

How and When Can Robots Be Team Members? Three Decades of Research on Human–Robot Teams

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Abstract

Artificial intelligence and robotic technologies have grown in sophistication and reach. Accordingly, research into mixed human–robot teams that comprise both robots and humans has expanded as well, attracting the attention of researchers from different disciplines, such as organizational behavior, human–robot interaction, cognitive science, and robotics. With this systematic literature review, the authors seek to establish deeper insights into existing research and sharpen the definitions of relevant terms. With a close consideration of 150 studies published between 1990 and 2020 that investigate mixed human–robot teams, conceptually or empirically, this article provides both a systematic evaluation of extant research and propositions for further research.

Keywords

mixed human–robot team, technology, team dynamics/processes, intra-team dynamics, inter-team dynamics, robotic teammate, robotic leader, robotic team assistant, robotic roles, overview

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In many current work settings, humans partner with robots to accomplish tasks in various fields. Many of these robots can be classified as social robots, which interact with humans in natural ways that feature speech, gestures, and facial expressions (Breazeal, 2003). Unlike industrial robots, they work like unique, contributing members of organizations and so-called human–robot teams (HRTs) (Hoffman & Breazeal, 2004).

The presence and uses of such teams are growing, especially in the face of the various restrictions imposed by the COVID-19 pandemic (Scassellati & Vázquez, 2020). An estimated 82% of business leaders already believed in 2018 that HRTs would be a daily reality within 5 years (Dell Technologies, 2018); when we recently surveyed 596 U.S. employees¹ (65% men, mean age = 36.92 years, SD = 10.85 years), we learned that they could easily imagine working with a robot as teammate (39%), team assistant (50%), or even team leader (34%). For example, robots can track projects, perform real-time scheduling, and support complex organizational decision-making processes.

Even as these uses and imagined applications expand though, research on HRTs remains limited by disciplinary siloes. That is, the concept is interdisciplinary, but we lack summary assessments of existing knowledge about or common definitions used in relation to HRT across each individual discipline. Nor do we have a sense of which factors or team member characteristics inform the ways of working and outcomes of such HRTs. With this review, we attempt to systematically synchronize extant definitions and detail prior research on HRTs according to its theoretical perspectives, empirical design, and major findings.

We focus on embodied robots, which we define as physical representations of AI in a physical world that recognize their environment and can interact with it (Bradshaw et al., 2009; Fong et al., 2003; High-Level Expert Group on Artificial Intelligence, 2019; Wolf & Stock-Homburg, 2021).² For the review, we conducted online searches using Google Scholar and EBSCO but also reviewed journals and conference proceedings related to human–robot interactions. As detailed in [Supplementary Appendix A](#), we searched 17 conferences and 40 journals. Most of them come from the fields of HRI, robotics, and computer science. We manually assessed each study type, embodiment form, robot level, focus topic, and team size and applied various related exclusion criteria. Ultimately, we reviewed 150 relevant studies, published between 1990 and May 2020 (for further details on the study selection, see [Figure 1](#) and [Supplementary Appendix A](#)). This review attempts to provide answers on two questions:

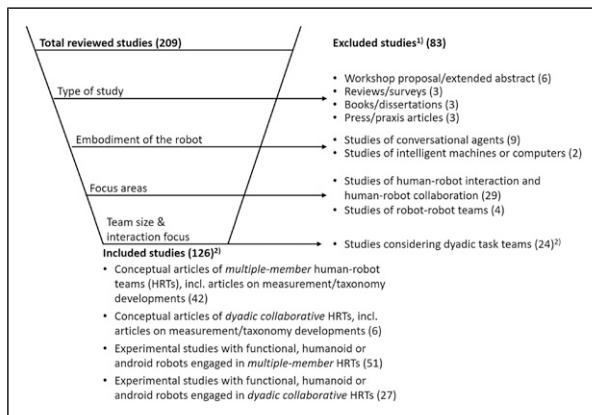


Figure 1. Overview of reviewed, included, and excluded studies. Note: (1) Please see [Supplementary Appendix A](#) for more details on the exclusion criteria. (2) In total, we reviewed 150 studies in detail. Details on the 24 studies considering dyadic task teams can be found in [Supplementary Appendix B](#).

1. How are human-robot teams defined in prior literature?
2. Which intra-member characteristics, inter-member characteristics, and contingency factors influence the input–process–output relationships in HRTs?

Proposed Typologies, Definitions, and Review Framework

Robot Typology

A vast multitude of robot typologies have been developed in the last various efforts to categorize robots (for an overview, see [Onnasch & Roesler, 2020](#)). We propose a business-oriented robot typology ([Figure 2](#)), which depends on two main dimensions: social interaction intensity ([Breazeal, 2003](#); [Deng et al., 2019](#); [Fong et al., 2003](#); [Nass et al., 1994](#)) and robot morphology ([Onnasch & Roesler, 2020](#)). In this context, we understand social interaction as the application of social models to the interaction with a robot.³ Across the two dimensions of our typology, we can identify four categories of robots that are particularly relevant to business contexts:

Social Interaction Intensity	Machine-like robot with high social interaction Sociable Trash Box (Yamaji et al., 2011) Care-o-bot (Kittmann et al., 2015)	Human-like robot with high social interaction Elenoide (Stock et al., 2019) Pepper (Pandey & Gerlin, 2018)	
	↑	↑	
	Machine-like robot with low social interaction Roomba (Forlizzi & DiSalvo, 2006) NIFTi ground vehicle (Kruijff et al., 2014)	Human-like robot with low social interaction Johnny 05 (SIM, TU Darmstadt) TIAGo (Pages et al., 2016) Robonaut (Ambrose et al., 2000)	
Machine-like		Human-like	

Figure 2. Robot typology with selected examples from literature. Notes: Due to anthropomorphism, robots can be attributed more prominent human (social) characteristics than they originally were designed to include (see arrows). Picture sources: Sociable Trash Box, Pepper, Johnny, TIAGo, Robonaut: all from ABOT database (<http://abotdatabase.info/>); Care-o-bot: Fraunhofer IPA (<https://www.care-o-bot.de/de/care-o-bot-3/download/images.html>); Roomba: iRobot (<https://shop.irobot.de/roomba-staubsaugerroboter-roomba-606/R606040.html>); NIFTi ground vehicle: Kruijff et al., 2014; Elenoide: leap in time GmbH Darmstadt.

- *Machine-like robot with low social interaction*: Robots like the Roomba vacuum (Forlizzi & DiSalvo, 2006) or the NIFTi ground vehicle (Kruijff, Kruijff-Korbayová, et al., 2014) are designed primarily with functionality in mind.
- *Human-like robot with low social interaction*: Robots like Johnny 05 (SIM TU Darmstadt, 2021), TIAGo (Pages et al., 2016), and Robonaut (Bluethmann et al., 2003) are humanoid robots with legs, arms, and heads. Despite this physical appearance, these robots are designed primarily to fulfill intended (work) tasks, not to engage in social interaction.
- *Machine-like robot with high social interaction*: Robots in this category, like the Sociable Trash Box (Yamaji et al., 2011) and the Care-O-Bot (Kittmann et al., 2015), lack a human physical appearance but can elicit social responses (Schmitt et al., 2017).

- *Human-like robot with high social interaction:* Robots like Elenoide (Stock et al., 2019) or Pepper (Pandey & Gelin, 2018) look very similar to actual humans and have strong social skills, including emotion recognition.

Team Typology

All-Human Teams. A common agreement defines human teams as collectives of three or more people (Stock, 2003), “who (a) exist to perform organizationally relevant tasks, (b) share one or more common goals, (c) interact socially, (d) exhibit task interdependencies . . . , (e) maintain and manage boundaries, and (f) are embedded in an organizational context” (Kozlowski & Bell, 2003, p. 334). They are dynamic, at three main levels (de Wit & Greer, 2008; DeChurch et al., 2013): “tasks (i.e., goals, ideas, and performance strategies), . . . relationships (i.e., personality clashes, interpersonal styles)” (DeChurch et al., 2013, p. 560), and the processes used to manage or achieve teamwork (de Wit & Greer, 2008).

Human–Robot Teams. Although HRTs have been investigated widely—e.g., as “robot[s] as team member[s]” (HRI’07, 2007) and “robots in groups and teams” (Jung et al., 2017)—no universal definition exists that reflects and is accepted by the broad range of disciplines that feature research in related topics (Figure 3). Therefore, our first research question attempts to provide an understanding of what one is talking about when referring to this concept to avoid meaning different things under the same name (see, e.g., Kelley, 1927; Marsh et al., 2019).

In particular, ongoing discussion centers on whether the minimum required HRT size should be two or three members. Dyads with just two members represent very specific constellations, and they lack the dynamics that are of core interest for HRT research (Abrams & der Pütten, 2020). Yet we found many conceptual and empirical studies that claim to investigate HRTs by studying dyadic teams. Another dimension in which researchers differ pertains to whether they focus on pure task interactions or on both task and social interactions within the team. Among the 93 reviewed studies that focus on HRTs with multiple members, we derive several elements pertaining to the composition of HRTs; Table 1 classifies extant research on HRTs according to the team type and composition it considers, along with the definitions it offers. As it shows, many researchers investigate human-directed robot teams (especially for USAR tasks) or autonomous mixed teams with no clearly assigned leadership. Relatively few empirical studies address human- or robot-directed mixed HRTs, and we find no studies of robot-directed human teams.

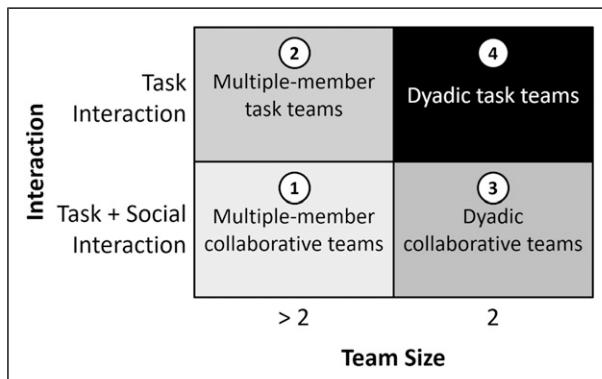
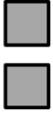
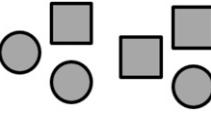


Figure 3. Overview of HRT definitions. Note: Definitions of HRTs include a narrow perspective of HRTs as multiple-member collaborative teams (1), and a broader perspective of HRTs as multiple-member task teams (2), dyadic collaborative teams (3), or dyadic task teams (4). The team types (1)–(3) are discussed in detail in this manuscript. Details on the dyadic task teams (4) can be found in [Supplementary Appendix B](#).

From these dimensions, four constellations of HRTs can be derived ([Figure 3](#)): (1) HRTs as *multiple-member collaborative teams*. That is, a *mixed human–robot team (HRT)* consists of at least three members (humans and robots) who perform joint tasks interdependently and interact socially to achieve common goals. (2) *Multiple-member task teams* have more than two members that focus primarily on task interaction. These teams can be found in space and USAR contexts, where robots work in teams with humans to increase efficiency and safety ([Bluethmann et al., 2003](#)). (3) *Dyadic collaborative teams* are human–robot dyads that interact interdependently, both socially and on a task level to achieve their common goals ([Breazeal, Hoffman, & Lockerd, 2004](#)). (4) *Dyadic task teams* only engage in task interaction to reach their goals, e.g., in manufacturing a car ([Liu & Tomizuka, 2014](#)).

Two perspectives can be differentiated regarding HRTs: a broader and a narrow perspective. From a *broader perspective*, HRTs fall into the three categories of multiple-member task teams, dyadic collaborative teams, and dyadic task teams. These broader perspectives, however, go beyond our narrow understanding of HRTs and rather aim at capturing the various perspectives in extant robotic research (in this review we do not consider the

Table I. Overview of Different Team Compositions, Sample Definitions, and Related Research.

Team Type	Team Composition	Sample Definition	Related Empirical Research
Human-directed robot team		“a single human operator can oversee and flexibly intervene in the operation of a team of largely autonomous robots” (Sellner et al., 2006, p. 1425).	Management: Pina et al., 2008; Sellner et al., 2006 Cognitive science: J. Wang et al., 2008; You & Robert, 2016, 2017, 2019a, 2019b HRI: Alboul et al., 2008; Crandall et al., 2003; Goodrich et al., 2007 Military: Brown et al., 2005 Robotics: Zheng et al., 2013 (Urban) search and rescue: Burke & Murphy, 2004, 2007; Kantor et al., 2006; Lee et al., 2010; Ranzato & Vertesi, 2017; H. Wang et al., 2010; Yazdani et al., 2016
Human-/Robot-directed mixed team		“human workers . . . perform physical tasks in coordination with robotic partners” 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” (Gombolay, Gutierrez, et al., 2015, pp. 295–296)	HRI: Law et al., 2020 Management: Gombolay, Gutierrez, et al., 2015, referring to human and robotic co-leads and human assistants; Gombolay, Huang, & Shah, 2015, referring to human leader, robotic and human assistants

(continued)

Table I. (continued)

Team Type	Team Composition	Sample Definition	Related Empirical Research
Robot-directed human team		"the partner [robot] . . . is instructing the primary human . . . on the task steps to complete. There are no shared decision making tasks" (Harriott et al., 2011 , p. 46) ^a	N/A; the only studies with such a team composition refer to robot-directed dyadic task teams
Autonomous mixed team	 	"humans and robots [work] together to accomplish complex team tasks" (Dias et al., 2008 , p. 1)	Cognitive science: Correia, Mascarenhas, et al., 2019 ; Jung et al., 2015 ; Strohkorb Sebo et al., 2020 ; Traeger et al., 2020 HRI: Gervits et al., 2020 ; Kwon et al., 2019 ; Tang & Parker, 2006 Robotics: Claure et al., 2020 ; Iqbal & Riek, 2017 ; Marge et al., 2009 Space: Fong et al., 2005 ; Fong et al., 2006 (<i>Urban</i>) search and rescue: Dias et al., 2008 ; Jung et al., 2013

Note: Team composition: ○ = human, □ = robot. The studies (with team sizes of at least $n = 3$) are categorized according to a best fit approach, so they might feature aspects of more than one research discipline. Overview over related empirical research is not exhaustive.

^a[Harriott et al. \(2011\)](#) only consider a dyadic task team.

dyadic task teams in depth, instead see [Supplementary Appendix B](#)). From a *narrow perspective*, combining the insights gleaned from all-human team definitions (e.g., [Stock, 2004](#)) and robotic research, we define HRTs as multiple-member collaborative teams.⁴

Proposed Framework

In this overview, we rely on an input–process–output (IPO) model ([Gladstein, 1984](#); [You & Robert, 2018b](#); see [Figure 4](#)). Categories 1 and 2 focus on two important *input factors*: intra-member team characteristics, such as the (physical) robot design, robot behavior, or human preferences and behavior (Category 1), and inter-member team characteristics, including team composition, autonomy, and leadership (Category 2). Category 3 includes studies of *team processes* ([Barrick et al., 1998](#); [Gladstein, 1984](#)) like (physical) coordination, communication, collaboration, and trust. The studies in these categories affect *team outputs* ([Barrick et al., 1998](#)) as “psychological and business-related outcomes produced by teams” ([Stock, 2004](#), p. 277). Studies in Category 4 investigate moderating effects on input, process, and output. Finally, some studies depict causal chains ([Stock, 2004](#)) from the inputs through mediators to outputs (Category 5). The coding scheme used to classify studies is explained in detail in [Supplementary Appendix A](#).

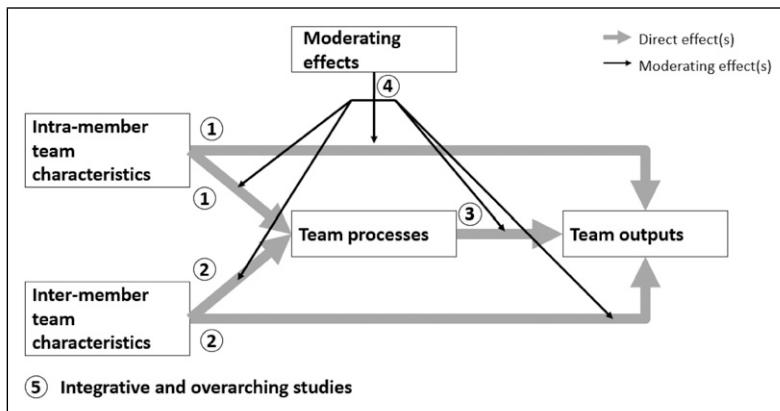


Figure 4. Proposed framework (adapted from [Stock, 2004](#)).

Conceptual and Empirical Findings Related to Human-Robot Teams

Category 1: Effects of Intra-Member Team Characteristics

Focus Areas and Major Findings. Table 2, 3 and 4, summarize the studies in this category in terms of the robot characteristics studied, the definition of HRT, samples, and key findings. Research on (*physical*) *robot design* for both dyadic HRTs and multiple-member HRTs tends to center on robotic hardware (e.g., degrees of freedom of components; Bluethmann et al., 2003), physical appearances in terms of anthropomorphism or robot size (Bartneck et al., 2006), or uses of gestures and facial expressions (Minato et al., 2004). The physical design of the robot is the explicit focus of conceptual and empirical studies on Robonaut, which was designed by NASA to be deployed in HRTs devoted to space exploration (e.g., Bluethmann et al., 2003; Fong et al., 2005). These studies address the physical design features needed to execute its

Table 2. Conceptual Studies on Multiple-Member HRTs Related to Intra-Member Team Characteristics and Their Effects.

Author/Subcategory/Discipline ^a / Team Interaction ^b	Key Findings ^{c,d}
Ambrose et al. (2000)/(physical) robot design/VI/T	• Overview of the design of NASA's Robonaut
Bluethmann et al. (2003)/ (physical) robot design/VI/T	• Information on the design of NASA's Robonaut
Fong et al. (2005)/(physical) robot design/VI/T	• Proposal of interaction framework "Human–Robot Interaction Operating System" (HRI/OS) • Proposal of metrics for evaluation of HRTs • Position paper that suggests that task-related "inefficiency" in the form of social behavior should be considered when designing social robots
Kelly and Watts (2017)/robot behavior/V/T+S	

Note: ^aDisciplines: I = HRI, II = Management, III = military, IV = Cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; Studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bTeam interaction: T = task interaction, T+S = task and social interaction.

^cNone of the studies specified underlying theories. In part of the studies, the robot morphology, robot level, and type of embodiment are not specified. The two studies that provide information (Bluethmann et al., 2003; Fong et al., 2005) use the physical, humanoid "Robonaut" robot on a lower or same level as humans.

^dIn most of the studies, the team setup is not specified. Only Kelly and Watts (2017) specify that they focus on a human-directed robot team.

Table 3. Empirical Studies on Multiple-Member HRTs Related to Intra-Member Team Characteristics and Their Effects.

Author/Subcategory/ Discipline ^a	Robot Morphology/ ^b Robot Level/Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/ Participants/Time Frame ^f	Underlying Theories	Independent Variables ^g	Dependent Variable(s) ^h	Key Findings
Claire et al.(2020)/ robot behavior/V	n.i./↔/n.i.	T + S  	n = 282/156 f, 124 m, 1 other, I not disclosed; age: M = 36 years (SD = 11); mTurk; from the US/ C	Equity models, fairness theory	• Robot fairness • User trust (+ / n.s.) • Perceived robot fairness (n.s.)	• User trust (+ / n.s.) • Perceived robot fairness (n.s.)	• "Fairness of resource allocation has significant effect on user's trust in the system" (p. 299)
Correia, Macarenhas, et al. (2019)/robot behavior/IV	Humanoid (ENY'S robotic head)/ ↔/Physical robot	T + S  	n = 70/32 f, 37 m, 1 unknown; age: range 22-62 years (M = 34.6, SD = 11.557)/ C	• Prosocial robot behavior	• Prosocial robot attributes (+)	• Perceived robot social attributes (+)	<ul style="list-style-type: none"> • Prosocial robots are rated more positively in terms of their social attributes (p. 143) • "The perception of competence, the responsibility attribution (blame/credit) and the preference for a future partner are only significantly different in the losing condition" (p. 143)

(continued)

Table 3. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup	Data Basis/ Participants ^e /Time Frame ^f	Underlying Theories	Independent Variable(s) ^g	Dependent Variable(s) ^h	Key Findings
Correia, Petiscá, et al. (2019)/human preferences and behavior/IY	Humanoid ("Enys", "Glin"; both identical physical appearance: EMYS)↔/Physical robot	T + S 	n = 30, n = 6 / 1: 17 m, age: range 19– 42 years, M = 23.03 (SD = 4.21), university students; 2: 38 m, age: range 17–32 years, M = 23.66 (SD = 3.24), 59 university students, 2 worker/ C/L (3 sessions in direct succession)	Learning goal theory	• Robot goal orientation (performance- driven vs. learning- driven)	• Competitiveness Index (higher for performance-driven) • McGill Friendship Questionnaire (higher for learning-driven) • Relationship Assessment Scale (higher for learning-driven) (p.) • Godspeed Questionnaire	<ul style="list-style-type: none"> • "When a partner is chosen without previous partnering experience, people tend to prefer robots with relationship-driven characteristics as their partners compared with competitive robots" • "After some partnering experience has been gained, the choice becomes less clear and additional driving factors emerge: (2a) participants with higher levels of competitiveness (personal characteristics) tend to prefer Enys [the performance-driven robot], whereas those with lower levels prefer Glin [the learning-driven robot], and (2b) the choice of which robot to partner with also depends on team performance, with the winning team being the preferred choice." (p. 1)

(continued)

Table 3. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level/Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/ Participants ^f /Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ⁱ	Key Findings
Fraune et al. (2020)/ robot behavior/I	Functional (Sociable)/ Trash Box (STB)/ nlu./Image/video of a robot, physical robot	T + S  ... 	n_1 = 630, n_2 = 711/ from USA (n = 333, 47% f, age M = 24.59, SD = 9.59) and Japan (n = 297, 7% f, age M = 21.55, SD = 3.35), recruited in universities; 2: from USA (42%), age M = 19.20, SD = 1.30), recruited from university/C	Social identity theory	• Robot behavior toward robots (none, social, functional) • Robot behavior toward humans (social, functional) • Country (US, Japan)	• Anthropomorphism of robot (partially + for robot-to-robot social, n.s. for other conditions) • Emotional and behavioral intention about robot (n.s.) • Entitativity of robot (n.s.)	• Social robot-robot behavior increases anthropomorphism, social robot-human behavior increases positive emotions and willingness for interactions (p.1) • Robots that are designed for positive human interaction resp. to be perceived intelligent should behave socially towards humans resp. also towards robots (p.1)
Gombolay et al. (2017)/robotic behavior: human preferences and behavior/I	Functional (Willow Gauge PR2 platform)/Physical robot	T + S  	n_1 = 17, n_2 = 18, n_3 = 20/all: recruited form local university; 1: 6 m, age: range 18–25 years, M = 19.5 (SD = 1.95); 2: 10 m, age: range 19–45 years, M = 27 (SD = 7); 3: 10 m, age: range 18– 30 years, M = 21 (SD = 3)/C	Situational awareness	• Degree of robotic autonomy in scheduling decisions	• Preference to work with robot (+)	• "human participants' actions decreased as the degree of robot autonomy increased" (p. 614) • "participants preferred working with a robot that included their preferences when scheduling and . . . preferred working with a robot that utilized them more frequently" (p. 613)

(continued)

Table 3. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/ Participants/Time Frame ^f	Underlying Theories	Independent Variable(s) ^g	Dependent Variable(s) ^h	Key Findings
Gombotay, Huang, and Shah (2015)/ robot behavior, human preferences and behavior/II	Functional (Willow Garage PR2 platform)/↓Physical robot	T + S 	n = 17/n/iC	n.i.	• Consideration of human preferences	• Willingness to work (+)	• Humans prefer working with a robotic team mate that considers their preferences
Jiang and Wang (2019)/robot behavior/V	n.i./n.i./n.i.	T + S 	n.i./n.i./n.i.	Regret theory	• Robot decision making (regret- decision model)	• Teaming performance (+)	• Team efficiency has to be kept in mind when allocating decision-making authority (robot taking decisions can lead to decreased efficiency and belief that the robot is unaware of team goals) • More human-like decision- making by robots can help to balance workload and performance in HRTs

(continued)

Table 3. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/ Participants/Time Frame ^f	Underlying Theories	Independent Variables ^g ^h	Dependent Variable(s) ^h	Key Findings
Law et al. (2020)/ (physical) robot design, robot behavior/	Humanoid (Willow Garage PR2)/ ↔/Image/video of robots	T + S 	n = 198, n = 42 / 1: 95 f, 1 other; age: range 18–77 years (M = 34.76, SD = 11.47); 2: 162 f, 3 other; age: range 18– 81 years (M = 36.52, SD = 11.85); both: mTurk/C	Emotional intelligence, social role theory	• Robot emotional intelligence (+) • Robot gender (+, male) • Vignette presentation (n.s.) — • Robot emotional intelligence (+) • Robot gender (+, male) • Vignette presentation (+, text) • Participant gender (n.s.) • Participant age (-)	• Trust in robot	• Robotic EI influences trust in a robot (p. 1) • "Gender stereotypical expectations related to EI [are] transferred to trust" (p. 1)

(continued)

Table 3. (continued)

Author/Sub-category/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup	Data Basis/ Participants ^e /Time Frame ^f	Underlying Theories	Independent Variable(s) ^g	Dependent Variable(s) ^h	Key Findings
Lei and Rau (2020)/ human preferences and behavior/IV	Humanoid (Nao)/ ↔/Physical robot	T + S 	n = 60/30; age: M = 22.2 years (SD = 2.29); (under-) graduate students (40%/60%)/C	CASA paradigm, common sense psychology, gender studies	• Task outcome (n.s.) • Human gender (-/+)	• Attribution of blame to robot • Attribution of credit to robot	• Gender effects play a role in the attribution of credit and blame to robot team members • "participants attributed more credit and less blame to the robot member than to themselves" (p. 1) • "the robot member was more blamed than the human member, whereas they received similar levels of credit" (p. 1)
Srothkorb Sebo et al. (2018)/robot behavior/IV	Humanoid (Nao)/↔ (not specified)/ Physical robot	T + S 	n = 105 (in 35 teams)/ experimental condition: age: M= 20.54 m, (SD = 7.13); control condition: 15[5] m, M = 21.333 years (SD = 11.00); recruited from university campus and surrounding town and summer program./C	Trust theories	• Robot vulnerability	• Team member interactions with robot (+)	• Perceived psychological safety (n.s.) • Team member interactions with other human team members (+)

(continued)

Table 3. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/ Participants ^f /Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ⁱ	Key Findings ^j
Traeger et al. (2020) / robot behavior/IV	Humanoid (Nao)/ ↔/Physical robot	T + S 	n = 153 (in 51 groups of 3 each); vulnerable condition: 28 f, 26 m, age: M = 20.13 years (SD = 7.13); neutral condition: 26 f, 15 m, age: M = 21.33 years (SD = 11.01); silent condition: 31 f, 17 m, age: M = 23.94 years (SD = 7.36)/C	n.i.	• Robot vulnerability	• Team member interactions with other human team members (+)	"people in groups with a robot making vulnerable statements converse substantially more with each other, distribute their conversation somewhat more equally, and perceive their groups more positively compared to control groups with a robot that either makes neutral statements or no statements at the end of each round" (p. 6370)

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics;
^bstudies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.
^cn. i. = no information provided by author(s).

^dRobot level: ↓ = robot on lower level, ↔ = robot on same level, ↑ = robot on higher level.

^eTeam interaction: T = task interaction, T+S = task & social interaction.

^fParticipants: ○ = human, □ = robot.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEmpirical findings: (-) = negative effect, (+) = positive effect, (n.s.) = not significant.

intended tasks (e.g., hands) and requirements for controlling Robonaut in harsh conditions (Bluethmann et al., 2003).

The second dimension, *robot behavior*, appears in both conceptual and empirical research on dyadic and multiple-member HRTs. Conceptual studies tend to focus on “inefficient” robots that are designed not to increase the efficiency of an HRT but rather to exhibit social behavior, to facilitate their integration into both teams and wider society (Kelly & Watts, 2017). Empirical studies on multiple-member HRTs pertain to prosocial behaviors (Correia, Mascarenhas, et al., 2019), fair resource allocations (Claure et al., 2020), social robot–robot and robot–human behavior (Fraune et al., 2020), vulnerable robotic utterances (Traeger et al., 2020), and vulnerable robotic behavior (Strohkorb Sebo et al., 2018). All these features signal a robot’s seeming personality, in line with the Computers Are Social Actors (CASA) paradigm and its prediction that humans treat robots as social entities (Nass et al., 1994). Such behaviors exert positive effects on robot or team perceptions or processes. In particular, prosocial robotic behavior enhances users’ perceptions of and behaviors toward robots, prompts better social attribute ratings (Correia, Mascarenhas, et al., 2019), and leads humans to become more engaged (Strohkorb Sebo et al., 2018). Empirical studies on dyadic HRTs that study specific prosocial robotic behaviors such as explanations (Hiatt et al., 2011; Wang et al., 2016a; 2016b; Wang et al., 2018) or inter alia apologies in the case of errors (Natarajan & Gombolay, 2020) reveal positive effects of such behaviors on trust and team performance. Finally, robot touch appears to lead to better ratings of the social performance, skills, and fairness of a robot (Arnold & Scheutz, 2018). However, perceptions of robot touch need to be considered in the context of the interaction; for example, gender effects might arise and have important influences.

The *human preferences and behaviors* dimension has not been studied broadly in an HRT context, possibly because it gets addressed more commonly in relation to HRI or HRC. We find one recent study of attributions of blame and credit, using a multiple-member HRT (Lei & Rau, 2020), which reveals that human team members “attributed more credit and less blame to the robot member than to themselves” (p. 1). Another study deals with membership preferences in HRTs (Correia, Petisca, et al., 2019), demonstrating that people who exhibit greater competitiveness prefer a performance-driven robot over a learning-driven one.

Finally, four studies of multiple-member or dyadic HRTs investigate interplays among the three subcategories (Gombolay et al., 2017; Gombolay, Huang, & Shah, 2015; Law et al., 2020; Richert et al., 2016): Thus, different dimensions of intra-member team characteristics appear intertwined and important for understanding the role of robots in team contexts.

Table 4. Empirical Studies on Dyadic HRTs Related to Intra-Member Team Characteristics and Their Effects.

Author/Subcategory/ Discipline ^a	Robot Morphology/ Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants/ Time Frame ^f	Underlying Theories	Independent Variables ^g	Dependent Variables ^h	Key Findings
Arnold and Schaeuz (2018)/robot behavior/r	Humanoid/ \leftrightarrow /Image/ video of a robot	T + S 	n = 332/135 f, age: 44.43 years; mTurk; US citizens/C	• Positive robot attitude • Robot touch	• Perceived robot capability (+/-n.s.) • Confidence in robot skills (+) • Perceived robot qualification (+/-n.s.) • Perceived robot fairness (+)	• Robot touch leads to better rating of the social performance, skills, fairness of a robot • However, gender effects from survey responses show that robot touch has to be considered with caution as the context and expectations from society can lead to a significantly varying perception of robot touch	• Robot touch • Praise (+) • Punishment (-)
Bartneck et al. (2006)/ (physical) robot design/r	Android (Tron-X PKD), animal-like (ABC)/ \leftrightarrow /Image/ video of a robot	T + S 	n = 12/age: range 21–54 years (M = 29.9); Master's and Ph.D. students in Psychology or Engineering/within subject design, C	• Human-/animal- likeness of robot	• CASA paradigm, Uncanny valley paradigm	• Robots on the other hand were treated differently depending on their physical appearance: very human-like or animal-like robots were praised more and punished less than computer and human, machine-like robots were treated like computer and human	(continued)

Table 4. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants ^f / Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ^h	Key Findings
Härt et al. (2011)/ robot behavior/IV	Humanoid (Mobile, Dexterous, Social (IDS) robot/ ↔/Image/video of a robot	T + S 	n = 35 / n.i. / n.i.	Theory of mind	• Robot explanation	• Perceived robot naturalness (+) • Perceived robot intelligence (+)	• A robot that uses a theory of mind (ToM) approach and offers explanations is perceived both more intelligent and natural than a robot that either shows only simple correction or blindly follows a human (p. 206).
Narayan and Gombolay (2020)/ robot behavior/I	Functional (Sawyer), humanoid (Kuri, Pepper, Nao)/n.i./ Physical robot, video/image of a robot, (as condition of experiment)	T + S 	n = 75/51.47% f; age: range 18-58 ($M =$ 25.298, $SD = 8.457$); from university/C (4x4x2x2; between- and within-subject)	n.i.	• Perceived anthropomorphism (+) • Robot behavior (+) • Robot presence (n.s.)	• Trust	• Behavior and anthropomorphism of the agent are the most significant factors in predicting the trust and compliance with the robot" (p. 33)
Richert et al. (2016)/ (physical) robot design, robot behavior/II	Functional,/ humanoid/n.i./ Simulation/virtual robot	T+S / n.i.	n.i. / n.i. / n.i.	CASA Paradigm, embodiment theories	• Personal characteristics • Robot characteristics	• Task performance (not reported)	• Proposal of experiments to gain insights into cooperation between humans and robots based on robot appearance and robot accuracy
N. Wang et al. (2016a)/ robot behavior/III	Functional/n.i./ Simulation/virtual robot	T + S 	n = 220/mTurk, USA/C	n.i.	• Robot explanations	• Transparency (+) • Trust (+) • Performance (+)	• A better understanding of decision-making processes of a robot can help improve trust • Explanations based on POMDP (Partially Observable Markov Decision Processes) can be a way to achieve this goal

(continued)

Table 4. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants/ Time Frame ^f	Underlying Theories	Independent Variable(s) ^g	Dependent Variable(s) ^h	Key Findings
N. Wang et al. (2016b)/ robot behavior/III	Functional/n./i/ Simulation/virtual robot	T + S 	n = 220/mTurk, USA/C (between-subject)	n.i.	• Robot explanations	• Transparency (+) • Trust (+) • Performance (+)	• A better understanding of decision-making processes of a robot can help improve trust in HRT's (similar experiment as in "The impact of POMDP-generated explanations on trust and performance in human-robot teams") • Explanations by robots (even if they don't indicate which components of a robot are faulty) have significant effects on transparency and self-reported trust of participants and result in better decision-making of a human team mate • Robot embodiment and acknowledgement of mistakes only have a marginally or no significant impact on self-reported trust, transparency or correct decisions
N. Wang et al. (2018)/ robot behavior/IV	Animal-like, functional/ ↓/simulation/ virtual robot (online HRI test bed)	T + S 	n = 61/14 f, age range 18–23 (M = 19.2); years higher- education military school in the US, participants received extra course credit for participation/C (2 sessions, 120 mins total, 8 missions)	n.i.	• Embodiment (n.s.) • Communication strategy in case of error (n.s.) • Explanations (+)	• Trust • Transparency • Transparency test score • Compliance • No. of correct decisions made	• Trust • Transparency • Transparency test score • Compliance • No. of correct decisions made

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↔ = robot on same level, ↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction.

^eTeam setup: ○ = human, □ = robot.

^fParticipants: f = female, m = male.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEmpirical findings: (−) = negative effect, (+) = positive effect, (n.s.) = not significant.

Disciplines, Study Characteristics, and Underlying Theories. We assign 23 studies to this category (15 of multiple-member HRTs, 8 of dyadic HRTs); most of them rely on cognitive science (7 studies), space (3), or robotics (3) foundations. Very little research in HRI or management includes teams with at least three team members; 4 studies from HRI and 1 that reflects a management-related perspective take dyadic perspectives though. Only one study shows a longitudinal approach with three sessions in direct succession (Correia, Petisca, et al., 2019). All 19 empirical studies are conducted online or in laboratory settings. They feature humanoid and functional robots. Several studies do not disclose the type of robot used. Studies of multiple-member HRTs mostly focus on collaborative teams. Teams include autonomous mixed teams (7 studies), a human-directed robot team (1), and human/robot-directed mixed teams (3). Studies of dyadic collaborative HRTs also consider autonomous human-robot pairings (4), human-directed robots (3), or do not disclose the team setup. About one-third of the studies indicate their theoretical foundation. They draw on theories such as fairness theory and equity models (Adams, 1963, 1965), the theory of mind (Hiatt & Trafton, 2010), emotional intelligence (Salovey & Mayer, 1990), social role theory (Hentschel et al., 2019), and situational awareness (Endsley, 1995). Further, some researchers base their work on the CASA paradigm (Nass et al., 1994).

Limitations. Most of the studies rely on student samples, with cross-sectional laboratory designs, which limits the generalizability of their findings (Levitt & List, 2005). No studies in this category feature real-world settings. They also ignore dynamic developments in teams over time (Bell & Marentette, 2011) and instead take static perspectives, suggesting the need for longitudinal studies. Furthermore, none of these studies investigates robot-directed human/mixed teams (see Table 1). Finally, some studies establish a sound theoretical basis for their research, but it is important to extend this effort and perhaps apply other behavioral theories, such as social identity theory (Tajfel, 1974).

Category 2: Effects of Inter-Member Team Characteristics

Focus Areas and Major Findings. Tables 5, 6, 7 and 8 provide an overview of the studies in this category. In conceptual studies of the *roles of humans and robots in HRTs*, we find discussions of the suitability of teams, which suggest that robots should not replace humans but rather be treated as complements with individual strengths (Groom & Nass, 2007). Conceptual research on dyadic HRTs discusses parallels between all-human teams and HRTs and the importance of shared mental models (Demir et al., 2020). Empirical research on multiple-member HRTs checks for the ideal ratio between humans and

Table 5. Conceptual Studies on Multiple-Member HRTs Related to Inter-Member Team Characteristics and Their Effects.

Author/Subcategory/ Discipline ^a /Team Interaction ^b	Underlying Theories	Key Findings ^{c,d}
Abrams & der Pütten (2020)/team perceptions/IV/T+S	In-group identification (e.g., social identity theory); cohesion theories (e.g., group development theory); entitativity theory (e.g., formation of perceived entitativity)	<ul style="list-style-type: none"> In-group identification, cohesion, and entitativity (I-C-E) framework can be used as a theoretical basis for research on human-robot groups Multi-agent groups are similar but not the same as all-human groups Dyads have unique processes that differ from group and team processes
Bradshaw et al. (2012)/ autonomy and control/III/T		<ul style="list-style-type: none"> Autonomy and coordination in human-agent-robot teamwork should be in the focus of future research to solve current problems
Dudenhoeffer et al. (2001)/autonomy and control/III/T+S	Shared mental models, situational awareness	<ul style="list-style-type: none"> Simulations are widely used in HRT and HRI research and can help to gain insights into this field, esp. when many robots are involved
Gladden (2014)/ leadership/I/T+S	French and Raven's bases of power	<ul style="list-style-type: none"> Charismatic robotic leaders (w/charismatic authority being a manifestation of referent power) will probably emerge naturally Introduction of three possible ways of charismatic robotic leaders Robots should be evaluated as complements to human team members (rather than duplicates) to take advantage of individual abilities of humans and robots
Groom and Nass (2007)/roles of humans and robots/ III/T+S	Shared mental models	

(continued)

Table 5. (continued)

Author/Subcategory/ Discipline ^a /Team Interaction ^b	Underlying Theories	Key Findings ^{c,d}
Manikonda et al. (2007)/autonomy and control/V/T	n.i.	<ul style="list-style-type: none"> • Proposal of framework for communication and collaboration in HRTs (strong technical focus)
Musić and Hirche (2018)/autonomy and control/V/T	n.i.	<ul style="list-style-type: none"> • Proposal of control approach for robot teams
Nikolaïdis and Shah (2012)/team perceptions/IV/T	Shared mental models	<ul style="list-style-type: none"> • Proposal to use shared mental models also for HRTs
Phillips et al. (2012)/ team perceptions/ III/T+S	Shared mental models	<ul style="list-style-type: none"> • "relevant human–animal team capabilities (...) can inform and guide the design of next-generation human–robot teams" (p. 1553)
Phillips et al. (2016)/ team perceptions/II/ T+S	Shared mental models, interdependence theory	<ul style="list-style-type: none"> • Human-animal teams can be used as analogous examples for the development/set-up of effective HRTs
Samani and Cheok (2011)/leadership/II/ T+S	n.i.	<ul style="list-style-type: none"> • Ideas on emotion-laden robotic leadership, advantages of robotic leaders, modes of robotic leadership
Scheutz et al. (2017)/ team perceptions/ IV/T+S	Shared mental models	<ul style="list-style-type: none"> • Proposal of formal and computational framework for development and usage of shared mental models in HRTs based on all-human teams
Sierhuis et al. (2003)/ autonomy and control/VI/T	n.i.	<ul style="list-style-type: none"> • Discussion of perspective on teamwork and sliding autonomy
Talamadupula et al. (2014)/team perceptions/V/T	Shared mental models	<ul style="list-style-type: none"> • Proposal of "automated planning problem instance" (p. 2957)

(continued)

Table 5. (continued)

Author/Subcategory/ Discipline ^a /Team Interaction ^b	Underlying Theories	Key Findings ^{c,d}
Yazdani et al. (2016)/ autonomy and control/VII/T	n.i.	<ul style="list-style-type: none"> • Proposal of cognition-enabled robot-control framework to foster a more natural communication between humans and robots

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a “best fit”-approach and might comprise aspects of more than one considered research discipline.

^bTeam interaction: T = task interaction, T+S = task & social interaction.

^cIn most of the studies, the robot morphology, robot level, and type of embodiment are not specified. The six studies that provide information (Abrams & der Pütten, 2020; Dudenhoeffer et al., 2001; Gladden, 2014; Manikonda et al., 2007; Talamadupula et al., 2014; Yazdani et al., 2016) focus on functional robots (e.g., Growbot [Dudenhoeffer et al., 2001], Pioneer P3-AT [Talamadupula et al., 2014]) and indicate different robot levels (lower/same and higher level) and embodiments (physical robot; simulation).

^dIn most of the studies, the team setup is not specified. The two studies that provide information focus on human-directed robot teams (Musić & Hirche, 2018; Yazdani et al., 2016).

robots (Burke & Murphy, 2004), how to include humans in HRTs (Strohkorb Sebo et al., 2020), consequences of the presence of robots on human decision-making (Fuse & Tokumaru, 2020), and the optimal organizational structure (Ranzato & Vertesi, 2017). Findings from these studies indicate that, inter alia, loosely coupled teams are most successful (Ranzato & Vertesi, 2017) and specialized interaction roles might impede the inclusion of human team members in HRTs (Strohkorb Sebo et al., 2020).

Investigations of *autonomy and control* in both dyadic and multiple-member HRTs either take a general view on the effects on teamwork (Bradshaw et al., 2012) or a more specific focus on adjustable autonomy (Sierhuis et al., 2003), in both conceptual and empirical efforts (e.g., Dias et al., 2008; Gombolay, Gutierrez, et al., 2015; Goodrich et al., 2007; Sellner et al., 2006). Findings indicate that somewhat autonomous robots and shared control can facilitate the work of human team members and make HRTs more efficient (e.g., Lee et al., 2010; Lewis et al., 2010; Sellner et al., 2006). Researchers also have proposed an algorithm to predict team performance, based on the robot’s performance in interaction with human team members or when it is autonomous (Crandall et al., 2003), as well as various control approaches for human-directed robot teams (Musić et al., 2019; Musić &

Table 6. Conceptual Studies on Dyadic HRTs Related to Inter-Member Team Characteristics and Their Effects.

Author/Subcategory/ Discipline ^a /Team Interaction ^b	Underlying Theories	Key Findings ^c
Demir et al. (2020)/roles of humans and robots/VII/n.i.	Shared mental models	• “results indicate that effective team interaction and shared cognition play an important role in human-robot dyadic teaming performance.” (p. 1)

Note. ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a “best fit”-approach and might comprise aspects of more than one considered research discipline.

^bTeam interaction: T = task interaction, T+S = task & social interaction, n.i. = no information provided by author(s).

^cRobot morphology, robot level, and type of embodiment as well as team setup are not specified.

Hirche, 2018), a control framework for USAR (Yazdani et al., 2016), an “HRT planning-execution framework” (Manikonda et al., 2007, p. 92), and a simulation framework that aims to support the development of command and control architectures (Dudenhoeffer et al., 2001).

Conceptual studies of *leadership* in HRTs cite potential stereotypes of robotic leaders (Gladden, 2014) or look into emotions evoked by, benefits of, and possible modes of robotic leadership (Samani & Cheok, 2011). These studies present robotic leadership as a future phenomenon and, in some cases, argue that it will emerge naturally (Gladden, 2014). Empirical studies also introduce a scalable, generalizable mathematical framework to model leader and follower behaviors in multiple-member HRTs and show that this framework enables robots to influence human teams (Kwon et al., 2019).

Finally, *team perceptions* might take the form of shared mental models, which have been predicted (e.g., Nikolaidis & Shah, 2012) and studied to determine their influence on team performance (Gervits et al., 2020), which appears positive. In addition, a conceptual framework of in-group identification, cohesion, and entitativity relies on parallels with dynamics in all-human teams (Abrams & der Pütten, 2020). Several studies investigate robots as in-group members of multiple-member or dyadic HRTs and identify positive effects on robot acceptance and anthropomorphization (e.g., Eyssel & Kuchenbrandt, 2012; Fraune et al., 2017). Another related topic pertains to the parallels between HRTs and human-animal teams, such as USAR teams that include rescue dogs (e.g., Phillips et al., 2016). Arguably, human-animal teams might provide models for developing HRTs.

Table 7. Empirical Studies on Multiple-Member HRTs Related to Inter-member Team Characteristics and Their Effects.

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/ Participants/Time Frame ^f	Underlying Theories	Independent Variable(s) ^g	Dependent Variable(s) ^h	Key Findings
Burke and Murphy (2004)/roles of humans and robots/VII	Functional/↓ (Inuktun Micro Variable Geometry Tracked Vehicle [n = 32], Inuktun Microtracs robot [n = 1])/ Physical robot	T  ... 	n = 33 (two field studies)/ experienced firefighters seeking USAR certification/ C	Shared mental models, situational awareness	• Operator situational awareness (+) • Goal-oriented team communication (+)	• Task performance	<ul style="list-style-type: none"> "a minimum 2:1 human-to-robot ratio is required for effective robot-assisted technical search in USAR" (p. 307) • Goal-oriented team communication and a shared mental model of the search space and the task lead to better task performance • Proposal of performance prediction algorithm for HRTs
Crandall et al. (2003)/ autonomy and control/I	n.i./n.i.	T  	n_1 = 13, n_2 = 23/ n.i./C (six 5-minute sessions each)	n.i.	n.i.	• Performance (+)	<ul style="list-style-type: none"> • Challenges of enabling sliding autonomy in HRTs can be overcome by the presence of six key capabilities (requesting help, maintaining coordination, situational awareness, granularity, prioritization, learning)
Dias et al. (2008)/ autonomy and control/VI	Functional (Pioneer, Segway ER) /↓, ↔/Physical robot	T    	n.i./n.i./C (15 minutes run)	Sliding autonomy methodology	Sliding autonomy	• Performance (+)	<ul style="list-style-type: none"> • Participants favored the ingroup over the outgroup, and humans over robots. Group had a greater effect than Agent, so participants preferred ingroup robots to outgroup humans." (p. 142)
Fraune et al. (2017)/team perceptions/V	Functional (Mugbot)/ ↔/Physical robot competing teams	T + S  	n = 48/21 f/C	Group theory, social identity • Agent (human, robot)	• Liking (higher for in-group and humans in most cases) • Authoritarianism (higher for ingroup in all cases)	• Presence of robot considering group norms (vs. no robot)	<ul style="list-style-type: none"> • "Robots attempt to comply with a group norm affects human's decision-making" (p. 5608)
Fuse and Tokumaru (2020)/roles of humans and robots/V	Humanoid (RoBoHol)/n.i./ Physical robot	T + S  	n = 14/japanese university students/ C (5 rounds)	n.i.	n.i.	• Change in answers given (+ for change between round 1 and 2, for others n.s.)	(continued)

Table 7. (continued)

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Setup ^d	Data Basis/ Participants/Time Frame ^e	Underlying Theories	Independent Variable(s) ^f	Dependent Variable(s) ^g	Key Findings
Gervits et al. (2020)/team perceptions/I	Humanoid PR2 by Willow Garage/ → Simulation/virtual robot	T ○ ■ ■	n = 26 (from 36 originally recruited)/ 19 m; age: M = 24.9 years (SD = 8.6); from University/ campus C	Shared mental models	• Robot shared mental models	• Performance (+)	• Shared mental models help to improve performance and efficiency of HRTs
Gombolyay, Gutiérrez, et al. (2015)/ autonomy and control/I	Functional/ →,↑/Physical robot	T + S ○ ■ ○	n = 24/14 m, 10 f; age: range 20–42 (mean age of 27.7 years); recruited via email and around a university campus/ C	• Presence of robot • Robot decision- making authority • Understanding of co- leader (-/+)	• Team efficiency (+/+) • Perceived likability, appreciation, and authority to the robot	• People prefer to give control authority over robotic teammates, however, providing robots more strongly improves their perceived value compared to giving similar authority to a human team mate" (p. 293)	
Goodrich et al. (2007)/ autonomy and control/I	n.i./↓/Simulation/virtual robot; physical robot	T ○ ■ ■	n = 80 (in four experiments with 16, 23, 11, 30 participants resp.)/ n.a./C ○ ■ ■	• Attention management aids (+) • Adaptive autonomy (+) • Information abstraction (+)	• Individual and team autonomy	• People tend to "assign a disproportionate amount of work to themselves when working with a robot (...) rather than human team mates only" (p.293)	

(continued)

Table 7. (continued)

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d /Team Setup ^e	Data Basis/ Participants ^f /Time Frame ^g	Underlying Theories	Independent Variables ^h	Dependent Variable(s) ⁱ	Key Findings ^j
Kwon et al. (2019)/ leadership ^l	n.i.↔, ↓/No embodiment	T 	n.i./n.i./n.i. n. humans = {3, ..., 6}	Adaptive leadership theory	• Robot intervention (use of leader- follower graph)	• Leadership scores (+) • Task execution time (+) • Success rate (+)	• Leader-follower graphs enable robots to influence human teams through "redirection of [the] team, or lead- ing of a team towards the optimal goal" (p. 2) • Automating path planning improved system performance. Effects of team organization were equivocal." (p. 438)
Lee et al. (2010)/ autonomy and control/VII	Functional (Pioneer P2- AT robots)/ ↓/Simulation/virtual robot (USARSim robotic simulation)	T 	n = 120 (in 60 teams)/ University of Pittsburgh community, paid, no previous experience with robot control/C n_robots=24	n.i.	• Robot autonomy (+) • Team organization (+/-)	• System performance	• Automation of path planning in USA-HRTs helps to improve performance • Effects of team organization favored operator teams who shared authority for the pool of robots" (p. 617)
Lewis et al. (2010)/ autonomy and control/VII	Functional (Pioneer P2- AT)/↓/Simulation	T 	n = 120 (in 60 teams)/ University of Pittsburgh community, paid, no previous experience with robot control/C n_robots=24	n.i.	• Shared team authority (+)	• System performance	• Proprietary control architecture for HRTs
Musci et al. (2019)/ autonomy and control/V	Functional KUKA LWR 4+/↔, ↓/Physical robot	T 	n = 48/12 IF/C (experiment was performed 10 times/participant)	n.i.	• Type of feedback (no vs. binary vs. relative)	• Task performance (n.s.+)	• Feedback through wearable finger tip devices helps to increase performance • Loosely coupled teams were found to be the most successful compared to tightly coupled hierarchical and consensus groups
Ranzani and Vertesi (2017)/ roles of humans and robots/VII	Functional/↓/Physical robot (remote)	T + S n. human = ? ... 	n = 30 (6 teams of 5 each with 3.2 gender ratio)/nJC	n.i.	• Team organization structure (loose) • Efficiency (+) • Communication (+) • Teammate trust (+)		

(continued)

Table 7. (continued)

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Setup ^d	Data Basis/ ^e Time Frame ^f	Participants ^g /Team	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ^h	Key Findings
Sellner et al. (2006)/ autonomy and control ⁱⁱ	Functional/Roving Eye, T Mobile Manipulator, (Crane)/Physical robot	○ □□□	n = 2, n ₂ = 3 ^j /: expert users of the robotic system; 2; n.i./C	Situational awareness, concept of sliding autonomy	• Autonomy	• Time to completion (-) • Success rate (+) • Human workload (-)	• Robots purposefully asking for help result in more efficient and robust systems and enable human operators to gain situational awareness	
Strohkorb Sebo et al. (2020)/ roles of humans and robots/	Humanoid (Iubo)↔ (not specified)/ Physical robot	T + S/ Round 1: ○○○□□	n = 78 (in 26 teams)/ 38 f; age: M = 16.82 years (SD = 0.72); from high school program held at Yale University/C	Social identity theory	• Specialized robot liaison (-) • Robot supportive utterances (+ /n.s.)	• Human inclusion (-/+)	• “specialized roles may hinder human team member inclusion, whereas supportive robot utterances show promise in encouraging contributions from individuals who feel excluded.” (p. 309)	

Round 2:
○○○□

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a “best fit”-approach and might comprise aspects of more than one considered research discipline.

^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↔ = robot on same level, ↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction.

^eTeam setup: ○ = human, □ = robot.

^fParticipants: f = female, m = male.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEmpirical findings: (-) = negative effect, (+) = positive effect, (n.s.) = not significant.

Disciplines, Study Characteristics, and Underlying Theories. Most of the 34 studies (30 of multiple-member HRTs, 4 of dyadic HRTs) in this category are rooted in HRI (9 studies) and USAR (8), along with cognitive science (6), military (4), robotics (4), management (2), and space (1) research fields. Despite finding a couple of studies that reflect a managerial perspective and many studies with an HRI foundation, we note the considerable number of studies with a USAR or military background. The 18 empirical studies are all cross-sectional, online, or laboratory experiments, though one field study pertains to USAR (Burke & Murphy, 2004). The team setups are mostly autonomous mixed teams (6 studies) or human-directed robot teams (8); one study considers a human/robot-directed mixed team with a human and robotic co-lead and a human assistant (Gombolay, Gutierrez, et al., 2015).

In terms of theoretical foundations, several researchers employ in-group identification theories (e.g., social identity theory [Tajfel, 1974]). Quite a few studies use the theory of (shared) mental models (Rouse & Morris, 1986) and further consider situational awareness (Endsley, 1995). Finally, some researchers draw on sliding autonomy methodology (Sellner et al., 2006) for HRTs.

Limitations. Some empirical studies rely on small sample sizes of less than 30 participants (e.g., Gombolay, Gutierrez, et al., 2015; Ranzato & Vertesi, 2017), and many feature quite young participants. The limitations of laboratory and cross-sectional studies, as detailed for Category 1, also hold for the studies in Category 2. We find slightly more variability in the considered team setups, but further research could broaden the considered constellations. Most studies in this category already leverage theoretical bases though.

Category 3: Effects of Team Processes

Focus Areas and Major Findings. Studies of team processes and their effects account for most extant research on HRTs (see Tables 9–12), perhaps because, unlike HRI or HRC, HRTs tend to be long-term in nature, so they require careful consideration of relevant processes, which are at least partially unique to each team (Abrams & der Pütten, 2020). Furthermore, HRTs have long been popular, especially in military and USAR settings, which require sophisticated coordination to fulfill their missions.

Researchers note some prerequisites of successful (*physical*) coordination in HRTs (Woods et al., 2004). When studying HRTs, researchers draw heavily on the concepts of coordination behaviors in all-human dyads that appear promising (e.g., Bradshaw et al., 2009; Iqbal & Riek, 2017; Shah & Breazeal, 2010) or focus on indirect perceptions. Empirical studies of training (e.g.,

Table 8. Empirical Studies on Dyadic HRTs Related to Inter-Member Team Characteristics and Their Effects.

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^{c,d} / Type of Embodiment	Team Interaction ^d / Team setup ^e	Data Basis/ Participants ^f /Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ⁱ	Key Findings
Eysel and Kuchenbrandt (2012) team perception[s]	Humanoid/ ↔/Videotape/ image of robot	T+S / n.i.	n = 78/German university students, 37 m, 40 f; age: M = 23.27 (SD = 3.29)/C	Social identity theory	• Robot in in- group (vs. out-group)	• Warmth (+) • Mind attribution (+) • Psychological closeness (+)	• Participants "rated the in-group robot more favourably . . . [and] also anthropomorphized it more strongly than the out- group robot" (p. 724)
Kuchenbrandt et al. (2013)/ team perception[s]	Humanoid (NaO)/n.i./ Physical robot	T+S / n.i.	n = 45/25 m, 18 f, age: M = 24.81 years (SD = 5.00), German university students/C	Social identity	• Robot in in- group (vs. out-group)	• Contact intentions (+) • Design preference (+) • Implicit anthropomorphization of robot (+)	• "Perceived in-group membership with the robot resulted in a greater extent of anthropomorphic inferences about the robot and more positive evaluations." (p. 409) • Additionally, participants with the robot in their in-group "showed greater willingness to interact with robot (+) in general." (p. 409)

(continued)

Table 8. (continued)

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^{c,d} / Type of Embodiment	Team Interaction ^d / Team setup ^e	Data Basis/ Participants ^f / Time Frame ^g	Underlying Theories	Independent Variables ^h	Dependent Variable(s) ⁱ	Key Findings
Marble et al. (2004) autonomy and control/VII	Functional/ Physical robot	T + S  	n = 11 / f, 10 m; 4 expert users, 7 no or some prior experience, INEEL employees/L (4 sessions in direct succession)	n.i.	• Dynamic robot autonomy	• Target detection (+) Situation awareness (+)	<ul style="list-style-type: none"> • Autonomy of a robot should be adjustable to allow for situation awareness and task completion • Participants varied greatly in their ability to trust a robot (i.e., allow autonomy) • Performance benefits from practice

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↔ = robot on same level, ↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction.

^eTeam setup: ○ = human, □ = robot.

^fParticipants: f = female, m = male.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEmpirical findings: (−) = negative effect, (+) = positive effect, (n.s.) = not significant.

Nikolaidis et al., 2015; You & Robert, 2016), coordination strategies and frameworks (Iqbal et al., 2016; Shah et al., 2011; H. Wang et al., 2010), and automated cooperation (Gao et al., 2012; J. Wang et al., 2008) all note positive effects, such as on team fluency, perceived robot trustworthiness, or team performance in HRTs.

Research on *communication in HRTs* for multiple-member HRTs identifies information flows supported by sensor networks (Kantor et al., 2006), uses of “Human–Robot Interaction Operating Systems” (Fong et al., 2006), back-channeling (Jung et al., 2013), real versus simulated videos (Canning et al., 2014), and conflict moderation through robots (Jung et al., 2015). For dyadic and multiple-member HRTs verbal versus non-verbal communication (e.g., Breazeal et al., 2005; Ciocirlan et al., 2019; Nikolaidis et al., 2018; Williams et al., 2015), based on partner’s knowledge and behavior (Lo et al., 2020) was examined. These studies mostly reveal positive effects of (extensive) communication in HRTs (Tables 9–12). Another research pathway involves communication interfaces (Marge et al., 2009), communication models (e.g., Kruijff, Janíček, et al., 2014; Nakano & Goodrich, 2015), and the design/implementation of HRT for conversational HRI (Zheng et al., 2013).

Research into *collaboration in HRTs* refers to linkages explicitly established in an HRT context, which should not be confused with the broader topic of HRC. Conceptual studies range in focus, including the optimal setup of “hybrid teams” with robots, virtual agents, and humans as team members (Schwartz et al., 2016), collaboration challenges (Fiore et al., 2011), collaborative tools (Bruemmer & Walton, 2003), the development of collaborative robotic teammates (Hayes & Scassellati, 2014), dynamic peer-to-peer teaming (Tang & Parker, 2006), task-oriented collaboration with semantic-based path planning (Yi & Goodrich, 2014), decision-making (Stewart et al., 2012), and mutual initiatives (Bruemmer et al., 2002). Researchers also examined collaboration frameworks (e.g., Hoffman & Breazeal, 2004; Marble et al., 2003) for dyadic HRTs and a framework of joint action perception (Iqbal et al., 2015) for multiple-member HRT. Finally, for *trust*, three studies of dyadic HRTs discuss and examine the impact of appropriate trust (i.e., beneficial for team performance) (Chen et al., 2020; Ososky et al., 2013) and its measurement (Freedy et al., 2007).

Disciplines, Study Characteristics, and Underlying Theories. More than one-third of the 55 studies in this category (35 studies of multiple-member HRTs, 19 of dyadic HRTs) are rooted in HRI (14 studies), cognitive science (12), or USAR (11), followed by robotics (10), military (7), and space (1) research. Most of the 32 empirical studies are cross-sectional or do not reveal the time frame for their experiments. Burke and Murphy’s (2007) longitudinal study includes

Table 9. Conceptual Studies on Multiple-Member HRTs Related to Team Processes and Their Effects.

Author/Subcategory/ Discipline ^a	Robot Morphology/ Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Underlying Theories	Key Findings
Alboul et al. (2008)/ (physical) coordination//	n.i. / ↓ / Physical robot	T ○ ... ○ □ ... □ T+S / n.i.	n.i.	• Proposal of theoretical framework for navigation in HRTs
Bradshaw et al. (2009)/(physical) coordination//	n.i. / n.i. / n.i.	Coordination theory		• Coordination in human-agent-robot teams as an essential ingredient of joint activities: Fulfillment of teamwork model and resulting expectations towards communication (towards leader and colleagues) will allow robots to be seen as team mates
Brown et al. (2005)/ (physical) coordination//	n.i. / ↓ / n.i.	T ○ ... ○ □ ... □	n.i.	• Proposal of reference framework for HRTs
Bruemmer et al. (2002)/ collaboration//	Functional (augmented ATRVIR) ↓, (↔, ↑)/Physical robot	T / n.i.	Role theory, shared mental models	• Proposal of a framework for mutual-initiative in HRTs
Bruemmer and Walton (2003)/ collaboration//	Functional (augmented ATRVIR) / n.i. / n.i.	T / n.i.	Shared mental models	• Discussion of approach for control architecture for human-robot teams in a military context

(continued)

Table 9. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Underlying Theories	Key Findings
Fiore et al. (2011)/ collaboration/III	n.i. / n.i. / n.i.	T+S / n.i.	n.i.	<ul style="list-style-type: none"> Successful interactions in HRTs are based on organizational (and corresponding roles), social, and cultural models Research has to work on gaining insights into how robots fit into such models and how they can understand organizational, social, and cultural factors Proposal of four research questions on collaboration in HRTs
Hayes and Scassellati (2014)/ collaboration/I	n.i. / n.i. / n.i.	T+S / n.i.	n.i.	<p>Situational awareness</p>
Krujiff, Janicek, et al. (2014)/ communication/VII	Functional ("General", P3-AT; NIFTi UGV and UAV) / Physical robot	T + S		<ul style="list-style-type: none"> Proposal and validation of "user-centric design methodology in developing systems for human-robot teaming in Urban Search and Rescue" (p. 1) Robot acceptance is important
Krujiff et al. (2012)/ communication/III	Functional /↓/Physical robot	T		<p>Situational awareness</p>

(continued)

Table 9. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level/Type of Embodiment	Team Interaction ^d / Team Setup ^e	Underlying Theories	Key Findings
Krijff-Korbayová et al. (2015)/ communication/V	Functional (NIFTi UGV and UAV) ↓/Physical robot	T  n_humans = ? n_robots = 4	Situational awareness	<ul style="list-style-type: none"> Description of the project "TRADR: long-term human-robot teaming for robot assisted disaster response" (p. 193) and the user-centric design approach that is used Proposal of "new interface concept, a Graphical Narrative Interface (GNI)" (p. 634) "We hypothesize that the GNI allows users to search and analyze spatiotemporal information more easily and quickly than a typical GUI." (p. 634) Proposal of an agent-based "architecture for Urban Search and Rescue and a methodology for mixing real-world and simulation-based testing" (p. 72)
Nakano and Goodrich (2015)/ communication/V	n.i./n.i./n.i.	n.i. / n.i.	n.i.	<ul style="list-style-type: none"> "We hypothesize that the GNI allows users to search and analyze spatiotemporal information more easily and quickly than a typical GUI." (p. 634)
Nourbakhsh et al. (2005)/ communication/VII	n.i./n.i./n.i.	T / n.i.	n.i.	<ul style="list-style-type: none"> Proposal of an agent-based "architecture for Urban Search and Rescue and a methodology for mixing real-world and simulation-based testing" (p. 72)
Schwartz et al. (2016)/ collaboration/I	Humanoid (Aila), functional (Artemis, Compi)/n.i./n.i.	n.i. / n.i.	n.i.	<ul style="list-style-type: none"> Discussion of setup of teams with robots, virtual agents and humans as team members ("hybrid teams")
Stewart et al. (2012)/ collaboration/V	n.i./n.i./n.i.	Decision theory	n.i.	<ul style="list-style-type: none"> Proposal of decision-making model for HRTs

(continued)

Table 9. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Underlying Theories	Key Findings
Tang and Parker (2006)/ collaboration/l	n.i./↔/n.i.	T / n.i.	Information invariance theory, schema theory	<ul style="list-style-type: none"> Proposal of human–robot teaming approach ASyMTRe, dealing “with the issue of how to organize robots into subgroups to accomplish tasks collectively based upon their individual capabilities” (p. 27)
Woods et al. (2004)/ (physical) coordination/ll	n.i./n.i./n.i.	T / n.i.	n.i.	<ul style="list-style-type: none"> Exploration of issues with human–robot coordination
Yi and Goodrich (2014)/ collaboration/V	n.i./↓/n.i.	T ○□	Shared mental models	<ul style="list-style-type: none"> Proposal of collaboration model using shared mental models

Note. ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a “best fit” approach and might comprise aspects of more than one considered research discipline.
^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↔ = robot on same level, ↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction, n.i. = no information provided by author(s).

^eTeam setup: ○ = human, □ = robot.

two runs over a 2-day period though. We find simulation studies (H. Wang et al., 2010), laboratory studies (You & Robert, 2016), and field experiments (Burke & Murphy, 2007). Studies of multiple-member HRTs mostly focus on task interactions, and the setups include human-directed robot teams (14) or autonomous mixed teams (9 studies) or else do not specify. With dyadic HRTs, researchers examine autonomous human–robot pairings (12), human-directed robots (4), or do not disclose their setups (4).

In this category, almost half of the studies report theoretical considerations. These range from coordination theory (Malone & Crowston, 1990), to role theory (Braga, 1972), and social signaling and back-channeling (Dennis & Kinney, 1998). Again, multiple studies rely on shared mental models (Rouse & Morris, 1986). Another popular theory is situational awareness, which is the basis for various studies as detailed in Tables 9–12.

Limitations. The study samples tend to be small and young; and many studies use laboratory settings to conduct cross-sectional experiments. Social robots are underrepresented relative to functional robots, despite being developed specifically to interact with people (Kirby et al., 2010), implying their particular suitability for HRTs. With regard to the theoretical basis, we see potential for studies to strengthen the theoretical soundness of the examined phenomena by integrating behavioral theories.

Category 4: Moderating Effects

Focus Areas and Major Findings. Moderator variables influence the strength of the relationships between independent and dependent variables (Baron & Kenny, 1986). These effects often stem from environmental or situational factors (Baron & Kenny, 1986), prompting researchers to examine moderating effects for multiple-member HRTs that reflect human capabilities (Claure et al., 2020), curiosity and control (You & Robert, 2016), task complexity (Jung et al., 2013), or number of sessions (Correia, Petisca, et al., 2019). For dyadic HRTs, researchers also examine the effects of number of sessions (Marble et al., 2004) and remote system experience (Marble et al., 2003). Most of these proposed moderators appear to exert positive effects on the relationships of the studied independent and dependent variables, as indicated by Tables 13 and 14. For example, curiosity positively moderates the effect between training and individual performance (You & Robert, 2016), task complexity positively influences the relationship between back-channeling and team functioning (Jung et al., 2013), and target detection increases with the number of sessions (Marble et al., 2004). Additional details on these studies are available in the descriptions in their respective main categories.

Table 10. Conceptual Studies on Dyadic HRTs Related to Team Processes and Their Effects.

Author/Subcategory/ Discipline ^a	Robot Morphology ^b /Robot Level ^c /Type of Embodiment	Team Interaction ^d Team Setup ^e	Underlying Theories	Key Findings
Breazeal, Brooks, et al. (2004)/collaboration/I	Humanoid (Leonardo) ↔/Physical robot	T + S ○ □	Collaborative discourse theory, joint intention theory	<ul style="list-style-type: none"> The authors follow a perspective "of a balanced partnership where the human and robot maintain and work together on shared task goals" (p. 270) Paper gives an overview of the different robotic features of the robot Presentation of approach for collaborative human–robot teamwork
Breazeal, Hoffman, and Lockerd (2004)/ collaboration/I	Humanoid (Leonardo) ↔/Physical robot	T + S ○ □	Collaborative discourse theory, joint intention theory	<ul style="list-style-type: none"> Proposal and validation of model for indirect perception in HRTs "Trust in HRTs should not simply be maximized, the goal should be to have appropriate trust (both in intention and ability)" Implicit and explicit communication in HRT give insights into how robots in HRTs could act "A robot should respond to communications differently, depending on whether they are implicit, explicit, verbal only, nonverbal only (gesture), or combined." (p. 244)
Oh et al. (2015)/(physical) coordination/V	n.i./n.i./n.i. (no robot involved in experiments)	T+S / n.i.	n.i.	<ul style="list-style-type: none"> Shared mental models
Orosky et al. (2013)/trust/ IV	n.i./↔/Physical robot	T + S ○ □	Shared mental models	<ul style="list-style-type: none"> Trust in HRTs should not simply be maximized, the goal should be to have appropriate trust (both in intention and ability)
Shah and Breazeal (2010)/ (physical) coordination/ IV	n.i./n.i./n.i. (no robot involved in experiments)	T+S / n.i.	Shared mental models	<ul style="list-style-type: none"> Implicit and explicit communication in HRT give insights into how robots in HRTs could act
Visser et al.(2020)/trust/IV	n.i./↔/n.i.	T+S / n.i.	Theory of mind, trust theories	<ul style="list-style-type: none"> Proposal of human–robot team trust model that has a longitudinal perspective on the development and calibration of trust in HRTs

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↑ = robot on same level, ↑↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction, n.i. = no information provided by author(s).

^eTeam setup: ○ = human, □ = robot.

Disciplines, Study Characteristics, and Underlying Theories. The 7 studies (4 of multiple-member HRTs, 3 of dyadic HRTs) in this category come from USAR (3 studies), cognitive science (2), robotics (1), and management (1) research. Researchers use both functional and humanoid robots to conduct cross-sectional (4 studies) online or laboratory experiments. Two studies reveal longitudinal designs, with 3 or 4 sessions, respectively, but another does not disclose its study setup. The teams represented by collaborative multiple-member HRTs are autonomous mixed teams (3 studies) or a human-led robot team (1 study). The dyadic HRTs involve human-directed robots engaged in both task and social interaction (2 studies). Three studies ([Claure et al., 2020](#); [Jung et al., 2013](#); [Marble et al., 2004](#)) adopt theoretical bases for their examinations, as detailed in the respective main categories.

Limitations. Relatively few studies in our sample consider moderating effects, and only two of them are longitudinal. It is unlikely that “one-size-fits-all” applies to HRTs ([Stock, 2004](#)), so moderators should be investigated further, especially with long-term investigations of teams involving both humans and robots.

Category 5: Integrative and Overarching Studies

Focus Areas and Major Findings. In this last category, we gather studies that propose overarching frameworks, metrics, and HRT designs; publications that address ethics in HRTs; and investigations of the inputs, processes, and outputs of HRTs, with an integrative perspective ([Tables 15–17](#)). The *overarching frameworks, metrics, and HRT design* studies include proposals of new metrics and taxonomies, beyond existing ones that focus on HRI or HRC ([Burke et al., 2008](#); [Pina et al., 2008](#)). They feature components for evaluating team performance ([Pina et al., 2008](#); [Visser et al., 2006](#)). [Ma et al. \(2018\)](#) also consider general design concepts. As an emerging topic, *ethics in HRTs* appears in conceptual investigations of both dyadic and team interactions ([Arnold & Scheutz, 2017](#); [Tamburrini, 2009](#)). Finally, *integrative studies* of mediated relationships in HRTs are relatively recent ([Tables 15–17](#)). Two studies deserve particular consideration: [Oleson et al. \(2011\)](#) identify a few antecedents of trust in HRTs (e.g., human, robot, and environmental characteristics). Then with an input–mediator–output–input (IMOI) approach, an extension of the established IPO framework for teams, [You and Robert \(2018b\)](#) offer a dynamic perspective on HRTs that might inform studies of long-term HRTs.

Disciplines, Study Characteristics, and Underlying Theories. The 15 studies in this category (13 of multiple-member HRTs, 2 of dyadic HRTs) are rooted in

Table II. Empirical Studies on Multiple-Member HRTs Related to Team Processes and Their Effects.

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level/Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants ^f / Time Frame ^g	Underlying Theories	Independent Variables ^h	Dependent Variable(s) ^h	Key Findings
Burke and Murphy (2007)/ collaboration/VI	Functional (Inertial) Micro Variable Geometry Tracked Vehicle (GV) robot/ Physical robot	T 	n = 6/29% m.; majority between 35-54 years; NASA-USAR task-force personnel, (two runs) 20 minutes over 2-day period; final n = 50 (# teams completing both runs)) n_1 = 24, n_2 = 137, n_3 = 183 (mTurk; 1: 1; f; age: range 18-31 years, M = 20.88 (SD = 2.59), all right-handed, fluent in English; 2: 48 f; age: range: 18-60 years, median = 31, US residents; 3: 91 f; age: range: 18-60 years, median = 31, US residents/C	Shared mental models, situational awareness	• Remote shared visual presence (+) • Visual contact (n.s.)	• Team performance	• Remote shared visual presence (+)
Canning et al. (2014)/ communication/VI	Humanoid & Design MDS, Willow Garage PR2, VGo, iRobot Createy/ J/Simulation/ virtual robot, Video/Image of robot	T / 1;  2 & 3; 	n.i.		• Video feed type (real vs. simulated)	• Task performance • Perceived collaboration (+ for real video)	• Examination of robot perceptions in remote team settings • Realism of the [video]feels becomes important when the human teammate knows about the robot's appearance and they work together on a task" (p. 438) • See study for details on results and interaction effects of study 3
Fong et al. (2006)/ communication/VI	Functional humanoid (K10 rover, Robonaut) / +>/Physical robot	T 	n.i./n.i./C	n.i.	• Reliability of robots (in)dependence, as a result of understanding of communication)	• Productivity (amount of useful work, exposure time in space) (+)	• Software frameworks are being developed (e.g., HRIO/S) to allow for effective work of humans and robots
Gao et al. (2012)/(physical) coordination/VI	n.i./Simulation/ virtual robot (USARsim)	T 	n = 48/19 f; age: range 19-47 years, M = 26.6 (SD = 5.5); 33 of them students/C n robots = 24	n.i.	• Team structure (pooled, sector) • Search guidance (no, suggestion, + for suggested guidance in sector enforced)	• Task performance • Task completion time n.s. for other conditions)	• Automated search guidance neither increased nor decreased performance" (p. 81) • Search guidance decreased average task completion time in sector teams" (p. 81) • "pooled teams experienced lower subjective workload than sector teams" (p. 81)

(continued)

Table II. (continued)

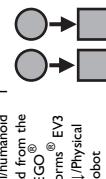
Author/Subject category/ Discipline	Robot Morphology/ Robot Level/T Type of Embodiment	Team Interaction/ Team Setup ^d	Data Basis/Participants/ Time Frame ^e	Underlying Theories	Independent Variables ^h	Dependent Variable(s) ^h	Key Findings
Iqbal et al. (2015)/ collaboration/V	Functional (Turtlebot)/ ↔Physical robot	T 	n = 2/n.i./n.i.	n.i.	* n.i.	* n.i.	• Proposal of an event-based model to enable robotic action in human-robot interaction
Iqbal et al. (2016)/physical coordination/V	Functional (turtlebot)/ ↔Physical robot	T / pilot:  main: 	n.pilot = 7, n.man = 27 (in 9 groups) pilot: 3 f; main: 14 f, age: M = 22.93 (SD = 3.98), mainly students/C	Robot movement based on synchronization- index based anticipation (vs. based on event cluster-based anticipation)	* Synchronization (+) • Robot Timing Appropriateness (+)	* Synchronization (+)	• Proposal and validation of “approach to enable robots to perform human group motion in real time to anticipate future actions and synthesize their own motion accordingly” (p. 909) * “the robot performs better when it has an understanding of high-level group motion than when it does not” (p. 909)
Iqbal and Riek (2017)/ (physical) coordination/V	Functional (turtlebot)/↔ Physical robot	T  	n = 18 (in 6 groups)/11 f; age: M = 24.7 years (SD = 4.5); undergrad and grad students/C	n.i.	* n.i.	* n.i.	• “results might suggest that an addition of a robot with heterogeneous behavior to a group significantly reduces the overall group coordination, and might be an important indicator of human–robot group dynamics.” (p. 1716)
Jung et al. (2013)/ communication/VII	Humanoid (Maddox and Nexus), functional (UAV, not specified)/ ↔Physical robot	T + S  	n = 73/age: range 18–40 years (M = 25.0, SD = 6.19); from university community/C	Back-channeling, social signaling	* Back-channeling	* Team functioning (+) • Perceived robot engagement (+) • Perceived robot competence (-)	• “subtle back-channeling by robots in human–robot teams helped team functioning (lower stress, lower cognitive load) and perceived engagement of the robots, especially when the task was complex, but at the same time led to robots being seen as less competent.” (p. 1563) • “the biggest benefit from back- channeling in human–robot teams may be seen when tasks are demanding and complex.” (p. 1563)

Table II. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants/ Time Frame ^f	Underlying Theories	Independent Variable(s) ^g	Dependent Variable(s) ^h	Key Findings
Jung et al. (2015)/ communication/V	Functional (Pioneer 3 robot base + OWI robot arm + arm- control board + speaker) ↔/Physical robot	T + S 	n = 106 (in 53 teams)/ 55 m; age: range 18-65 Years (M = 24.5, SD = 8.0); recruited from university/C	n.i.	• Robot intervention	• Awareness of conflict (+)	• "We found that the robot's repair interventions increased the groups' awareness of conflict after the occurrence of a personal attack thereby acting against the groups' tendency to suppress the conflict." (p. 229)s
Kantor et al. (2006)/ communication/VII	Functional/J/Physical robot	T 	n.i./n.i./C	n.i.	• n.i.	• Team performance (n.s.)	• Perceptions of team members' contributions (n.s.)
Kruifjff-Korbyayova, et al. (2014)/ communication/VII	Functional (NIFTI UGV and UAV)/ J/Physical robot	T 	n.i./n.i./n.i.	Situational awareness	• n.i.	• Team performance (n.s.)	• Description of the experiences in designing, developing and deploying systems for USAR
Marge et al. (2009)/ communication/V	Functional (Pioneer P2-DX, Segway Robotic Mobility Platform (RMP)/ ↔/Simulation/ virtual robot	T + S 	n.i./n.i./n.i.	n.i.	• n.i.	• n.i.	• Description of the human- robot-interface TeamTalk
Nevatia et al. (2008)/ collaboration/VII	Functional/ J/Simulation/ virtual robot	T  n_robots = {2, 3, 4, 5}	n.i./n.i./n.i.	n.i.	• n.i.	• n.i.	• Proposal and validation of an "integrated system for semi-autonomous cooperative exploration, augmented by an intuitive user interface for efficient human supervision and control" (p. 203)
H. Wang et al. (2010)/ (physical) coordination/ VII	Functional (Pioneer P2-AT)/ J/Simulation/ virtual robot (USARSim robotic simulation)	T  n_robots = 24	n = 60 participants (acting in teams of 2 → 30 teams) University of Pittsburgh, paid, no previous experience with robot control	Situational awareness	• Automated path planning (+)	• System performance	• Having a human in the loop improves task performance, especially with larger numbers of robots" (p. 2103)
					• Team organization (shared authority for robots) (+)		• For USAR tasks, automated path planning helps to improve team accuracy and performance
							• Sharing authority for robots during team organization also helps to improve performance (re/accuracy and finding)

(continued)

Table II. (continued)

Author/Sub-category/ Discipline ^a	Robot Morphology/ Robot Level ^b /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants' Time Frame ^f	Underlying Theories	Independent Variable(s) ^g	Dependent Variable(s) ^h	Key Findings
J. Wang et al. (2008)/ (physical) coordination/ IV	Functional (PDX) robots, Zergs/ ↓Simulation/ virtual robot	T 	n = 9; age: range 19-33 years; from Pittsburgh university/C	Crandall's neglect tolerance model, situational awareness	• Needed physical proximity	• Team performance (-) • Coordination demands (n.s.)	• "Automating cooperation [by using subtasks] reduced CD [coordination demands] and improved performance." (p. 9)
Williams et al. (2015)/ communication/IV	Functional (VGo, Romp)/ ↓Physical robot	T 	n = 28, n ₂ = 28 / 1&2: 14 f, age: range 18-65, mostly students/C	n.i.	• Robot-robot communication (verbal, silent)	• Perceived creepiness • silent communication of task- dependent, human- understandable information + for silent communication	• "silent communication of task- dependent, human- understandable information among robots is perceived as creepy by cooperative, co- located human teammates" (p. 24)
You and Robert (2016)/ (physical) coordination/ IV	Functional/humanoid (adapted from the LEGO [®] Mindstorms [®] EV3 sets)/Physical robot	T 	n = 60/36 f; age: M = 22.86 years (SD = 4.51); from university in US/C	n.i.	• Training	• Perceived efficiency of the robot (1 & 2; n.s.) • Perceived cooperativeness of the perceived perceptions of that robot" (p. 38)	• "increased natural language interaction with a robot enhances humans' general perceptions of that robot" (p. 38)

(continued)

Table II. (continued)

Author/Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants ^f / Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ⁱ	Key Findings
Zheng et al. (2013) ^j	Humanoid (Robovie-II) -> customer & operator; n.a.; simulation: simulation/virtual robot; case study: physical robot	T 	n_customer = 15, n_operator = 16; n_simulation = 15; n_case_study=n.i./customer: 8 f, age: M = 22 years; operator: 7 f, age: M = 21 years; simulation: 6 f, age: M = 20 years; case study: n.i.; all Japanese undergrad students/C	n.i.	n.i.	n.i.	• Introduction of simulation tool for 'models for operation timing, customer satisfaction and customer-robot interaction' (p. 843), and 'techniques for managing interaction flow and operator task assignment' (p. 843)

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.
^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↑ = robot on same level, ↑↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction, n.i. = no information provided by author(s).

^eTeam setup: ○ = human, □ = robot.

^fParticipants: f = female, m = male.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEmpirical findings: (−) = negative effect, (+) = positive effect, (n.s.) = not significant.

Table 12. Empirical Studies on Dyadic HRTs Related to Team Processes and Their Effects.

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants ^f /Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ^h	Key Findings
Bozorgi et al. (2015) / communication/ VII	Functional (Quadcopter)/I, ↔/Simulation/ virtual robot	T + S 	n.i./n.i./n.i.	n.i.	• n.i.	• n.i.	• Transparency on robotic behavior and reactions through communication helps to increase the success of HRTs
Brazeal et al. (2005) / communication/I	Humanoid (Leonardo)/I, ↔/Physical robot	T + S 	n = 21/10m; age: range 20–40; local campus, no interaction with robot before/C	Shared mental models	• Non-verbal social cues and behavior	• Task performance (understandability of the robot, efficiency of task performance, robustness to errors) that arise from miscommunication (+)	• Non-verbal communication plays an important role also in the effectiveness of HRTs
Chen et al. (2020) / trust/V	Functional/n./ Simulation/virtual robot. Physical robot	T + S 	n_1 = 201 (simulation), n_2 = 20 (real robot); age: range 18–65 years, mTurk from the US, 2; age: range 21–65 years, from University/C	n.i.	• Trust • Team performance (+/-: appropriate level of trust needed for best performance)	• Trust (+ for task communication)	• Proposal of computational model to integrate trust into robotic behavior • "maximizing trust alone does not always lead to the best performance" (p. 9-1)
Ciocian et al. (2019) / communication/ IV	Humanoid (TAgO)/ n.i./Simulation/ virtual robot	T+ S / n.i.	n = 71/40 m, 30 f; age: range 14–53 years, M = 24 years (SD = 6)/C	Trust theories	• Communication (no communication, text and verbal task communication, text and verbal informal communication)	• Trust at the end of the experiment was higher than the initial trust when the participants had a text and verbal interaction communication related to the task" (p. 7)	• "the decrease in trust when the robot fails to perform the tasks is lower when [there] is text and verbal interaction between the robot and the participant" (p. 7)
Freddy et al. (2007) / trust/II	Functional(unmanned ground vehicle)/ ↔/Simulation/virtual robot	T + S 	n = 124 f; age: range 18–25 years, most with several years of gaming experience, 1.5 hours of training/L (15 trials/participant, 3 trials of 3 competency levels in firing behavior each)	Collaborative performance model	• Robot competency • Trust	• Time to complete mission (-) • Operator intervention (-) • Human intervention (-/+; appropriate level of trust needed)	• Introduction of an objective measure of trust dependent on the number of operator overrides/interventions • Knowledge about robot competencies and characteristics (e.g., level of performance) can help to foster trust

(continued)

Table 12. (continued)

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment ^d	Team Interaction ^d / Team Setup ^e	Data Basis/Participants ^f /Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ^h	Key Findings
Hoffman and Brazeal (2004)/ collaboration ^l	Humanoid ("Leo") ^j , ↔/Physical robot	T + S  	n.i./n.i./C	Dialog theory, joint intention theory	• n.i.	• n.i.	• Proposal of a framework for dynamic collaboration • To establish successful HRTs, robots and humans have to share the same goals, communicate with each other and show commitment to jointly reach their goals
Hoffman and Brazeal (2007)/ collaboration ^l	Functional (Symon, forklift-like)/ ↔/Simulation/ virtual robot	T + S  	n = 32/15 f; MIT community, laboratory/C	n.i.	• Robot anticipatory action • Perceived robot contribution to team fluency (+)	• Task efficiency (+/-s.) • Perceived robot contribution to team fluency (+)	• Anticipatory action of a robotic teammate helps to increase task efficiency and improves "the perceived commitment of the robot to the team and its contribution to team's fluency and success" (p. 1)
Koppula et al. (2016)/ collaboration ^l	Functional/↔/Physical robot (Kodak [PR2])/simulation/ virtual robot	T + S  	n = 5/n.i./n.i.	n.i.	• Anticipatory planning • Perceived robot commitment (+) collaboration (+)	• Perceived robot commitment (+) collaboration (+) • Satisfaction with robot (+) • Willingness to work with the robot (+)	• Proposal of graphical model to anticipate human actions
Lo et al. (2020)/ communication ^l	Functional/↔/Physical robot	T + S  	n = 16/8 f, visitors or students at the campus/C	n.i.	• Robot motion planning approach (nested inference for corrobative acts (NICRA) versus legible motion)	• Perceived clarity of intent (+) • Motion predictability and naturalness (+) • Perceived social appropriateness (+) • Perceived safety, intelligence, capabilities, thoughtfulness, and fluency to team with of the robot (n.s./+)	• Proposal of model for multi-agent planning based on partner's knowledge and behavior (NICRA) • Experiment shows that NICRA "is perceived as significantly more natural, socially appropriate, and fluent to team with, while being both more predictable and intent-clear" (p. 326)

(continued)

Table 12. (continued)

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment	Team Interaction ^d / Team Setup ^e	Data Basis/Participants ^f /Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ^h	Key Findings
Marble et al. (2003)/ collaboration/VII	Functional (ATRV)r/ Physical robot	T + S	n = 11 / f: 10 m: 4 expert users, n.i. 7 no or some prior experience, INEEL employees/C	Mixed-initiative interaction	• Adaptation to autonomy (not reported)	• Utilization of robot autonomous capabilities depends on previous robotic experience of users (inexperienced users utilize autonomy more willingly)	
Nikolaidis et al. (2015)(physical) coordination/IV	Functional/ Simulation/virtual robot. Physical robot.	T + S	n ₁ = 36, n ₂ = 24 / 1: recruited from MIT; 2: n.i./C	Shared mental models	• Team training (human–robot cross-training)	• Control challenges should be considered • "cross-training yields statistically significant improvements in quantitative team performance measures, as well as significant differences in perceived robot performance and human trust" (p.171)	
Nikolaidis and Shah (2013)(physical) coordination/IV	Functional/., ↔/Physical robot	T + S	n = 36/recruited from MIT/C	Shared mental models	• Team training (human– robot cross-training)	• Team fluency (concurrent motion, idle time) (+)	• This study supports the hypothesis that the effective and fluent teaming of a human and a robot may best be achieved by modeling known, effective human teamwork practices. (p. 171)
Nikolaidis et al. (2018)	Humanoid (HERB)/ ↔/Video/image of communication/I	T + S	n ₁ = 151 (from initial 200- exclusions)/ 60% female, age: M = 35 years, from US, mTurk/C	Game theory	• Robot communication	• Mental model convergence • Mental model similarity (+)	• A good way to achieve effective and fluent human–robot teaming may be to model effective practices for human teamwork (p. 33)
						• Team fluency (concurrent motion, idle time) (+)	• Human–robot cross-training leads to statistically significant improvements in quantitative team performance measures" (p. 33) (compared to standard reinforcement learning techniques)
						• Perceived robot performance (+)	• "Trust in the robot (+ /n.s.) commands is the most effective form of communicating objectives, while retaining user trust in the robot." (p. 221)
						• Human trust (+)	

(continued)

Table 12. (continued)

Author/ Subcategory/ Discipline ^a	Robot Morphology ^b / Robot Level ^c /Type of Embodiment ^d	Team Interaction ^d / Team Setup ^e	Data Basis/Participants ^f /Time Frame ^g	Underlying Theories	Independent Variable(s) ^h	Dependent Variable(s) ^h	Key Findings
Shah et al. (2011) / (physical) collaboration/	Humanoid (Nexi; a Mobile- Dexterous-Social (MDS) robot)/ ↔/Physical robot	T + S 	n = 16 subjects/10 m; age: M = 29.4 years (SD = 16.1), recruited from the MIT and Greater Boston area/C	n.i.	• Usage of robot plan execution system Chaski ↔ • Robot trustworthiness (+) • Team fluency (n.s.) • Perceived robot performance (n.s.) • Sharing of common goals (n.s.)	• Human idle time (-) • Time to complete task (n.s.) • Robot trustworthiness (+) • Team fluency (n.s.) • Perceived robot performance (n.s.)	• Chaski (task-level executive for robots) is able to reduce human idle time significantly and by this supports the hypothesis that it can help to increase team performance

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↔ = robot on same level, ↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction, n.i. = no information provided by author(s).

^eTeam setup: ○ = human, □ = robot.

^fParticipants: f = female, m = male.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEmpirical findings: (−) = negative effect, (+) = positive effect, (n.s.) = not significant.

cognitive science (6), HRI (5), ethics (2), management (1), and military (1) research. All 9 empirical studies are cross-sectional, but they feature both laboratory and field experiments. Teams are complex though, so the comparatively few studies that take an integrative perspective seems surprising. These studies include both functional and humanoid robots, such as those adapted from Lego® Mindstorms® sets (You & Robert, 2018b; 2019a; 2019b), but not any social robots. Multiple-member HRTs all reflect human-directed robot teams that are, in most cases, collaborative. Studies of dyadic HRTs also mostly consider dyadic collaborative teams and include human-directed robots or an autonomous human–robot pairing.

About half of the studies in this category specify their theoretical foundation and build, for example, on motivational theories of individual and team motivation (Kanfer et al., 2008). Other theories include media synchronicity (Dennis et al., 2008); the technology acceptance model (Davis, 1986) and the unified model of technology acceptance and use of technology (Venkatesh et al., 2003); social identity theory; the IPO model; notions of trust in relation to teamwork (Zaheer et al., 1998), technology (McKnight et al., 2011), and robots (Yagoda & Gillan, 2012); and social categorization and attraction theories (Hogg & Turner, 1985).

Limitations. We note several limitations pertaining to integrative, overarching studies of HRTs, beginning with a lack of consideration of social robots, which are especially relevant to HRTs and integrative investigations of them. Another important consideration is the time frame; many team processes only develop over time and should be examined with a dynamic approach to gain more insights. Finally, HRT designs other than human-directed robot teams need to be examined from an integrative perspective.

Discussion

Summary of Findings of Existing Research

Despite vastly different definitions of HRTs and distinct research foci, researchers from multiple disciplines all pursue insights into their aspects and related processes. In [Figure 5](#) we summarize the main categories and subcategories linked to the IPO model of teams. Because so few studies examine moderating effects, we cannot identify further subcategories. In addition, we find that extant research exhibits a dominant focus on HRT inputs and processes, so we do not elaborate further on the subcategories of team outputs.

Intra-member team characteristics are considered less frequently than other topics and primarily in relation to team setups and processes, probably due to their interdependencies with HRI and HRC. Nonetheless, research on

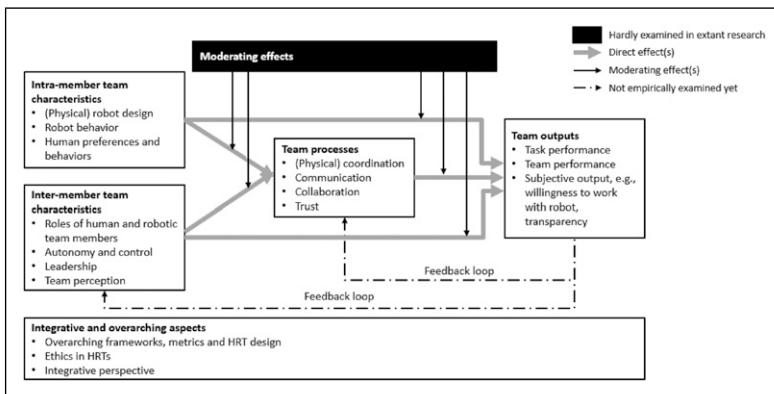


Figure 5. Overview of main categories and subcategories examined in the IPO model of teams.

robot behavior is rooted in a HRT context and reveals that positive robot behaviors and transparency exert positive effects on team processes and outcomes. In studies that examine both physical and behavioral robotic characteristics, we also find important hints for research directions, especially in terms of a holistic robot design. Human preferences and behaviors are equally interesting topics to include in efforts to understand HRTs fully.

Inter-member team characteristics have been examined more extensively; autonomy, control, and leadership are included in many studies. Vastly different definitions of HRTs, across a variety of team setups (e.g., leadership), affirm the logic of this central focus. Yet we also note that all empirical studies on (sliding) autonomy and control in HRTs indicate that (partially) autonomous robots and shared control can facilitate the work of human team members and make HRTs more efficient.

Compared with individual team members and team characteristics, *team processes* in HRTs and their effects have been investigated very intensively. Physical coordination has long been a topic, primarily with a focus on robotics aspects and the development of coordination concepts, but collaboration in HRTs has come to the attention of researchers only more recently. Here, interesting parallels are being drawn between HRTs and all-human teams with regard to the benefits of coordination or communication mechanisms. In general, studies indicate that well-choreographed coordination and communication efforts are key success factors for HRTs.

The presence of *moderating effects* in HRTs is coming more into focus, and it remains an important consideration because moderator variables exert effects on the relationships of team inputs, processes, and outputs. There is not one size that fits all HRTs, so further investigations should seek insights into relevant moderators and their effects.

Finally, *integrative and overarching studies* are lacking, despite their importance for gaining a holistic, deep understanding of the mechanisms in HRTs. Here, we note that HRTs are complex systems that require intensive research, and using insights from all-human team research could help clarify them, especially in real-world settings. For example, You and Robert (2018b) discuss a loop in the IPO model that conceptually may be plausible for HRTs.

Summary of Limitations of Existing Research

Overall, HRTs have been widely addressed by research, yet this domain still has a way to go to establish what constitutes successful and sustainable HRTs for society and business. Therefore, along with the key insights, we delineate three overarching limitations of extant research on HRTs. First, the cognitive sciences domain is emerging, but most research comes from USAR, space exploration, or robotics efforts, involving mainly functional robots. This single-sided view on HRTs must be broadened to encompass managerial and cognitive perspectives too. Second, shared mental models and social identity theory offer good starting points, but opportunities for applying behavioral theories, as have been addressed by research into all-human teams, are vast. Third, because it often features student samples, small samples, laboratory studies, and cross-sectional examinations, extant HRT research leaves some considerable gaps that point to a research agenda, as we discuss in the next section.

Limitations of this Review

This literature review has a number of limitations. Foremost, there may be relevant publications that were not included in this review despite a thorough literature search and efforts to avoid selection bias. We also focused on publications in English to be included in our review. With this review, we focus on robots as team members, but we openly acknowledge the other forms of human–technology teams, beyond HRTs, such as teams with virtual assistants. These interactions might be useful for HRTs too. To the best of our knowledge, no studies address teams with non-robotic but artificial team members in a business context. Therefore, another review might provide an overview of non-robotic artificial team members (e.g., virtual assistants) and compare the insights with our findings related to research into robotic team

Table 13. Studies Related to Moderating Effects in Multiple-Member HRTs.

Author/Discipline ^a / Main Category	Independent Variable(s) ^b	Dependent Variable(s) ^b	Moderator Variable(s)	Moderating Effect ^b
Claire et al. (2020)/V/ Cat. 1	• Robot fairness	• User trust • Perceived robot fairness	• Human capabilities	• (+ for weak performers; n.s. otherwise)
Correia, Petisca, et al. (2019)/V/Cat. 1	• Robot goal orientation (performance-driven vs. learning- driven)	• Competitiveness Index • McGill Friendship Questionnaire • Relationship Assessment Scale • Godspeed Questionnaire	• Session number	• Mixed results, see study for details
Jung et al. (2013)/VII/ Cat. 3	• Back-channeling	• Team functioning • Perceived robot engagement	• Task complexity • Perceived robot competence	• (+) • (+) • (n.s.)
You and Robert (2016)/ IV/Cat. 3	• Training	• Individual performance • Team performance	• Curiosity • Control	• (+ /n.s.) • (n.s./)

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bEmpirical findings: (-) = negative effect, (+) = positive effect, (n.s.) = not significant.

Table 14. Empirical Studies Related to Moderating Effects in Dyadic HRTs.

Author/Discipline ^a /Main Category	Independent Variable(s) ^b	Dependent Variable(s) ^b	Moderator Variable(s)	Moderating Effect ^b
Marble et al. (2004)/VII/Cat. 2	• Dynamic robot autonomy	• Target detection • Situation awareness	• Session number	• (+) • (+)
Marble et al. (2003)/VII/Cat. 3	• Mixed-initiative interaction	• Adaptation to autonomy • Perceived ease to predict outcome of control	• Remote system experience	• n.s. • (-)
Richert et al. (2016)/Cat. I	• Personal characteristics • Robot characteristics	• Task performance	• Subjective behavior o Stress o Cooperation	• Not reported

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bEmpirical findings: (-) = negative effect, (+) = positive effect, (n.s.) = not significant.

members. We also recognize the common risk of a publication bias for our study (Jager et al., 2020). A publication bias largely occurs before and during scientific review processes, leaving us with limited possibilities to overcome it completely (information on our efforts to address potential biases can be found in [Supplementary Appendix A](#)).

Future Research Agenda

Beyond these considerations pertaining to our review, we note some unexplored areas, both conceptual and empirical, that highlight the vast opportunities for learning more about the design, theoretical concepts, and practical implications of HRTs. We structure those opportunities into two broad categories: How can robots be team members, and when?

How can robots be team members? It would greatly advance the field if research were to *explain the mechanisms that underlie interaction in HRTs, based on behavioral theories*. Currently, no overall theory exists for HRTs, which leads to unsteady theoretical foundations. Moreover, most studies do not offer solid theoretical justification for their predictions (see, e.g., summary of limitations). An approach already being used by some researchers relies on investigations of all-human teams as bases for HRT research, which ensures a more theory-driven effort (Krämer et al., 2012). In addition to social identity theory (Tajfel, 1974), shared mental models, and gender studies, leader–member exchange theory as applied to all-human teams (van Breukelen et al., 2006) might be a suitable theoretical basis for research on HRTs with social robots in particular. Another valuable effort might seek insights into *how individuals, companies, and society can prepare for HRTs*. Since all studies we found during our review are focusing on existing HRTs (see [Tables 2–17](#)), many open questions remain regarding how to prepare for HRTs. Researchers have a broader responsibility than core HRT topics; in particular, they should address the transition toward HRTs and how individuals, companies, and society can engage beneficially in it.

When can robots be team members? To address this broad question, we recommend research that undertakes two main comparisons, as well as two examinations. First, we call researchers to compare *different types of HRTs in organizations*. Traditional team research distinguishes permanent versus project-based teams, top management versus work teams, and so forth (for an overview, see Hollenbeck et al., 2012). Interaction modes, processes, and outcomes likely differ across these teams (Hollenbeck et al., 2012; LePine et al., 2008). But according to our review, different types of HRTs tend to be studied in isolation (see [Table 1](#)), rather than compared in terms of similarities

Table 15. Conceptual Integrative and Overarching Studies on Multiple-Member HRTs.

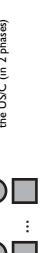
Author/Subcategory/ Discipline ^a /Team interaction ^b	Underlying Theories	Research Framework ^c	Key Findings ^d
Arnold and Scheutz (2017)/ ethics/VIII/T+S	n.i.	n.i.	<ul style="list-style-type: none"> • There are many ethical questions currently unsolved in HRI • "Robots do not have to be teammates to work with a team, especially given the ethical and empirical question of how the whole range of physical presence with a robot can affect others." (p. 449) • Overview of important considerations for the design of HRTs, including team and teamwork components • Inappropriate levels of trust can lead to misuse and/or misuse of robots • Proposal of a framework for human-robot trust
Ma et al. (2018)/HRT design// T+S	n.i.	n.i.	
Olson et al. (2011)/ integrative study/IV/T+S	n.i.		<ul style="list-style-type: none"> • Proposal of "Motivational Theory of Human-Robot Teamwork" based on: emotional stability, extraversion, openness to experience, agreeableness, conscientiousness of a robot • Robot ethics is a growing field that gains importance with the developments of new robots and technology • Proposal of working framework for HRTs based on IMOI (inputs-mediators-outputs-inputs) framework
Robert (2018)/integrative study/VI/T+S	Motivational theories of individual and team motivation	n.i.	
Tamburini (2009)/ethics/VII/ T+S	n.i.	n.i.	
You and Robert (2018b)/ integrative study/VI/T+S	IPO model, trust theories	n.i.	

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.
^bTeam interaction: T = task interaction, T+S = task & social interaction.

^cEffect: → = positive effect, → = negative effect, ← = not significant, ← → = effect not reported.

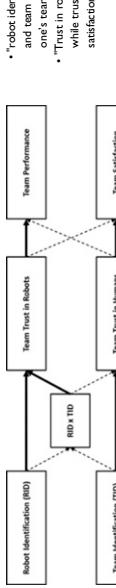
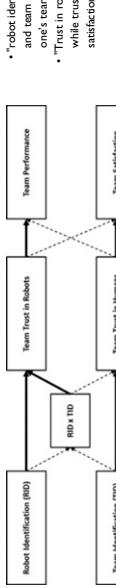
^dNone of the studies provide information on robot morphology, robot level, or type of embodiment. Only two studies provide information on team setup, focusing on autonomous mixed teams (Ma et al., 2018) and human-directed robot teams (You & Robert, 2018b), respectively.

Table 16. Empirical Integrative and Overarching Studies on Multiple-Member HRTs.

Author/ Subcategory/ Discipline ^a	Morphology ^b Robot Level / Type of Embodiment	Team Interaction ^c /Team Setup ^d	Data Basis/Participants/ Time Frame ^e	Underlying Theories	Research Framework ^f	Key Findings
Burke et al. (2008) Metrics	Functional (Telex, UGV, Mobile UAV, Dragonrunner UV Aerialbot, UAV)/Physical robot	T 	n = 31 participants from FEMA ISAR team; in the USC (in 2 phases)	n.i.		<ul style="list-style-type: none"> • Proposal and validation of measurement instruments for assessment of usability (team member), incidents (observer) and team processes (observer) in HRTs
Giachiedi et al. (2013) Integrative study/III	T/Combinations of virtual robot n/n/Simulation/ integrative study/III	T/Combinations of n_robot=2(4) & n_team=6(12)	n.i./n.i./n.i.	Shared mental models	<ul style="list-style-type: none"> • Performance • Effectiveness (see key findings and study for detailed results and interaction effects) 	<ul style="list-style-type: none"> • Proposal and validation of agent-based simulation model for the examination of team designs • "there are limits to the number of robots that a team can effectively manage" (p. 25) • "larger teams have more robust performance over the noise [i.e., not controllable] factors" (p. 15) • "robot reliability is critical to the formation of human-robot team" (p. 15) • "high centralization of decision-making authority created communication bottlenecks at the commander in large teams" (p. 15)
Pina et al. (2009) Metrics	n.i./n.i.	T + S 	n = 16/age: range 19-49 years/C (four 8 minute sessions with different robotic team sizes)	n.i.		<ul style="list-style-type: none"> • Proposal of generalizable metric classes for the evaluation of HRTs and illustration of need for these with case study
Robert and Tou (2015) Integrative study/IV	Functional/ humanoid (adapted from the LEGO® Mindstorms® EV3 sets)/ Physical robot	T + S 	n = 30 (15 teams)/14 f. age: M = 27 (SD = 7.48); from large university in USC (laboratory)	n.i.		<ul style="list-style-type: none"> • "subgroups formed between humans and their robots were negatively correlated with various team outcomes" (p. 1)

(continued)

Table 16. (continued)

Robot	Morphology/ ^a Robot Level/Type of Embodiment	Team Interaction/ ^b Setup ^c	Data Base/Participants/ ^d Time Frame ^e	Underlying Theories	Research Framework ^f	Key Findings
You and Robert (2017) ^g integrative study/IV	Functional/humanoid (adapted from the LEGO® Mindstorms® EV3 set) ↓Physical robot	T + S 	n = 114 (in 57 teams); 51 m.; age: M = 23 years (SD = 5.3); from online subject pool at a Midwestern university in USC (duration approx. 25–30 minutes)	Media richness (channel expansion theory, cognitive model of media choice, media synchronicity), technology acceptance model, unified model of technology acceptance and use of technology, social identity theory, social categorization and attraction theories, trust theories		• Emotional attachment of teams to robots leads to better performance • Both robot and team identification increased a team's emotional attachment to its robots" (p. 377)
You and Robert (2019) ^g integrative study/IV	Functional/humanoid (adapted from the LEGO® Mindstorms® EV3 set) ↓Physical robot	T + S 	n = 108 (54 teams); main; age: M = 24 years; from subject pool at a Midwestern university in USC (duration approx. 25–30 minutes)	Social categorization and attraction theories, trust theories		• Robot identification increased trust in robots and team identification increases trust in one's teammates" (p. 244) • "Trust in robots increases team performance while trust in teammates increases satisfaction" (p. 244)
You and Robert (2019) ^g integrative study/IV	Functional/humanoid (adapted from the LEGO® Mindstorms® EV3 set) ↓Physical robot	T + S 	n = 144 (age: M = 23.6 SD = 4.1); from large university in USC (duration approx. 25–30 minutes)	Social identity theory, trust theories		• Subgroups can form in HRTs (when humans identify with their robots) • Robot identification and team identification moderate ... negative effects of subgroup formation on teamwork quality and subsequent team performance" (p. 1)

Note: ^aDisciplines: I = HRI, II = management, III = military, IV = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics; studies are categorized based on a "best fit" approach and might comprise aspects of more than one considered research discipline.

^bI.I. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level, ↔ = robot on same level, ↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction.

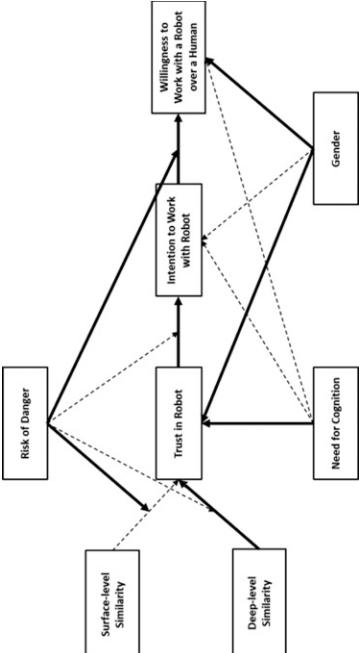
^eTeam setup: ○ = human, □ = robot.

^fParticipants: f = female, m = male.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEffect: → = positive effect, ← → = negative effect, — → = not significant, — · → = effect not reported.

Table 17. Empirical Integrative and Overarching Studies on Dyadic HRTs.

Robot	Morphology ^b	Type of Embodiment	Team Interaction ^d	Data Basis/Participants ^f	Time Frame ^e	Research Framework ^h	Key Findings ^g
Visser et al. (2006) metrics/III	n.i./n.i.	T + S	●	n = 124 f, age: range 18- 25 years/C (3x5x6 mixed factorial design (2 within, 1 between))	n.i.		• Proposal and validation of measurement methodology for team performance of HRTs • Human-robot (work- style) similarity helps to increase trust in a robot, leading to willingness to work with robots and ultimately to preference for robotic co-worker rather than human co- worker
You and Robert (2018a) integrative study/II	Functional (PR2)/ 1/Image/ video of robot	T + S	●	n = 200/77 m, age: range 18-68 years (M= 36.5, SD = 10.77), mturk, US/ C			

Note: ^aDisciplines: I = HRI, II = management, III = cognitive science, V = robotics, VI = space, VII = (urban) search and rescue, VIII = ethics;
 studies are categorized based on a "best fit"-approach and might comprise aspects of more than one considered research discipline.

^bn.i. = no information provided by author(s).

^cRobot level: ↓ = robot on lower level ↔ = robot on same level ↑ = robot on higher level.

^dTeam interaction: T = task interaction, T+S = task & social interaction.

^eTeam setup: ○ = human, □ = robot

^fParticipants: f = female, m = male.

^gTime frame: C = cross-sectional, L = longitudinal.

^hEffect: → = positive effect, ← = negative effect, —→ = not significant, —→ = effect not reported.
 None of the studies indicated underlying theories.

and differences. Insights along these lines could improve the management of HRTs in organizations and support human teammates. Second, research comparisons might address *different application scenarios of HRTs in organizations*. Most HRT research addresses specific application scenarios, such as rescue robots in USAR (Kruifff-Korbayová et al., 2015) or robots working on the International Space Station (Fong et al., 2005). Insights on HRTs in organizations in an office environment are still scarce (see disciplines of studies in different categories). With an online survey, we learned that acceptance of robots in work-related HRTs has increased, especially during the COVID-19 pandemic. Results suggest four potential roles for robots in (Figure 6): (1) robotic *team assistant* supporting administrative and co-ordination work, (2) robotic *knowledge expert* providing expertise in a specific field, (3) robotic *scrum master* (Scrum Alliance, 2021) working with the team and ensuring that the team lives up to agile values and principles, such as through coaching, and (4) robotic *team leader* with institutionalized authority over other team members. Third, researchers should examine *HRTs in real-life settings*. The studies we reviewed are overwhelmingly conceptual or cross-sectional laboratory studies (see study characteristics in different categories), with limited capacity to transfer the findings to real-life settings (Levitt & List, 2005). Especially, noting current developments in the world economy and the increasing relevance of robots in everyday contexts, continued research

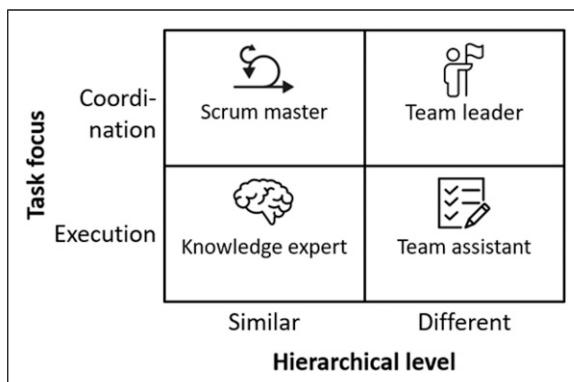


Figure 6. Potential roles of robots in HRTs. Note: Sources for icons: top left icon: Scrum by Sharon Showalker; top right icon: leader by Oksana Latysheva; bottom right icon: to do list by ArtWorkLeaf; bottom left icon: Brain by Alla Zeluska, all from thenounproject.com

should examine HRTs in real-life settings. Fourth, we hope more studies examine the *long-term effects of HRTs*. Cross-sectional studies (see study characteristics in different categories) cannot accurately depict longer-term relationships among team members, so continued studies should seek to grasp all consequences of implementation efforts for HRTs. To do so, appropriate methods for the long-term investigation of HRTs should be developed.

Conclusion

Human–robot teams are an emerging phenomenon and part of the future of work and society. Yet extant research lacks some important insights. With this review, we establish some unexplored research areas, many of which pertain to real-life, long-term HRT deployment considerations. We offer six propositions for continued research, reflecting the strong relevance of the topic and considering current developments in the world economy. We hope this review provides inspiration for ongoing HRT studies.

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Supplemental Material

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Notes

1. The survey participants were recruited via Amazon Mechanical Turk. We sought business leaders; they had an average of 6.99 ($SD = 6.431$) years of leadership experience in various industries, including IT (23.2%), banking/insurance (13.8%), and health care/social sectors (9.9%). These leaders were responsible for teams (45.3%), departments (29.9%), business areas (11.1%), or the whole company (13.8%). The

survey introduced social robots and their potential roles in organizations and issued the prompt “I can imagine having a robot as an assistant/colleague/supervisor,” which participants answered on a 5-point Likert scale (1 = “not at all,” 5 = “absolutely”).

2. Our focus explicitly is not on robot–robot teams, human–computer, or human–machine interactions. Disembodied agents limit communication channels, compared with embodied agents, [Deng et al. \(2019\)](#), which in turn can limit the generalizability of findings. Furthermore, detailed considerations of the roles of agents in teams extend beyond the scope of this review.
3. In line with [Breazeal \(2003\)](#) and [Fong et al. \(2003\)](#), the low level of social interaction (see Figure 2) includes so-called “socially evocative” ([Breazeal 2003](#), p. 169) robots that elicit social responses from humans without responding socially to them.
4. Using our proposed definition, we can distinguish HRTs from related concepts, such as human–robot interaction (HRI) or human–robot collaboration (HRC). In particular, HRI is “the study of the humans, robots, and the ways they influence each other” [Fong, Thorpe, and Baur \(2001](#), p. 257), and HRC implies humans and robots “working jointly with others or together especially in an intellectual endeavor” [Green, Billinghurst, Chen, and Chase \(2008](#), p. 1). Similar to HRTs, the involved parties (robots and humans) interact, such as by expressing or responding to emotions [Kreijns et al. \(2003\)](#). Yet HRC and HRTs are narrower than HRI, in that they pursue the achievement of joint goals ([Bradshaw et al. \(2009\)](#); [Marge et al. \(2009\)](#); [You and Robert \(2018b\)](#)). Uniquely in HRTs, team members work both interdependently and together ([Bradshaw et al. \(2009\)](#); [Ma et al. \(2018\)](#)).

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