviour corresponding to each one of these steps.

A.2 Tools

In addition to the components developed to run the DREAM application, I created two tools to automate and simplify the use of the YARP middleware while conforming to the development standards imposed on the project.

A.2.1 yarpGenerator

The software development guidelines of DREAM imposed a specific structure for folders of new components developed with a number of constant part throughout the required 6 files. Additionally, adding or removing one port required changes in 5 files in more than 10 location. To ease this procedure, I proposed to add two new class: the yarpInterface and the yarpController. yarpInterface class exposes all the yarp output port required by the component to C++ function and integrates function asynchronously called when messages arrive on input ports. And the yarpController corresponds to a C++ only file where the code can be developed without reliance of YARP. This class (and others) can call functions from yarpInterface to send messages and be called by callbacks in yarpInterface to react to messages. The yarpGenerator is a tool generating automatically

compilable code, compliant with the development standards. Appendix B presents the techreport created to describe the tool.

A.2.2 scriptManager

The second tools aims at providing a graphical way to read and edit the xml files describing the scripts used in the therapies.

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