Power in Human-Robot Interaction

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ABSTRACT

Power is a fundamental determinant of social life, yet it remains elusive in Human-Robot Interaction (HRI). This paper unveils power's pervasive but largely unexplored role in HRI by systematically investigating its varied manifestations across HRI literature. We first introduce definitions of power and then delve into the existing HRI literature through a lens of power, examining studies that directly address power and those exploring power-related social configurations and concepts such as authority, dominance, and status. Leveraging Fiske and Berdahl's model and French and Raven's bases of power framework, we also explore the nuances of power in many HRI studies where power is not explicitly addressed. Finally, we propose power as a core concept to advance HRI— explaining fragmented existing findings through a coherent theory and delineating a cohesive theoretical trajectory for future investigations.

CCS CONCEPTS

• **Human-centered computing**;

KEYWORDS

power, social power, power dynamics, influence, theory

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1 INTRODUCTION

Power permeates the structure and context of the social world we live in. As such it is arguably the most influential factor in social interaction. Bertrand Russell famously stated, "The fundamental concept in social science is Power in the same sense in which Energy is the fundamental concept in physics." [162] Despite occupying such a critical position in social interaction, power has yet to receive much discussion in the field of Human-Robot Interaction (HRI).

Yet power is everywhere in HRI, deeply embedded even in the very definition of robots: The word "robot" comes from the word "robata" in Czech, meaning "slave" or "forced labor" [88], making the hierarchical positioning of robots unmistakably clear. The Oxford English Dictionary [182] defines a robot as "a machine—especially one programmable by a computer—capable of carrying out a complex series of actions automatically." Here the word "automatically" is of special importance in its relationship to power. Overbeck and Park's work on social power [146] distinguishes two types of power: social power, which is the control over valued resources, and personal power, which is, in Galinsky et al.'s words [54], "equivalent to the concept of autonomy". Here, autonomy encompasses not only automaticity but also suggests that the ultimate goal of robot development is a progression from automaticity to full autonomy [26]. Consequently, the development of robots entails the creation of machines with a growing degree of autonomy. The history of the development of robot technology, when viewed through the lens of power, can thus be seen as a history of humans augmenting power in machines and computerized systems.

Despite its deep roots in HRI, power has remained elusive in HRI studies, notwithstanding a few exceptions. Studies on robot bullying and abuse highlight vivid examples where people assert their power over robots [22, 38, 189, 215]. Other recent work has begun to focus on power dynamics in society and issues around gender and race [20, 158], or introduce feminist theory into HRI [212] to examine power held by roboticists and relevant stakeholders. This work often adopts perspectives from the humanities and social sciences and addresses power as the force in the social structure that has enabled, facilitated, and shaped certain types of interaction over other types, creating inequality between different groups of people.

Seeing how these studies have illustrated that power occupies a pivotal role in the social context surrounding HRI, we propose that it is crucial to also take a look into the power dynamics in existing HRI literature, specifically at the interaction level which has been the focus of much HRI work to date. Power exists not only in social relations between people but also in those between people and robots, which is thus directly amenable to be shaped by design. With a tangible treatment of power in HRI, we can answer questions such as: How is power manifested in the interaction between humans and robots? How do these humans and robots gain power or lose power? And how should we, as designers, engineers, and researchers, perceive and shape power in these interactions?

In this paper, we take stock of the research on power in HRI. We begin by outlining basic concepts of power, and then investigate power in the interaction between humans and robots, starting with HRI studies that directly address power and its related concepts. We then use French and Raven's framework from social psychology to delve into the power dynamics in HRI studies that have not explicitly addressed power, showing that power has actually been pervasive in existing studies. We conclude by demonstrating how adopting this tangible lens of power can help us construct a systematic understanding of the existing HRI literature, and how it can shed light on the future research trajectory.

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2 DEFINING POWER

Though omnipresent, power has long been known as an elusive and 'essentially contested concept' [114, 115, 177]. Despite the rich diversity in conceptualizations of power, given the scope of this paper, we would like to point to three primary perspectives on power that have emerged in academic discourse. First, there is the classical Weberian conception of power, characterized as "power over" or power as domination [42, 114, 204]. The second perspective views power as empowerment, often conceptualized as "power to" [10, 17, 150]. Lastly, melding elements from the first two views, the feminist discourse introduces the notion of "power with" [59], emphasizing it as the capacity to act collaboratively and in solidarity [5, 6, 35, 77]. Power also carries varied interpretations across normative discourses—typically grounded in the humanities, including feminist theory—and empirical ones from social sciences [78].

Michel Foucault's discourse on power has been profoundly influential in the past three decades. His analysis primarily views power as 'power over', where, as he articulates, power involves certain individuals exerting control over others [47, p.217]. Foucault's definition hinges on power-over relationships as well as its manifestation through actual exercise. His analysis, which sees modern power as both shaping and subjugating individuals, has been influential yet controversial, particularly among feminists analyzing domination. Data feminism scholars [46], for instance, employ the concept of power to address structural privilege and oppression. This work draws on Black Feminist sociology's 'matrix of domination [37, 209]', elucidating how power systems are established and experienced and how power disparities manifest across structural, disciplinary, hegemonic, and interpersonal levels.

These perspectives of power all illustrate the complexity of power, as well as its diverse manifestations in daily life [78]. Here we take a closer look at power at the interpersonal interaction level, especially from the perspectives of social and behavioral science. We do this for two main reasons: 1) because it aligns well with existing HRI studies, which predominantly rely on behavioral science approaches, and 2) to introduce a lens of power that is tangible for HRI designers, engineers, and researchers.

One of the early definitions of power in empirical social science and behavioral science is **influence**: A person O is said to have power over P when O influences P's behavior [1, 42, 162]. However, this definition is considered suboptimal because it defines power by its effect (influence) and not the power per se, which can cause confusion in designing studies and interpreting results.

An alternative definition of power avoids this problem by defining power as **potential influence** or **the capacity to influence**. For example, social psychologists French and Raven defined power as "The strength of power of O/P in some system A is defined as the maximum potential ability of O to influence P in A" [53], and Cartwright developed further on this definition and stated, "If O has the capability of influencing P, we say that O has power over P" [25]. With this definition, therefore, power can exist even if there is no perceivable influence.

Yet another approach to power avoids the entanglement of power's definition and its effects by defining power as **resource control or outcome control.** For example, Dépret as well as Fiske and Berdahl defined power as "asymmetrical control over another person's outcomes" [44] or "relative control over another's valued outcomes" [50]. Similarly, Galinsky, who contributed to the literature of social power with an enormous number of studies, has defined power as "asymmetric control over valued resources in a social relationship" [118]. By defining power in this way, these researchers bypass the need for "influence" in the definition of power and therefore avoid a paradoxical conclusion that previous definitions lead to. This paradox, target volition, indicates that even if O originally has the capability of influencing P, as soon as P decides not to be influenced, O loses the power because P can no longer be influenced, and thus the capability ceases to exist. For these researchers, power should still exist even if it is resisted. Otherwise, it will be contradictory that the resistance is resisting against nothing. As a result, the new definition that does not require the concept of influence has become widely adopted in social psychology and has dominated power studies in recent years.

These three conceptual definitions, however, do not specify where the power comes from. For *the capacity for effect* definition, we do not know from where the capacity originates, and how people can gain it or lose it. For *the resource or outcome control* definition, it remains unclear what the "resource" and "outcome" refer to. It is, therefore, imperative to clarify the source of power so that researchers can define and manipulate it operationally in behavioral science studies. In one of the most cited papers on power, French and Raven [53] proposed their theory on the bases of power. They suggest that there are five fundamental bases of power: Reward power, Coercive power, Legitimate power, Expert power, and Referent power (details will be in Section 3.3). This theory of different power sources provides us with a systematic way to operationally manipulate power, as well as to analyze social interaction through the lens of power.

Although individual researchers may prefer one definition over others, these definitions are very closely related and each may be used in different stages of a study. In their paper on social power, Fiske and Berdahl summarized the relationship between definitions with a model, which we have adapted slightly as the basis of our discussion of power in this paper (see Fig. 1).

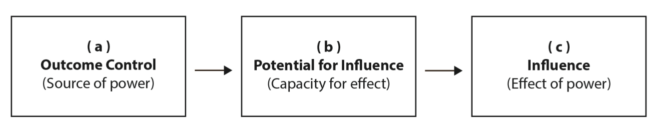

Figure 1: Fiske and Berdahl's model on relationships between *Source of Power, Capacity for Effect* (which can be considered to be equal to *power*), and *Effect of Power.* This figure is adapted from Fig. 29.1 in Fiske and Berdahl's paper [50].

3 POWER IN HRI LITERATURE

Having seen the definitions, here we revisit prior HRI research as concrete examples. We will first review studies directly addressing power, followed by those on power-related concepts. Then, we will discuss studies that did not address power explicitly yet are actually related to power. We hope this will shed light on how power has been defined, manipulated, and studied in HRI, as well as highlight future research opportunities.

To provide a snapshot of power and power-related concepts in current HRI studies, we searched the ACM HRI conference papers (through the ACM Digital Library) using terms such as "power" and "social power" [1] in April 2023, as summarized in Fig 2.

We first searched "power" in the abstract and title in order to see how power has been used as a core concept in HRI studies, finding 31 papers. After review, 15 papers were excluded for different uses and definitions of power, like power wheelchairs [94, 199] and battery power [45]. The remaining 16 [69, 72, 80, 86, 90, 92, 93, 116, 122, 128, 136, 207, 208, 210, 221, 224] are all relevant to power's significant influence on HRI, like using the concept of social power to design persuasive robots [72] or focusing on the influence of robot's persuasive power [207]. Searching "social power" found 4 papers directly using the concept [70, 73, 126, 156], emphasizing social robot behaviors in HRI (more in Section 3.1).

We also searched for three concepts closely related to power: authority, dominance, and status, [2] based on Jamy Li's previous analysis [106]. For authority, we found 97, where 88 papers are related to robots' power, such as robot as authority figure [159] or how authority influenced trust [106, 166]. Nine papers, mainly about institutional authority (e.g., [191, 195]), were excluded. Searching for dominance yielded 32 relevant from 76 such as dominant behavior in a human-robot pair [108] or the robot's proactivity [129]. The exclusion includes arm dominance (left- or right-handed) [148, 149] or the PAD framework (valence, arousal, dominance) in emotion theory (e.g., [7, 28, 163, 164, 178]). For "status," 49 of 75 for 'status' AND 'power' were relevant, discussing robot social status [18, 84, 137, 151] and power dynamics and asymmetries (e.g., [152]) in contexts such as bullying [134] or partnership [223]. Excluded 26 papers deal with energy power like microphone input power [165] or computational power (e.g., [127]).

Again, the primary objective of this search exercise is to offer a brief overview of power and power-related concepts in existing HRI studies. Our subsequent discussion includes various scholarly sources beyond ACM HRI publications, like RO-MAN and THRI.

3.1 HRI Studies That *Directly* Addressed Power

To our knowledge, few HRI studies have directly addressed power, with some exceptions including research from sociology and feminism perspectives [212], and studies by Hashemian and colleagues [67, 68, 70, 71, 73–76]. Hashemian and colleagues' studies followed French and Raven's bases of power framework, manipulated different power bases (in particular reward power, coercive power, and expert power), and measured the robot's persuasiveness as the effect of power (influence). Results showed robots' persuasiveness varies with different power bases [74], affecting perceptions [74, 75], but it's unclear if some bases are more effective than others [70, 75].

[1]Due to their broad use and multiple meanings, the search results for "power" returns too many results. Therefore, We first searched for "power" in the title and abstract. For the term "social power", we conducted a search in full papers.
[2]The search strings we utilized are: "dominance," "authority," and '"power" AND "status"'. Due to numerous unrelated returns, we opted for '"power" AND "status"' instead of just "status".

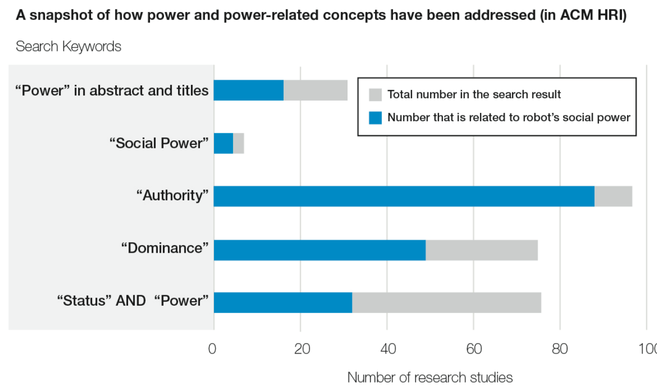

Figure 2: An overview of power and power-related studies in the ACM HRI literature. Social power is seldom mentioned while the concepts closely related to power, such as authority, dominance, and status, have received more attention (Data accessed on April 2023).

The paper by Taylor et al. [193] also directly mentioned power. It designed a Robot-Centric Team Support System for medical teamwork, aiding nurses to challenge higher-power physicians by mediating communication. This study showed robots' potential to alter power dynamics by empowering lower-power workers.

Ju's early HRI power overview [88] discussed how people are afraid of losing control of robots, a concern that becomes more pressing as technology develops. Informed by her own research, Ju also notes that people usually do not prefer robots that are dominant [108] or too proactive [130]. Her idea—that social structure, social class, and social power in human-human interaction (HHI) will affect HRI—resonates strongly today and has inspired this paper.

3.2 HRI Studies That Addressed Power-Related Concepts

Despite only a handful of studies having investigated power directly, many HRI studies studied concepts closely related to power, such as authority, dominance, and status. We also discuss studies that are highly related to the existing social power configuration, including gender, race, age, sexuality, and disability.

3.2.1 Authority. Authority is intimately linked to power in sociology and has even been defined as "accepted power" [62]. However, the added "accepted" still differentiates it from power. In social psychology, authority often refers to a type of legitimate power[198], which is given by the social structure. People follow others with authority because they identify with their socially validated power. We thus consider authority, the legitimate power that drives people's internal motivations to comply, as a subset of power.

Authority has long been studied in HRI [3, 14, 40, 60, 66, 79, 99, 172, 197, 219, 220]. As early as 2006, Torrey et al. [197] found that an expert-like dialog style and minimal background information make robots seem more authoritative. Young and colleagues [40, 55, 56, 219, 220] explored robots as authoritative figures, following Milgram's obedience studies [124]. The results showed that people consistently obeyed robots. They therefore suggested that robots might take over simple management tasks in the future [220] and highlighted the danger that robots can be used to manipulate people [219]. Similarly, Sembroski et al. [172] compared whether people will follow the instruction from a robot or a high-authority or a low-authority experimenter. They found out that people usually followed the human's instruction, but they followed the robot instead when the robot was considered an in-group member and the human was low-authority, showing that authority plays a crucial role when interacting with both humans and robots.

3.2.2 Dominance. Dominance is another concept that is tightly connected to power. Dominance, as opposed to submission, often refers to an active, extroverted, talkative, or controlling style of communication [15]. In HRI work, dominance is often used to describe a kind of controlling and aggressive communication style [8, 20, 107, 108, 140, 155, 161], which did not necessarily lead to real influence in these studies. While we can think of dominance as "the look of power" in folk psychology, it is interesting that a robot's dominance often does not lead to better influence. That is, many agents do not really gain power by acting dominantly. For example, Li et al. [108] had participants watch videos of a human interacting with either a dominant or a submissive robot. The result showed that the participants found the dominant robots less trustworthy.

Many other studies in HRI focused on the effect of a robot's perceivable dominant behavior. Rae et al. [155] investigated how telepresence robots' height affected how the remote controller was perceived by the local user in terms of persuasiveness, attractiveness, and dominance. The results showed that both the roles of the participants and the height of the robots influenced how the operator was perceived. Others have also investigated how a robot's movement can express its dominance. Ammi et al. [8] found that dominance can be communicated through haptic handshaking movement but not facial expression. Li et al. [107] found that robots that move fast, in the foreground, and are more animated are considered more dominant and "of higher status" than those who are slow, in the periphery, and less animated.

3.2.3 Status. While in early literature, power and status are tightly intertwined, status is prior to the exercise of power, as Locher [111] puts it: "Status is hence not seen as synonymous to power, but as its seat". Status, despite being extensively discussed in HHI, has received little direct attention in HRI. Oftentimes, it is just mentioned as the "social status" of robots as the background of the interaction. This is probably because esteem, honor, and respect are such "human" concepts that researchers haven't connected it with robots yet.

3.2.4 Gender, Race, Age, Sexuality, and Disability. Recent HRI studies also focus on power structures, critically exploring dynamics including gender [23, 32, 51, 97, 185], racism [19], perceived age [152, 179], sexuality [48], and disability [11, 200] that collectively shape structural privilege and oppression. For instance, research has investigated the role of gender stereotypes [23, 85, 145, 157, 158, 192] in shaping perceptions of robots, illustrated by Strait et al. [183] whose findings reveal a significant prevalence of dehumanizing and sexualizing comments directed at female robots compared to their male and neutral robots. Furthering the discourse on gender, Winkle et al. [213] introduced feminist robot design to challenge prevailing gender norms, particularly around female politeness, while Tanqueray et al. [191] advocated for gender fairness as a principle in robot design. Addressing racism, a study by Bartneck et al. [19] elucidated that robots are not only perceived to possess race but also encounter explicit racism, especially those racialized as Black. Striving to transcend conventional notions of gender and sexuality, inspiration from the 2LGBTQIA+ community for designing sex robots was proposed [48]. To ameliorate power dynamics inherent in the design process, some scholars [11, 200] engaged individuals with disabilities as co-creators when designing robots to serve them, ensuring their empowerment in the process. Some research has even taken a step further to show the interwoven complexities of these different social dynamics, such as William's work [209] illustrating the responsibilities of roboticists to recognize and act upon the status quo of White Patriarchy. These investigations on the myriad forms of power structures have prompted critical discussions on inclusivity and representation in HRI [98].

3.3 HRI Studies That *Implicitly* Addressed Power Based on French and Raven's Framework

Here we discuss how power can be seen as a central theme throughout the HRI literature, even in studies that did not mention power explicitly. While power's different perspectives and definitions offer valid insights into its various manifestations in daily life [78], many previous HRI studies have adopted perspectives and paradigms of empirical social science. We thus leverage the arguably most influential power theory in social psychology, the aforementioned French and Raven's bases of power framework. We will first look at "formal power" or "position power", which is the power that derives from the social structure, including legitimate power, reward power, and coercive power, and then look at "personal power", including referent power and expert power.

3.3.1 Legitimate power. Legitimate power is the authority and legitimacy given by the social norm or the social structure, including organizational hierarchy. While no studies in HRI have directly mentioned legitimate power, many studies have incorporated this concept in the form of "framing" or "social role". Sebo et al.'s extensive review on human-robot teamwork in HRI [171] systematically analyzed robots' roles in HRI studies. We would like to highlight that their categorization—robot as leader, peer, or follower—directly corresponds to legitimate power. They found that when robots are expected to provide information, they are often placed in a leadership position. When acting as companions, robots are often peers. And when the cost of mistakes can be serious, robots are often controlled or looked after by humans, taking a follower role.

Following this categorization, we discovered that many existing HRI studies have incorporated the concept of legitimate power through assigning roles to robots. High-power roles include museum direction giver [216], teacher or tutor [12, 91], evacuation guide [160], arbitrator [174], evaluator [180], coach [49, 66, 125], and experimenter [55, 56]. In some other studies, the roles were not specified explicitly, but the behavior implied that the robots were in a high-power position, such as being imitated by humans [108] or making moral decisions [119]. For roles that are equal in power, robots can be described as coworkers [110, 218], or peers that play and learn alongside children [121, 190].

Most robot roles seen in HRI studies are of lower power. Examples include service giver [101, 138], medical help provider [110], assistant for elderly [36, 154], student [27, 33, 81, 105], imitator [108], younger peer [61], delegatee [214], or one that needs information from humans [206]. It is worth noting that many HRI studies have investigated controlling interfaces for robots. From the perspective of power, these studies all imply that robots are in a lower power position since people not only influence but actually dictate robots' behavior. Seldom discussed in research on people, this complete control of behavior is the ultimate form of power by definition, and the field of HRI lends itself well to investigating what this extreme form of power means to humans.

Many studies actually go beyond mere roles and directly manipulate legitimate power as an independent variable. Rae et al. [155] manipulated a robot's position as a leader or a follower. Groom et al. [64] and Howley et al. [83] manipulated whether the robot was a teacher or an assistant. Song et al. [180] manipulated whether the robot was in an evaluative role. Lei et al. [104] also manipulated whether the robot was a supervisor, peer, or subordinate.

3.3.2 *Reward Power and Coercive Power.*

Reward power and coercive power work in a similar way but in the opposite directions. People gain reward power by controlling how much reward others can get, and they gain coercive power when they can punish others who do not obey.

For example, studies by Hashemian et al. manipulated a robot's reward power directly by letting the robot give participants a gift [73], monetary reward [71], or social reward such as telling a joke [75]. In general, reward power is found to be useful in increasing a robot's influence. Other studies have manipulated reward power in a more nuanced way. For example, Claure et al. [34] studied how robots may influence team dynamics by distributing resources, including social attention and the components needed for an assembly task, both of which can be considered a type of reward. Koay at al. [95] studied how people reacted to robots that block their pathways, which is also a way of controlling desirable resources. As we have seen in other studies where robots are in a high-power position, people also expressed discomfort when robots were in control of their way.

Coercive power has also been addressed in some HRI studies, including blaming [63, 201], threats [52], and scolding [87, 156], but whether it is effective for robots is inconclusive. Groom et al. [63] studied how a robot's blaming attribution (self-blaming or blaming human teammates) can affect its perceived competence and friendliness and found that people strongly preferred self-blaming robots. Van der Hoorn et al. [201] demonstrated a similar phenomenon, finding that people reacted more positively to robots who blame themselves for mistakes made by others. Jois and Wagners [87] found out that robots' punishment made people make more mistakes, and people tended to comply less with a robot's punishment compared to a human's. However, Rea et al.[156] found out that, although a "less polite" robot physical coach using harsh language was perceived as less friendly, it did make the participants exercise harder. This "disliked yet effective" effect of robots' coercive power warrants further investigation.

3.3.3 *Referent Power.*

Personal power such as referent power or expert power is rarely addressed explicitly in the HRI literature. However, many HRI studies to date address referent power or expert power implicitly.

In French and Raven's framework, referent power is related to personal charisma and is held by people whose personalities and personal traits attract admiration and identification from others. Looking from a broader perspective, these keywords—charisma, personality, and personal traits—correspond well to some of the most investigated concepts in HRI studies, including likability, politeness, and the appearance and behavior design of robots, which encompasses a huge portion of research in HRI.

What is special in studying referent power in HRI is twofold. First, much of HRI research and design strives to build understanding about how to make robots more engaging and attractive – in other words, how to provide them with referent power. Consequently, many terms used in HRI studies are milder versions of those in human referent power research. For example, "likeability" represents a milder form of "charisma", and designing the appearance and behavior of robots is thus akin to altering the personal traits of robots, which in turn influences their referent power.

Second, designing robots allows us to have a deeper understanding of human behavior, as well as to explore new possibilities that are naturally not in human behavior [29]. For example, eye gaze as it is naturally occurring in communication between people has been extensively studied. Studies in HRI, on the other hand, allow us to study gaze behavior that does not occur naturally in interaction, such as the effects of longer and less frequent fixation [2]. Similarly, Lee et al. [100] tested robots that are much shorter than humans in order to be "not threatening". They found that height did play an important role in power hierarchy: the very short service robot was often described as "servile, obedient, and submissive" (p.12).

Seeing referent power from this broader perspective, we find that many HRI studies on various phenomena can actually be seen as studies on referent power. As discussed above, studies on likeability [41, 183, 194], politeness [43, 109, 156, 168, 173, 176, 183, 196], human-robot similarity and mirroring [108, 211, 218] are all highly related to referent power. Moreover, studies on robots' appearance and behavior are also all highly relevant to referent power, such as the effects of gaze [2, 20, 65, 138, 140, 144, 181, 194, 222], body height [14, 100, 155], walking and orientation [126, 175], proximity [31], gestures [31, 65, 109], speaking style [9, 176, 183, 196], movements and hand-shaking [8, 107], and voice design [24, 123].

In the discussion section, we will show how these disparate studies on the design of robots' appearance and behavior—currently quite patchy—actually share the same underlying power structure and can be analyzed more systematically through the lens of power.

3.3.4 *Expert Power.*

Similar to referent power, many studies in HRI have addressed expert power, but mostly implicitly. Expert power is the power one gains due to their skills, knowledge, or experience. We argue that studies that address a robot's performance, intelligence, competence, efficacy, and fluency are all, to some degree, about expert power. This constitutes an enormous body of work not only in HRI but in the larger field of robotics. It is worth noting that some design considerations that we previously categorized as factors for referent power can also be related to expert power if they have a functional aspect, i.g., many of Moon and her colleagues' work on robot gaze and hesitation gestures [131–133].

With this view, there are too many studies about expert power to be fully covered in this paper, so we will focus on the *perceived* expert power and how to design or manipulate it. Some earlier HRI studies have already hinted at the importance of perceived expert power. For example, Lee et al.[100] stated that their goal was to design robots by "relying on appropriate features that convey the right level of intelligence and functionality", demonstrating the idea that we can design for an adequate level of expert power.

Along this line, many studies have also investigated perceived expert power [214, 217]. For example, Paepcke and Takayama [147] manipulated perceived expert power by varying robot descriptions which impacted perceived competence. Similarly, Andrist et al. [9] explored the effect of both actual and perceived expert power, manipulated through the detail level in the robot's utterance or its rhetorical ability, respectively, establishing that both strategies can enhance the robot's influence on participants.

In sum, we demonstrated how a large body of HRI work, while not addressing power explicitly, can be seen as being fundamentally about power. In other words, it is possible to understand these findings as findings about power.

4 DISCUSSION

Our review demonstrates the pervasiveness of power in the HRI literature. It also confirms William's [209] assertion that current HRI research treats power as a predominantly interpersonal construct. Here we will discuss how theories on power can explain hitherto seemingly unrelated findings through one coherent body of theory and outline future power-related research opportunities in HRI.

4.1 Seeing Through The Past: An Interpersonal Power Framework for HRI

As a conceptual lens, power can help us revisit previously studied phenomena and allow us to explain a broad range of HRI phenomena from one coherent perspective and thus move the field from a focus on effects towards building generalizable theory.

In section 3.3, we have shown how French and Raven's theory helps us to see the overarching theme of the source of power—the (a) in Fiske and Berdahl's model in Fig 1—in many HRI studies. Here we would like to point out that the effects of power (influence)—the (c) in Fig 1—are also omnipresent. This should not be surprising, as the reason we build robots is often to influence people's behavior. This influence can be manifested in vastly different ways, including persuading people [31, 57, 65, 70, 71, 73–75, 113, 125, 203, 211], making people to take a robot's advice [89, 153, 160, 175], making people comply with a robot's request [4, 12, 55, 58, 66, 141, 167, 169, 206], making people do tasks in a certain way [40, 56, 139], making people to adapt to the robot's behavior [142, 143], making people willing to give their personal information [103, 202], and even making people feel guilty [117]. Here we would like to make it clear that these vastly different behaviors, usually the dependent variable of a study, are all typical effects of power.

However, due to the lack of a coherent theory, these results were often not systematically analyzed as a whole, which should have led to deeper understanding of the mechanisms driving these various phenomena. The reason why power is omnipresent yet invisible in HRI is that most studies jump directly from, in Fig 1, (a) power's bases (often independent variables) to (c) power's influence (often dependent variables), without considering (b) power (capacity for effect). Without mentioning power—the underlying force, the interpretation of these results is unavoidably patchy. This can be problematic because it makes us overlook different power bases and how they can all contribute to power in different ways, as well as the diverse effects of a robot's power, which is the influence caused by power, also manifested in vastly different ways.

Here we would like to demonstrate the value of adopting a theory of interpersonal power by reinterpreting two studies previously seen as less related. Powers and Kiesler's highly-cited paper [153] investigated how a robot's physical attributes influenced people's advice acceptance. The study found that speaking with a male voice makes robots seem more knowledgeable, and a short chin makes robots seem more sociable. Both designs rendered the robot's advice more likely to be taken. Seen through the lens of French and Raven's theory, the study manipulated a robot's expert power (how knowledgeable it seemed) by designing its voice (male or female) and manipulated its referent power (how sociable it was perceived) by designing the robot's appearance (chin length). Both bases of power then resulted in the effect of power (influence), which was manifested in the form of advice-taking. The whole structure follows Fiske and Berdahl's power model (Fig. 1): they designed for the source of power (a), which generated power (b) that created the influence on humans (c).

Twelve years after Powers and Kiesler's paper, Lucas et al [113] investigated the effects of a robot's error-making and social dialog on its persuasiveness. Their study examined the impact of a robot's mistake-making and the timing of social interaction (before or after the mistake) and found that errors can, as expected, decrease a robot's influence. However, the timing of social interaction plays an interesting role: if it happens after a robot's mistake, it can repair trust in the robot; however, if it happens before the mistake, it can "backfire" and marred the robot's influence.

On the surface, Lucas et al.'s study about errors and social dialog appears unrelated to Powers and Kiesler's paper about appearance and voice design. However, the two studies are deeply related if seen through a lens of power. First, the second study also follows the same Fiske and Berdahl's model: the design (making mistakes and interacting socially) created the power, which was then measured by its actual influence (the persuasion, very similar to Powers and Kiesler's advice-taking). Second, these two papers were actually manipulating the same types of power. While Powers and Kiesler manipulated expert power by voice and referent power by the design of chin length, Lucas et al. manipulated expert power by whether the robot made a mistake, and referent power by whether there was a social dialog.

This leads to our third, and most important insight, that both papers, seemingly unrelated, actually engage in the same line of research, even if they are twelve years apart. Powers and Kiesler demonstrated that the design of robots can generate expert power and referent power, both of which can make a robot more influential. Lucas et al. then built on this and elaborated further that, although expert power and referent power both work, they do not perform independently. These two types of power may interact and cancel each other if not designed well. Referent power without expert power may backfire, causing a robot to lose its influence.

The example above illustrates that a lens of power allows us to systematically recognize factors contributing to robots' power and discern the same overarching themes across different studies, yielding more cohesive and meaningful insights. This lens reveals connections between studies previously considered unrelated, facilitating the application of their outcomes to effectively inform robot design, as shown in Fig 3.

By bringing in a perspective of power, we hope that our HRI community can become capable of understanding previous literature through this fundamental element of social interaction. We therefore can go beyond the individual studies to focus on these systematic questions: What causes a robot to have power? How do these different power bases interact with each other? What are the possible effects of a robot's power? Are there any key mediators that modulate the manifestation of power? These questions emerged after we analyzed previous literature following the power model, and they can all be mapped onto critical parts in Fig. 3.

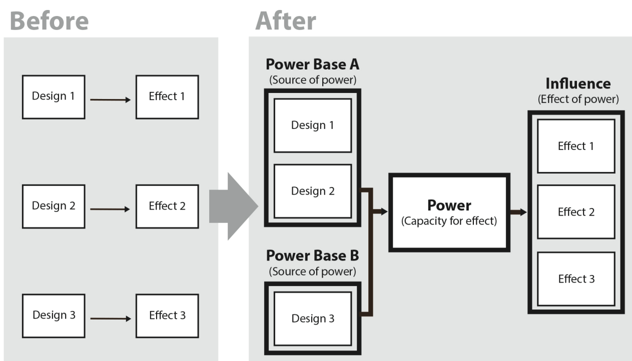

Figure 3: Previously, without a systematic structure, research findings may seem unrelated, so it is difficult to draw design insights from them. After introducing the frameworks of power, previous research can be viewed systematically, revealing new insights and future research opportunities (i.e., exploring how various power bases interact).

4.2 Looking Forward: Emerging Opportunities for Future HRI Research

Introducing a power framework not only enables us to see through previous research with a coherent perspective but also sheds light on future endeavors in HRI.

4.2.1 Power Factors and Mechanisms that are Exclusive to HRI. We have extensively applied French and Raven's model of five power bases, based on research on human-human interaction (HHI), to our analysis and discussion about HRI. This naturally leads to a question: are there power-related phenomena that do not exist in HHI, but are exclusive to HRI? Our review of existing HRI studies reveals several factors and mechanisms that are unique to robots.

The first factor is human-likeness, a paramount concept in HRI not directly transferable to research on people. Strait et al. [184] showed that people work better with human-like robots than mechanical robots, which may originate from the design of the robot, or more fundamentally, from the perception of human vs. non-human. Ashktorab et al. [13] showed that people found their teammates more likable, intelligent, and creative if they believed these teammates were humans compared to robots, showing that the framing itself matters. However, a higher level of human-likeness does not always lead to higher influence, as demonstrated by the famous phenomena in HRI, the uncanny valley [135]. Löffler et al. [112] have also shown that a moderate level of likeness (animal-likeness in their study) is preferred. Ghazali et al. [57], too, have shown that a robot with many human-like social cues might lead to higher reactance instead of more influence, further illustrating the intricate dynamics between human-likeness and power.

The second power factor we found is a robot's level of autonomy, which is influenced by how much people are in control of a robot's behavior. This is a factor that is highly related to the definition of power but has seldom been addressed in HHI, since it is rare that a human's behavior can be directly controlled by others, unlike robots. In HRI, Baraglia et al. [16] investigated different levels of automation and found that people preferred controlling the timing for robots to help. However, Bhattacharjee et al. [21] concluded that more robot autonomy is not always better. Mok et al. [130] even found out that when their drawer robot acted too proactively, it can "negatively affect people's perception of their own social status relative to that of the robot's". In general, people seem to prefer having control over the robots, i.e., having power over robots. However, there are also cases where people like to cede control when the robot is highly effective [60]. The tradeoff between task efficiency and the negative feeling of losing power to robots is an interesting topic that calls for more future research.

The third factor is people's feelings of "instilling" power in robots (i.e., "I made this robot") [30], which we refer to as "creator power." Sun and Sundar [187] found that people tend to evaluate a robot more positively if it is assembled by themselves, which is mediated by their sense of ownership and accomplishment. Studies have also let people participate in AI building so that AI governance can be perceived as more legit [102]. This kind of creator power is seldom seen in HHI, except for the relationships between parents and children, but becomes common, designable, and manipulable in human-agent interaction.

Furthermore, it is also worth noting that some mechanisms—how power works—seem to differ between HHI and HRI. First, Power is traditionally highly related to authority and dominance in HHI, but research in HRI has shown that they do not work well in robots. The findings that persuasive robots should avoid authority [206] and that people generally preferred low-power robots [63, 108, 188] hints that traditional ways of exhibiting power are prone to backfiring and psychological reactance in HRI. Instead, a different "soft" approach to power might be more effective, such as showing vulnerability [120, 186]. This "no power actually makes robots more powerful" phenomenon has indeed been noticed academically. For example, Lacey & Caudwell [96] have discussed the danger of robots manipulating people by being too cute.

Second, on the note of the danger of manipulation, we would also like to emphasize that "more power is not always better." Unlike humans whose power is restrained and balanced by social norms and systems, robots are able to cast influence in unprecedented ways. Robots with too much power can lead to overreliance, overtrust, or even addiction [170]. Previous research has also shown that robots given power can be more influential than some humans [82], which can be risky if used in a malicious way, echoing the rising social concern about the increasing use of intelligent agents. This concern about power, along with the factors and mechanisms exclusive to HRI, all call for further explorations.

4.2.2 Redefining Power for Behavioral HRI Research. A focus on power can also create opportunities for future research by re-examining the concept of power from an HRI perspective.

We have shown in section 2 the mainstream definitions for power in HHI literature from empirical social science and behavioral science. However, each definition faces certain challenges when applied to HRI. We have shown that the definitions of both (c) and (b) in Fig 1 have problems, leading scholars in HHI to adopt (a) in recent years. However, (a) is also problematic in HRI. According to this definition, O gains power over P when O has control over P's valued outcomes, which results in an immediate issue for HRI: what do robots value? The problem with this definition is that the relationship between humans and robots becomes too asymmetrical. Robots can be designed to own many resources that humans value, but humans might find it difficult to control robots. To push this definition to an extreme, it is possible that only robots can have power over humans, but not vice versa, which is an odd situation that many would not be happy to see.[3]

This is why we suggest that the (b) definition—that power is the capacity for influence—is a more suitable definition among the three for HRI. Although (b) has the problem of target volition, it is the same for (a), that if a person O decides not to value a resource, P who owns the resource loses the power over O. Considering all the advantages and disadvantages, we adopted (b) for the current paper as the definition of power.

However, one problem with this definition is that "capacity" is difficult to manipulate or measure. This is why we adapted and adopted Fiske and Berdahl's model, by combining it with French and Raven's bases of power theory, to form a "safe path" from (a) to (c) in Fig. 1. Because the capacity to influence (power) is invisible and intangible, we followed Fiske and Berdahl's model closely and introduced French and Raven's theory as operationally manipulable power bases (the source of power). We then proposed to measure power by its different types of influence (the effects of power). This "safe path" framework could therefore be used to examine power-agenda in existing and future HRI studies. As aforementioned, it also helps to explain why power has largely been neglected in the HRI literature: most of the studies jump from (a) to (c) in Fig 1, skipping (b), which is the power itself.

While this behavioral framework on power encapsulates the core arguments of this paper, we are fully aware that it is not the only resolution for defining power in HRI because behavioral science is just one perspective to view power. Also, this framework still uses existing definitions, and all the existing definitions, including Max Weber's "the probability that one actor within a social relationship will be in a position to carry out his own will despite resistance" [205], all presume actors have their own will. Since it can be disputable whether artificial agents have their own will, directly applying these definitions in HRI will inevitably be problematic. Furthermore, in HRI we also need to take into consideration whether the "will" comes from the robots themselves, the designers, the engineers, the researchers, or the robot owners, all adding to the complexities of the problem.

We therefore propose that, to better encapsulate the concept of power in the interaction between humans and robots, new definitions and conceptualizations of power are needed. Moving forward, it is important to address power in HRI by drawing from a broad range of disciplines. For example, recent work by Winkle and colleagues draws from sociology and feminism to elicit reflections on power beyond the interpersonal level and instead focus on the social structures and stakeholder relations in larger networks [212]. Similarly, we believe that exploring insights from other disciplines can also broaden our understanding of power in HRI. For example, how might the perspective of power in network studies—that one can gain more power when being in the position of central nodes of information flow [39]—add to the power discussion in HRI? How can power as it is treated in cultural studies—the force that shapes cultural norms, values, and practices, creating symbols and meanings—inform HRI? Or, how can we better understand and make sense of the power that roboticists wield, as discussed by William's work [209]? We believe that these new perspectives are not only promising future research directions for HRI but also a step toward an interdisciplinary understanding of power.

5 CONCLUSION

Power as a concept has been fascinating researchers for decades. Its complexity is evident in the vastly different definitions and understandings of power across diverse fields. As power has received little explicit attention in HRI, the aim of our paper is to call attention to this important concept. We showed how theories on interpersonal power can consistently explain observed phenomena across various HRI studies. Given the predominantly behavioral focus of past HRI research, our discussion largely focused on interpersonal power, i.e., the power that a robot wields over others. However, we also recognized and called for more various perspectives of power as they are essential in seeing the whole picture of power in HRI. As this paper shows, power permeates almost all aspects of our social interaction with robots and with humans. Addressing power in HRI, therefore, can not only help us make sense of existing HRI work but also guide future research and enhance our community's contribution to the wider academic community.

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[3]On this note, one way this definition can work is for us to deliberately design for vulnerability and dependence in robots so that their cognitive or physical weakness allows them to be controlled by humans, such as vulnerability and cuteness mentioned previously.

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