Human-Robot Teams: A Review

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Abstract. Research on human-robots teams (HRTs) as teams in which humans and robots work together is an emerging interdisciplinary field that still has white spots that are only slowly being considered by researchers. This review aims to provide an overview over different viewpoints towards HRTs and to synchronize extant definitions. We review extant conceptual and empirical research on HRTs and categorize it following an input-process-output model for teams. After systematically examining what research already knows about HRTs, we identify areas that require further research to gain a deeper understanding of HRTs and discuss proposals for future research.

Keywords: Human-Robot teams · Social robot · Robots at work

1 Introduction and Relevance

Imagine having a new team assistant joining your team and instead of a human it is a robot that enters your office and introduces itself. This or similar constellations are not far-off science fiction anymore, but closer to our work reality than we think.

According to a recent study, 82% of business leaders believe that human-robot teams (HRT), comprising of both human and robotic team members [1], will be reality in about five years [2]. Already today, humans partner with robots in order to accomplish work tasks in a variety of areas, such as urban search and rescue teams [3, 4] and space teams [5, 6].

Research on HRTs is a rising interdisciplinary field, but disciplines often focus on rather specific areas. This makes it difficult to build new research on existing knowledge on HRTs. Additionally, there is no common understanding regarding the definition of an HRT.

This review attempts to systematically synchronize extant definitions of HRTs. Furthermore, research on HRTs is discussed in terms of underlying focus areas, research disciplines and major findings. Finally, other important and so far unexplored application areas of HRTs will be considered for future research.

This review focuses on conceptual articles and empirical studies that investigated HRTs with functional, humanoid or android robotic team members. We further include studies on metrics/taxonomies to account for the conceptual background of human-robot teaming. Ultimately, this article reviews over 80 studies that investigated HRTs and were published between 1997 and 2019.

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Based on this review, gaps in extant research will be identified and areas for future research will be discussed. Accordingly, three research questions were set:

1. How can HRTs be defined?
2. What do we know about HRTs?
3. What are fruitful areas for a future research in the area of HRTs?

The paper is organized as follows. We start with the definition of the term HRT and introduce the conceptual framework of this review (Sect. 2). Then, we give an overview of the important findings of the reviewed studies (Sect. 3). In Sect. 4, we discuss future research directions in the field of HRTs.

2 Key Definitions and Framework of the Review

2.1 Definition of Human-Robot Teams

Despite being increasingly considered by a number of research disciplines, there is no universal definition of HRTs that is used over a broad range of disciplines and research focuses. In the following, we rely on team research from psychology and insights from robotic research to develop a basic definition of the term HRT.

Research on human-human teams (HHTs) has achieved a common agreement on the definition of a team (see, e.g., Stock [7]). Here, a team is defined as "a collection of individuals who are interdependent in their tasks and who share responsibility for outcomes" [7, p. 275]. In robotics research, most authors do not explicitly define the term HRT. However, the investigated team types allow conclusions of the various studies' understanding of the composition of the HRT under investigation. Table 1 provides an overview of team types and sample definitions of HRTs in the investigated research.

A large number of researchers considers human-directed robot teams (esp. in (urban) search and rescue (USAR)) or autonomous mixed teams with no clearly assigned leadership (esp. in human-robot interaction (HRI)) as HRTs in their research and only very few empirical studies with HRTs defined as human-/robot-directed mixed teams, or robot-directed human teams exist. These different viewpoints result in inconsistencies in the definition of HRTs, e.g., regarding autonomy in a HRT [8, 11] or a task- vs. relational perspective on HRTs [1, 11].

Relying on extant research on HHTs [7] and research on HRTs, we define a human-robot team (HRT) as *humans and robots, who perform joint tasks, share common goals, interact socially and exhibit task interdependencies.*

2.2 Framework of the Review

To structure the review, we decided to categorize the considered studies following the structure of an adapted input-process-output (IPO) framework of teams that has evolved in organizational behavior literature [12] and was in this specific form introduced by Stock [7]. According to this framework, which is depicted in Fig. 1, two main input factors, namely individual robotic team member characteristics and team factors, can be

Table 1. Overview of different team types and sample definitions

Team type	Sample definition
Human-directed robot team	In this team, "a single human operator can oversee and flexibly intervene in the operation of a team of largely autonomous robots" [8, p. 1425]
Human-/Robot-directed mixed team	In this team, "human workers […] perform physical tasks in coordination with robotic partners" [9, p. 295] and "human and robot co-leaders [have] identical functions and capabilities, by restricting the human co-leaders' capabilities such that they were the same as those of the robot" [9, p. 296]
Robot-directed human team	In this team, "the partner ([…] robot) is instructing the primary human […] on the task steps to complete. There are no shared decision making tasks" [10, p. 46]
Autonomous mixed team	In this team, "people and robots collaborate on tasks, sharing the same workspace and objects" [1, p. 1]

differentiated. Team processes like coordination, communication and conflicts within the team [13] then in turn influence team outputs [13], that Stock refers to as "psychological and business-related outcomes produced by teams" [7, p. 277].

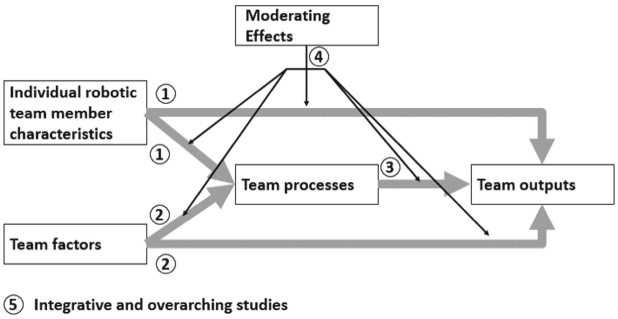

Fig. 1. Framework of the review (adapted from Stock (2004) [7]).

In total, five different categories of studies are considered in this review: Studies that investigate individual robotic team member characteristics or their effects on team processes and/or outcomes are cumulated in category 1 (Sect. 3.1). Studies that analogously investigate team factors and their effects are considered in category 2 (Sect. 3.2). The third category covers studies that investigate team processes and their effects on team outcomes (Sect. 3.3). Category 4 incorporates studies that investigate moderating effects on the links between inputs, processes and outputs (Sect. 3.4). Lastly, studies that cover a causal chain spanning from the inputs via mediating processes to outputs or that deal with overarching HRT topics are included in category 5 (Sect. 3.5). These studies differ

from the other studies in that they are not limited to "one-step relationships" but consider mediated relationships (causal chains) [7]. Please note that it is possible for studies to fall into more than one of the above-mentioned categories without being treated as integrative [7].

3 Conceptual and Empirical Findings Related to Human-Robot Teams

3.1 Category 1: Effects of Individual Robotic Team Member Characteristics

A lot of research on individual robotic (team member) characteristics and their effects we reviewed is not anchored in HRTs. It rather falls within the much broader scope of HRI and is therefore excluded from the detailed review in this paper. Nonetheless, two subcategories of research on HRTs in this category can be differentiated based on their focus areas robot design and robot behavior.

Research on *robot design* is the explicit focus of conceptual and empirical studies on "Robonaut" - a robot designed to be deployed in a HRT in a space context [5, 6, 14]. Further, gender effects [15] and the effects of the human-likeness of robots on praise and punishment in HRTs [16] are investigated. On the other hand, research on *robot behavior* as an aspect of HRTs empirically investigates robotic touch and attitudes [17], the accomodation of human variability [18], robotic behavior explanations [19] and prosocial behavior of robots [20]. Conceptual research focuses on the concept of "inefficient" robots [21] that are not designed to boost efficiency but rather offer socially supportive behavior.

Because of space restrictions it is not possible to discuss the reviewed studies in detail. Table 2 provides an overview of the major disciplines, goals and key findings for all five considered categories of studies.

3.2 Category 2: Effects of Team Factors

The reviewed research on team factors and their effects includes the two subcategories of metrics for HRTs and the roles of human and robotic team members in a HRT including robotic leadership.

With regards to *metrics,* new metrics going beyond existing ones solely focusing on HRI have been developed for HRTs. These metrics also aim at the evaluation of team performance of HRTs [22, 23].

A comparably large number of research has already been conducted on the *roles of human and robotic team members in HRTs*. One popular conceptual work on humans and robots in mixed teams by Groom and Nass [11] discusses the suitability of teams versus other forms of joint actions. Other works look closer into the ratio between humans and robots [3], autonomy and control in HRTs [4, 8, 24–29] or teaming between humans and robots [30–33]. Further research on roles in HRTs has been conducted on role allocation [34], willingness to cooperate [35] and robotic leadership [36–39].

3.3 Category 3: Effects of Team Processes

During our review process we found that studies on team processes and their effects in HRTs form the majority of extant research that is focused on HRTs. This may in part be due to the popularity of HRTs in the context of USAR, where human-directed robot teams are already used today. The studies in this category can be clustered into the four topics: coordination, communication, collaboration and trust in HRTs.

Table 2. Overview over major disciplines, goals and key findings of studies for all categories

Category	Major disciplines	Major goals	Key findings
1: Effects of individual robotic team member characteristics	Space, Robotics	• Identification of guidelines for physical design and behavior that lead to successful HRTs [6]	• The perception of robotic behavior depends on other team members' characteristics [17] • Robot behavior should not be a "black box" for human team members in HRTs [19]
2: Effects of team factors	USAR, military, HRI	• Identification of suitable team constellations for HRTs [34] • Definition of metrics for HRTs [23]	• Different levels of autonomy in HRTs can enhance team performance [24] • Modes for HRTs need further development to identify effective work practices in HRTs [22]
3: Effects of team processes	USAR, HRI	• Understanding of parallels of team processes in HRTs with processes in HHTs [40]	• Trust in HRTs helps to increase team performance and satisfaction [41] • Solid interaction frameworks are needed for HRTs [42]
4: Moderating effects	Robotics	• Identification of relevant moderators in HRTs [24]	• Team capabilities, physical danger and team identification are important moderators [24, 33, 35] • Comprehensive understanding of moderating effects is needed [24]

(*continued*)

Table 2. (*continued*)

Category	Major disciplines	Major goals	Key findings
5: Integrative and overarching studies	Cognitive science, ethics	• Understanding of underlying mechanisms and procedures [43]	• First conceptual considerations of IPO model in HRTs that spares empirical evidence [43] • Individual, team-level and multilevel relationships have to be considered for HRTs [43]

On *coordination in HRTs* researchers have developed coordination concepts [42, 44–47] or studied this topic empirically. The empirical works look into mental models [48, 49], local world state observation [50], cooperative navigation via haptic feedback [51], coordination strategies [28], plan execution based on parallels between HRTs and HHTs [52] and shared decision-making considering human preferences [53].

Research on *communication in HRTs* looks into aspects of information flow [54], backchanelling [55], reasoning [56], conflict moderation [57] and effects of non-verbal communication [58], as well as the conceptual development of communication models [59–61] and interfaces [62]. There is further a number of works on the communication between humans and robots that are rooted in the broader context of HRI.

The third topic of *collaboration in HRTs* has been considered conceptually with a focus on challenges [63], collaborative tools [64], semantic-based path planning [65] and mutual initiative [66, 67] with the latter also being studies empirically [68]. Empirical studies on this topic are working on developing collaboration frameworks [1] – e.g., using spatial representation and reasoning [69] -, or consider joint action perception [70], remote shared visual presence [71], as well as effects of anticipatory actions in HRTs [72, 73]. Further research looks into collaborative problem solving [74], workload in HRTs [10], compares physical collaboration in HRTs with all-human teams [40] and examines emotional attachment and its effects [75].

Finally, with regards to *trust in HRTs* various researchers studied, e.g., trust and leadership [76], appropriate trust in HRTs [77], the measurement [78] and calibration [79] of trust in HRTs, parallels with human-animal teams [80, 81], or the effects of trust on team performance [41].

3.4 Category 4: Moderating Effects

The investigation of moderator variables is based on a situational perspective in psychology that indicates that phenomena are usually not independent from environmental or situational factors [82]. Accordingly, researchers have started examining moderating effects for the IPO framework in HRTs. In the context of HRTs, researchers so far have examined moderators in form of team capabilities to overcome challenges due to sliding autonomy in HRTs [24], risk of physical danger [35] and robot and team identification

[33]. It is unlikely that "one size fits all" applies to HRTs as is also indicated for HHTs [7]. Therefore, moderators should be further investigated in future HRT research.

3.5 Category 5: Integrative and Overarching Studies

In this category we gather studies that consider inputs, processes and outputs of HRTs from an integrative perspective as well as studies on ethics in HRTs. On the first topic of *integrative studies*, in 2018 You and Robert [43] have developed an input-mediators-output-input model for HRTs which is an extension of the established IPO framework for teams. Gombolay, Guiterrez, Clarke, Sturla and Shah [9] consider decision authority in HRTs, resulting team processes and workloads and the outcomes team performance and worker satisfaction. Richert [74] studies collaborative problem solving in HRTs from an integrative perspective, Robert [83] holistically examines motivation in HRTs and Wang et al. [84] consider the chain of embodiment, communication and trust and performance in HRTs. Finally, the overarching topic of *ethics in HRTs* is considered in a number of conceptual research that examines the ethics of bilateral and team interactions [85, 86].

4 Conclusion

4.1 Summary on Existing Research

It appears that research on HRTs is well on its way working on gaining more insights into this upcoming interdisciplinary topic. Our review showed that due to the interdependencies with HRI and human-robot collaboration, individual robotic team member characteristics are rarely examined in a strict HRT setting. Team factors of HRTs on the other hand are already being examined more extensively and especially the roles of human and robotic team members in a HRT are in the focus of a lot of research. When it comes to team processes in HRTs, another large number of studies has already been conducted. The coordination, communication and collaboration of HRTs is a central aspect of the same and it is interesting to see the parallels that are being drawn between HRTs and all-human teams. Only few studies consider moderating effects and although their number is slowly increasing, these studies as well as integrative studies on HRTs are still lacking comprehensiveness.

4.2 Avenues for Future Research

As this article shows, there are several unexplored areas in both the conceptual and empirical research of HRTs. Especially with current developments around the world, there is room to learn more about the design, theoretical concepts and practical implications of HRTs. We thus suggest the following three proposals for future research:

Proposal 1: *Examine the IPO framework of teams for HRTs*

As suggested by team research in general [7] and robotics research in particular [43], the IPO framework constitutes a suitable theory for all-human teams as well as HRTs.

As shown in this review, multi-level concepts for HRTs have been examined only little so far. HRT research should therefore dive deeper into this topic and examine the IPO framework for teams more extensively.

Proposal 2: *Focus on social robots and their introduction in HRTs*

Social robots as robots that are primarily created to interact with humans [87] feature a phenomenon called automated social presence (ASP). ASP makes humans feel like they are with another social entity when interacting with a robot [88]. Due to these particular social features, social robots are increasingly being applied in many fields of our daily lives [89] and should also be examined in future research on HRTs. As a hasty and inconsiderate use of robots can overstrain people and have a lasting negative influence, a special focus of this research should be on the introduction of social robot in HRTs. We therefore further suggest that future research should explicitly consider the transition process towards HRTs.

Proposal 3: *Examine HRTs in organizations*

As indicated before, social robots can take over a variety of roles and HRTs are expected to have significant influence on the future of work [2]. Especially with current developments in the world economy and the increasing relevance of robots in an organizational context, future research should focus on the examination of HRTs in organizations to gain insights into the effects of such developments.

5 Final Remark

Human-robot teams are an emerging phenomenon of the future of work and our society, that is currently lacking important insights. With our review we were able to show that there are white spots in this research topic, especially with a focus on long-term deployment of HRTs. We made three suggestions for future research on HRTs to accommodate for the high relevance of the topic. We hope that the review provides a good and extensive overview of HRTs and inspiration and ideas for future research.

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