Mind-Body-Identity: A Scoping Review of Multi-Embodiment

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ABSTRACT

Multi-embodied agents can have both physical and virtual bodies, moving between real and virtual environments to meet user needs, embodying robots or virtual agents alike to support extended human-agent relationships. As a design paradigm, multi-embodiment offers potential benefits to improve communication and access to artificial agents, but there are still many unknowns in how to design these kinds of systems. This paper presents the results of a scoping review of the multi-embodiment research, aimed at consolidating the existing evidence and identifying knowledge gaps. Based on our review, we identify key research themes of: *multi-embodied systems, identity design, human-agent interaction, environment and context, trust,* and *information and control*. We also identify 16 key research challenges and 12 opportunities for future research.

CCS CONCEPTS

• **Computer systems organization → Robotics**; • **Computing methodologies → Philosophical/theoretical foundations of artificial intelligence**; • **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

human-robot interaction, multi-embodiment, agent migration, social agents, robot identity

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1 INTRODUCTION

Robots and artificial agents can have multiple embodiments and transfer their social presence from real to virtual environments to meet user needs. How agents in robotic systems are embodied and move between these embodiments are design choices that can affect how users interact with and trust agents of these systems. Users tend to form mental models of agents as social entities, which can differ from the underlying system architecture [10, 90]. Therefore, designers of robotic systems must decide how users should perceive the social presence of a multi-embodied agent to ensure that their systems are fit for purpose.

Early work on multi-embodiment focused on the process of *agent migration* for a single social presence. In agent migration the identity or persona of an agent moves between different embodiments [26, 65], environments [20, 70], locations [81, 83], or media [57, 58], so that users can interact with the agent in each destination. The migration process supports extended human-agent relationships beyond the original interaction environments and extends the agent's functionality and capabilities. Multi-embodiment has the potential to support enhanced communication and flexibility in robotic systems. However, design considerations for developing and implementing multi-embodied systems are still largely unknown.

An overview of the available evidence on the design of multi-embodied agents is difficult to obtain, but some relevant reviews have previously been conducted. In 2009, Holz et al. [32] surveyed social agents embodied across Milgram's reality-virtuality continuum [53]. However, their review focused on the degree of embodiment of social agents in the environment, rather than on multi-embodiment and identity. Holz et al. [31] later presented a survey and taxonomy of Mixed Reality Agents in 2011, limited to categorising social agents embodied in mixed reality into axes of *agency, corporeal presence*, and *interactive capacity*. Deng et al. [18] comprehensively reviewed physical embodiment in socially interactive robots. More recently, Gilles and Bevacqua [24] briefly reviewed the agent migration literature in a review of virtual assistants. However, their review was limited to the context of autonomous vehicles. To our knowledge, a comprehensive review that covers the breadth of the multi-embodiment literature is yet to be conducted. Motivated by the increasing interest in multi-embodiment as a design paradigm, and the lack of clear design guidelines for implementing robotics systems with multi-embodied agents, there is a need to map the existing evidence to guide the direction of future research. This gives rise to the research question: **what are the core themes, challenges, and knowledge gaps related to multi-embodiment?**

We conducted a scoping review [55] to understand and map the existing research landscape for multi-embodied agents to set the scope for future research. We identified and reviewed 56 papers published up to 27 July 2023. We found six main themes in the

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research: multi-embodied systems, identity design, human-agent interaction, environment and context, trust, and information and control. Our contributions to the human-robot interaction (HRI) field in this review are threefold. First, we describe, consolidate, and categorise the research on multi-embodied agents, including agent migration and robot identity. Second, we identify 16 research challenges examined by the existing body of research. Third, we highlight gaps in the literature and identify 12 opportunities for future research to inform the design of multi-embodiment systems.

2 KEY CONCEPTS

Before analysing the literature on multi-embodied agents, we first need to define the key concepts that underpin our review, including embodiment, multi-embodiment, and identity.

2.1 Embodiment

Embodiment is a key requirement for enabling naturalistic communication in HRI. A cross-disciplinary term, embodiment has been researched in philosophy, psychology, neuroscience, and computer science [18, 38]. The definition of embodiment differs depending on its research field, context, and application. In psychology and neuroscience, embodiment is a multidimensional concept relating to the human *"experience of one's own body"*, which arises from the cumulation of top-down and bottom-up cognitive processes and includes the sense of *ownership*, *location*, and *agency* [49, 84]. In philosophy, embodiment is concerned with how humans define and experience the sense of self [38], the separation of the mind and body, and the influence of the body on cognition [18, 87].

For robotics and artificial intelligence, embodiment relates to the existence of a physical embodiment in an artificial body (robot) or a visually perceived virtual body (virtual agent) that enables a human or artificial agent to interact within an environment [44]. In HRI, an artificial agent can be embodied in a robot, a virtual avatar, or a body that combines physical and virtual components using extended reality (XR; virtual, augmented, or mixed reality). Further, an artificial agent, such as a voice assistant, might be disembodied without a visual or physical form in its interaction environment [16]. In HRI, embodiment can also refer to the embodiment of a human user in either their own body, a virtual avatar, or within a teleoperated robot. However, in this review, embodiment henceforth refers to *the embodiment of an autonomous artificial agent in a visible body*, whether physical, virtual, or a combination of both.

2.2 Multi-Embodiment

A robot can be considered as being composed of two core components; its physical body and the computational systems that control it. A robot can therefore be understood as an artificial agent that is physically embodied in a mechanical form [4]. Similarly, embodied virtual agents are artificial agents with a virtual bodily form [16], visually displayed to the user using computer graphics.

Unlike humans, artificial agents can inhabit multiple embodiments [50]. The term 'multi-embodiment' was introduced by Lee et al. [46] in 2021 to describe agents with a dynamic embodiment that move across or simultaneously inhabit multiple bodies. Multi-embodiment offers versatility to the design of robotic systems, providing artificial agents the ability to meet user needs and facilitate flexible interaction in physical and virtual environments. Designers of robotics systems can use multi-embodiment as a design pattern to extend the social presence and reach of artificial agents.

Luria et al. [50] defined four different ways artificial agents can be embodied including *one-for-one*, *one-for-all*, *re-embodiment*, and *co-embodiment*. In the *one-for-one* embodiment, a single social presence exists in a single embodiment. In a *one-for-all* design, one social presence can appear to operate in many embodiments simultaneously, such as the model of social presence exhibited by conversational agents such as Siri, Alexa, or Google. In *re-embodiment* design, an agent's social presence moves between different embodiments. Most research in the multi-embodiment literature so far has explored the concept of re-embodiment, also referred to as agent migration. For *co-embodiment* designs, agents can share an embodiment with one or more other social presences coinhabiting the body at the same time.

2.3 Identity

For humans, identity is a complex social and psychological construct that includes how we view ourselves [22], the social aspects of how we present ourselves to others [25], and how others perceive and recognise us as unique individuals from other people [36]. Of these, the social aspects of identity are most relevant for identifying multi-embodied agents, as it is the *identity* or *social presence* of the agent that moves or is active in different embodiments. Robots are seen as social actors [56], whether or not by intentional design. To the user, robots and artificial agents often appear to be a single entity, with a one-to-one mapping of an agent to a body. However, an agent is an artificial construct crafted out of software algorithms, not a person. Further, agents are rarely a single 'entity' when technical architecture and hardware are taken into consideration [90]. The social presence of the agent can also be perceived differently by different users, based on individual tendencies to anthropomorphise [21], level of experience with the system, and prior knowledge [26, 27]. User roles can also affect the perception of social presence, with systems designers having different perceptions of the agent to the end user. For the design of robotic systems with multiple embodiments, where one agent entity can inhabit multiple bodies at the same time, or multiple agents might share the use of a single embodiment, the design of agent identity is a core design consideration [90].

Definitions of agent identity vary across the multi-embodied agent literature. Martin et al. [51] defined agent identity as *'that which causes the agent to remain the same within the mind of the user'* with a focus on the visual appearance of a migrating virtual agent. Aylett et al. [5] defined agent identity as *'those features that persist and make it unique and recognizable from the user's perspective'*. Kriegel et al. [42] asserted that the identity of a migratable agent involves *'consistent patterns of behaviour and affect over time'*, which users interpret as personality. Similarly, Arent et al. [4] proposed that how the agent behaves might also be an important feature enabling users to recognise an agent's identity.

3 SCOPING REVIEW

We conducted a literature scoping review on multi-embodied agents by searching Google Scholar using Publish or Perish 8 software.

Table 1: Multi-embodiment literature mapped to the key research themes.

	Multi-embodied systems	Identity design	Human-agent interaction	Environment and context	Trust	Information and control
User study	[27] [72]	[3] [2] [10] [50] [51] [63] [80]	[26] [34] [40] [58] [78] [76] [77] [74]	[70] [88] [14] [68] [67]	[65] [61]	[79] [5] [28] [39] [83] [81]
Technical paper	[33] [62] [75] [20] [60] [11] [6] [43] [42] [30] [93] [37] [82]					
Position paper		[8] [19] [45] [59] [86] [90] [91] [35]			[66] [89]	
Review paper				[32] [31] [24]		

Our final search was conducted on 27 July 2023. The search terms used were "agent migration", "migratable ai", "agent chameleon", and "ubiquitous cognition" in combination with relevant terms of "agent", "robot", "re-embodiment", "co-embodiment", and "embodied agent" with no restriction on the date of publication. This search resulted in an initial set of 623 items. To reduce the number of results, we excluded all duplicates (20 items), items not written in English (24 items), and items that were not journal articles or conference papers (146 items). We read the title, keywords, abstract, introduction, discussion, and findings and removed any items not relevant to the topic of multi-embodied agents or the fields of HRI or human-computer interaction (383 items). This narrowed the results to a total of 50 papers. After the exclusion process, we used citation chaining to identify relevant papers from the reference lists of the final 50 items. We further included papers found through our initial literature review that were not captured using the search terms, to ensure we had captured most of the relevant papers. We added a further 6 papers through this process.

Our final results set included 56 papers published on multi-embodiment between 1999 and 2023 (see Table 1). We analysed and categorised these papers using the following process. The first author read all papers, and an initial set of themes were identified using Affinity mapping. Affinity mapping (or the KJ Method) is a sense-making technique for understanding qualitative data by labelling and grouping concepts into related themes [71]. We organised the themes into the overarching topics and underlying research challenges they addressed. This process was repeated several times: reviewing and coding the papers, revising and refining themes, until we arrived at the final set of 6 topics and 16 research challenges. Finally, we identified knowledge gaps where further work is needed to make progress towards the research challenges.

We identified six key research topic themes: *multi-embodied system design, identity design, human-agent interaction, environments and contexts, trust*, and *information and control*. We mapped each paper to the key themes (see Table 1) and classified each paper into the type of work presented (user study, technical paper, position paper, or review paper). We identified the core research challenges addressed by each paper. We also identified papers that supported other research challenges in the reported findings and papers that identified unexplored research opportunities. Note that the research challenges overlap in some papers. Finally, research opportunities and potential research questions were proposed and discussed.

3.1 Multi-Embodied System Design

A clear theme in the research (15 papers) focused on exploring and demonstrating the feasibility of implementing system designs that can support multi-embodied agents (see Table 1). We identified the following research challenges related to multi-embodied system design: *system architecture* and *migration cues.*

3.1.1 System Architecture. The design of system architecture for supporting multi-embodied agents is a key focus of the multi-embodiment research. Further, the transferability of research findings into functional and safe real-world applications is a key challenge for HRI and human-AI interaction [13]. We found 13 technical papers on designing and developing systems for multi-embodied agents. Papers on this topic focused on proposing frameworks and piloting systems for agent migration [30, 33, 42, 43, 62, 75, 93], agent chameleons [20, 60], ubiquitous agents [6], cloud-based robot systems [37], and datasets for migratable AI [82]. The first agent migration system was demonstrated in 1999 by Imai et al. [33], who presented their ITAKO tour guide system with an agent that migrated from a computer to a mobile robot. This system was composed of software components for the *agent personality, agent core*, and *agent shell.* More recently (in 2021), Kaptein et al. [37] developed a cloud-based system for long-term interaction with an artificial health advisor to assist diabetic children in self-managing their health. The agent was embodied in a NAO robot in the clinic, and participants could interact with the virtual robot outside the clinic via a mobile application. They applied four design considerations for implementing such systems in the real world: *cloud-based robot control, modular design, a common knowledge base*, and a *hybrid artificial intelligence for decision-making and reasoning.* Tejwani et al. [82] collected a dataset for training future migratable AI systems and trained generative and information retrieval models on the data. **Knowledge Gap:** *Despite recent work, there is still a significant gap in available guidelines for the design of safe, transferable, and scalable multi-embodied agent systems for real-world applications.*

3.1.2 Migration Cues. A key design challenge for systems with multi-embodied agents is communicating to users that an agent is migrating or has migrated from one embodiment to another [5, 26]. Migration cues inform users about the migration process and whether an agent's social presence is currently active in an embodiment. We found only 2 papers that directly investigated migration cues. Gomes et al. [26] explored the transfer of agent needs between a robotic pet and a virtual pet but reported that participants failed to perceive a continuous agent identity across embodiments, despite their visual similarity. Segura et al. [72] reported that timing delays in the migration between embodiments and perceived unresponsiveness of the agent in an embodiment could result in users perceiving multiple entities, instead of a continuous social presence. Migration cues were used with varying success across the research and included cues such as progress bars [41], migration sounds [39], light activity [41, 50, 57, 58], device or robot activity [26, 72], migration triggers [28], verbal cues [50, 57, 58], and transition metaphors [20, 70], to indicate the migration process. **Knowledge Gap:** *Many different types of migration cues are proposed in the literature, but a systematic examination of the effectiveness of each cue is yet to be conducted.*

3.2 Identity Design

Multi-embodiment requires careful and considered identity design to retain the identity of a migrating agent across embodiments [40, 51, 68, 74]. We found 15 papers on identity design and identified research challenges of: *identity cues, identity performance, models of social presence*, and *dynamic appearance*. Research on this theme explored how agents can be embodied, the way users perceive multi-embodied agents, design cues to enable users to identify agents, and how identity can be constructed or performed for the user.

3.2.1 Identity Cues. A core challenge for multi-embodiment is ensuring that users can recognise and identify an agent's social presence as it moves or is active across different forms [51]. This is especially challenging if embodiments do not share common features or characteristics [2]. Martin et al. [51] were the first to propose and define identity cues as a way of maintaining a consistent agent identity across embodiments. We found 3 papers focused on identity cues. These papers explored design cues for agent identification across dissimilar embodiments [2, 51] and similar embodiments [3]. Martin et al. [51] showed that identity cues such as common features, colours, and markings can be used to identify virtual agents across dissimilar embodiments. Arent and Kreczmer [2] showed that migration path was an identity cue for migration between robots without common visual features and communication modalities. Arent et al. [3] explored robot behaviour as an identity cue for agents migrating between morphologically similar robots. Identity cues are widely used across the literature and can be categorised into: *visual cues* [39, 42, 51], *auditory cues* (voice [42], sounds [39], speech [9]), and *behavioural cues* [39, 42, 80]. **Knowledge Gap:** *Although many types of identity cues have been proposed and used, there is a need for a systematic analysis of the effectiveness of these cues for enabling user recognition of agent identity.*

3.2.2 Identity Performance. The identity of artificial agents is performative by nature, particularly in multi-robot systems [90]. Robots could be designed to perform identities fluidly [35], via overarching artificial intelligence systems that use different identities to manage user perceptions and the human-agent relationship. Therefore, how to design identity performance in multi-embodied agents is another key challenge. We found 3 position papers on this challenge discussing performativity as a design tool [90], identity performance strategies [35] and the ethics and risks of identity performance [91]. We found no empirical studies focused on identity performance.

Williams et al. [90] proposed 'performativity as a key design tool for robot designers' and discussed how the relationship between mind-body-identity might influence trust in multi-robot systems. Jackson et al. [35] proposed identity performance strategies for managing the human-agent relationship and suggested robots might spin up 'scapegoat identities' to complete trust-damaging actions that users won't like. Jackson et al. [35] also proposed that designers might choose system designs with 'composite identity' where robots perform unique identities as a deliberate strategy to make users feel more at ease with robot groups, as groups of robots can appear threatening to users [23]. Winkle et al. [91] discussed how robot identity can change quickly in a manner unmatched by humans, allowing rapid adaptation to suit interactions, context, or goals. They identified the potential risks of performative robot identity, which could perpetuate the norms and values of today's society for human groups who share commonalities with the identity characteristics being performed (such as gender or race). In related work, Miranda et al. [54] identified gaps in the HRI research around robot identity for intersectionality, neurodivergence, and race, and called for more research into areas where robot identity performance might combat stereotypes and other harmful norms. **Knowledge Gap:** *Identity performance strategies for multi-embodied agents are yet to be evaluated through user research.*

3.2.3 Models of Social Presence. The relationship between a robot's body, mind, and identity is highly flexible [9]. Unlike humans, agents can be socially present in more than one body at a time and can interact with many users simultaneously across multiple locations [42]. Therefore, another challenge for multi-embodiment is establishing how users perceive the social presence modelled by a multi-embodied system. Understanding this perception will provide guidelines for systems designers so that they can design multi-embodied agents that will be perceived by users in the way the designer intends. We found 3 papers focusing on this research challenge. Research topics addressing this challenge included user ability to understand agent intentions [64], social presence models [50], and the presentation of robot groups [10].

Ono et al. [64] implemented an early theory of mind mechanism in a migrating agent. Luria et al. [50] explored social presence models for re-embodying and co-embodying agents. They found that users were comfortable with re-embodying agents, but reactions to co-embodying agents were more complex. They found some participants felt excluded when two co-embodying agents talked to each other, and some participants perceived differing levels of social presence for agents co-embodying in the same body. Bejarano et al. [9] considered how human participants observed robot groups and presented a taxonomy of design cues for robot group identities. To the user, a robot group can appear as separate individuals, even when controlled by a single robot architecture. However, the 'mind' of a single robot entity might be distributed simultaneously across multiple embodiments [9, 89]. Bejarano et al. [9] found that when robot groups exhibited shared behaviours and qualities across the group, participants more frequently formed mental models of a one-for-all intelligence distribution model. Robots exhibiting unique behaviours and qualities within robot groups led participants to more frequently form a mental model of one robot mind for one body. Their findings suggest that mental models of the social presence of robots differ from human social group psychology theories. They also present initial recommendations for modelling social presence in robots. **Knowledge Gap:** *There is limited research on how visual design cues and nonverbal behaviour affect user mental models of social presence in groups of multi-embodied agents.*

3.2.4 Dynamic Appearance. Multi-embodied agents embodied in virtual or mixed-reality environments can be designed with dynamic appearance. This is the ability of an agent to dynamically adjust its morphology or appearance to meet changing user requirements or environmental conditions whilst preserving its identity. Note that dynamic appearance differs from identity performance; the intent is to retain the user perception of the same agent identity, rather than to dynamically change the identity of the agent. We found 3 papers which addressed multi-embodied agents with dynamic appearance, with research topics of agent mutation [51], Agent Chameleons [20], and the impact of first impressions [80].

Duffy et al. [20] presented their Agent Chameleons architecture and introduced the concept of agent chameleons; agents with the ability to migrate between environments and mutate their form to suit the environment. They demonstrated a robotic agent that migrates between physical and virtual environments and changes its virtual representation by adding an umbrella in response to simulated rain. Martin et al. [51] investigated whether users can recognise mutating virtual agents that dramatically change their appearance across embodiments. Syrdal et al. [80] explored children's perceptions of how a migrating agent should behave and what it should look like. Their findings suggest that the form in which the agent initially presents itself could impact subsequent perceptions of the agent across different embodiments. **Knowledge Gap:** *Little is known about how users perceive agents whose virtual representations differ from their real-world embodiments.*

3.3 Human-Agent Interaction

We found 8 papers relating to the theme of human-agent interaction. All papers with this theme were user studies investigating the relationship and interactions between humans and multi-embodied agents. The research challenges we identified for this topic are: *forming relationships, relationship maintenance*, and *customisation and personalisation.*

3.3.1 Forming Relationships. A challenge for multi-embodiment is forming an initial relationship with the user and building trust and rapport. We found 4 user studies that researched initial relationships with multi-embodied agents. These papers investigated building a relationship [34], emotional attachment [58], closeness [26], and friendship [74] with multi-embodied agents. Imai et al. [34] proposed a communication model to enhance human and robot cooperation. Ogawa and Ono [58] established that humans can form emotional attachments with a migrating agent that could migrate between a computer, robot, and desk lamp, thereby influencing human behaviour and cognitive abilities. Gomes et al. [26] showed that children felt closer to an artificial pet that could migrate between a robotic toy and a virtual smartphone character after interacting with it in both embodiments. Sinoo et al. [74] found that children can form friendships with multi-embodied agents, which increases motivation to continue to use healthcare support systems. **Knowledge Gap:** *Although the greater body of work on multi-embodied agents focuses on initial once-off interactions, there is limited evidence on rapport-building strategies and how initial perceptions can foster long-term engagement.*

3.3.2 Relationship Maintenance. A key challenge in HRI is transitioning social robotic systems to long-term interaction [37]. If multi-embodied agents are to collaborate effectively with humans, then users will need to form lasting relationships beyond simple once-off interactions with migrating agents. Human-agent relationships must form, and be retained across embodiments and between interactions. We found 4 user studies that focused on relationship maintenance for multi-embodied agents in a home environment. Syrdal et al. [78] found that participants felt closer to embodiments that could move around shared spaces in real-time. Syrdal et al. [76] reported participants accepted using a multi-embodied companion in the home over 10 weeks. Koay et al. [40] showed that participants habituated with a companion over the course of twice-weekly interactions for 5 weeks, felt more certain of the companion's identity, and found the migration cues clearer as time progressed. Syrdal et al. [77] found that participants adapted to the use of a robot for physical tasks in the home over an 8-week period, but reported frustration with the agent assisting with cognitive tasks. **Knowledge Gap:** *The long-term influence of multi-embodiment on human-agent relationships in contexts outside the home, and strategies multi-embodied agents can use to maintain user relationships, are yet to be examined.*

3.3.3 Customisation and Personalisation. Personalisation is a key research challenge for HRI [15, 17, 48]. However, we found only 1 paper that directly addressed the challenge of designing personalised or customised multi-embodied agents. Koay et al. [40] allowed users to personalise how a companion robot sought user attention using lights, colours and movements of its head and body. However, their results were unclear on what benefits such customisation provided. In the wider research, Reig et al. [68] reported that participants indicated they would highly value the ability to customise the agent's personality and identity. They also reported that many participants wanted to interact with agents similar in personality to themselves. Winkle et al. [91] asserted that customisable social identity cues have great potential for long-term interaction. **Knowledge Gap:** *There is little research on user customisation of multi-embodied agent appearance, behaviours, and identity.*

3.4 Environment and Context

We found 8 papers on the theme of environment and context. We identified research challenges of: *contexts, tasks and roles*, and *environment.* Research in this theme explored environments (real-world, augmented reality, mixed reality, and media) and contexts (real-world applications) where multi-embodiment can be applied.

3.4.1 Contexts, Tasks and Roles. A key research challenge for multi-embodied agents is establishing the kinds of contexts, tasks, and roles where multi-embodiment is suitable. We found 3 papers that focused on this challenge. Walters et al. [88] found that carers and residents of a residential care home were generally positive towards using multi-embodied robots to assist in caring for the elderly. Reig et al. [68] reported participants were comfortable with a migrating personal assistant who could assist with general non-complex life tasks. Reig et al. [67] systemically explored when robots should and should not re-embody in customer service roles, for impersonal and personal contexts, value delivered, and required expertise. They reported that participants were comfortable with the overall concept of re-embodying robots taking on multiple roles but found complexities across different contexts and roles that require further examination. Migrating agents have been researched in the context of museum tour guides [33], networking facilitators [62], artificial pets [26], educational agents [70], health advisors [37], personal assistants or companions [40, 66, 81, 83, 88], service robots [65, 68], and maintenance robots for space missions [89]. **Knowledge Gap:** *There is a need to further systematically explore the contexts, tasks, and roles in which multi-embodiment is suitable in non-service contexts. There is also a general lack of research in multi-embodied agents for larger human-robot teams.*

3.4.2 Environment. Multi-embodied agents can embody in physical, virtual, and extended reality environments in shared spaces or distributed locations. Another challenge for multi-embodiment is therefore exploring ways that agents can embody across Milgram's reality spectrum [53]. We found 5 papers that focused on this challenge. These papers included 2 user studies investigating augmented reality agents [14] and blended reality characters [70], and 3 review papers on social agents across the reality spectrum [32], mixed reality agents [31], and migration between devices [24].

Holz et al. [32] surveyed social agents across Milgram's reality-virtuality continuum. Holz et al. [31] categorised Mixed Reality Agents (MiRA), defining them as agents embodied in a mixed-reality environment that can migrate between environments and exist as blended-reality agents, composed of a mix of real and virtual components. Robert and Breazeal [70] found that children were more engaged with a blended-reality character that seamlessly transitioned from a physical robot to a virtual form, than with a purely screen-based agent. Campbell et al. [14] found that the use of augmented reality (AR) agents provides faster navigational assistance to users than AR signifiers such as directional arrows or bubbles. In other papers in this review, Barakonyi and Schmalstieg [6] piloted two applications of ubiquitous animated agents in AR where agents migrated between multiple AR applications and computer environments. Ogawa and Ono [58] found an emotional relationship formed between users and a multi-embodied agent that migrated between different types of media including a tablet computer to a desk lamp. **Knowledge Gap:** *To our knowledge, multi-embodied agents have not yet been explored in virtual reality (VR) environments.*

3.5 Trust

We found 4 papers that focused on the theme of trust and multi-embodied agents. We identified 2 research challenges for this research theme: *trust in body and identity* and *trust repair and recovery strategies*. Two of these papers presented theoretical perspectives and planned future work on how human trust for multi-embodying agents might be constructed, and two reported on the results of user experiments. Research in this theme focused on how users trust agents that employ multi-embodiment and how these agents might maintain user trust through trust recovery strategies.

3.5.1 Trust in Body and Identity. Who and what users trust is challenging for the design of multi-embodied systems. System designers need to understand the relationship between human trust for artificial agent identities and human trust related to the body the agent inhabits. We found 2 papers that investigated trust in the body and the identity of multi-embodied agents. These papers focused on deconstructed trustee theory [89] and trust transfer [61].

Williams et al. [89] introduced Deconstructed Trustee Theory. They proposed that the 'trustee' in migrating agents might be deconstructed into trust in the robot's physical body (embodiment) and trust in its identity. They found that a robot who performed blameworthy actions led to divergence in the perceived trustworthiness of body and identity. Okuoka et al. [61] investigated multi-device trust transfer and found that trust can transfer between embodiments for migrating agents. They also found the degree of trust transferred between devices is greater for migrating agents than agents with a one-for-one social presence model. **Knowledge Gap:** *Further work is needed to examine the interplay between trust in multi-embodied agent bodies, trust in their identities, and trust in overarching systems, technologies, and designers.*

3.5.2 Trust Repair and Recovery Strategies. Establishing and maintaining trust is a key challenge in HRI [29]. To achieve effective long-term relationships with users, multi-embodied agents will need to use trust repair and recovery strategies when they make errors or experience technical failure. We found 2 papers in the research that examined trust recovery after failure [65] and trust recovery after trust-damaging actions [89]. Reig et al. [65] investigated trust recovery for multi-robot systems after a robot failure. They explored strategies of re-embodiment where the robot's intelligence is transferred to another robot embodiment as a recovery strategy. They found users had higher perceived trust and competence in the system when a robot self-recovered from failure by either re-embodying or updating rather than another robot completing the task. However, Williams et al. [89] found that robots that allow other agents to take control of their embodiment are perceived as less competent. **Knowledge Gap:** *Further work is needed to understand how systems with multi-embodied agents can maintain user trust, and what kinds of recovery strategies are appropriate for real-world applications across physical and virtual embodiments.*

3.6 Information and Control

We found 6 papers in the research that explored how multi-embodied agents store and use user information, and how migration and information are controlled. We identified 3 research challenges: *information and memory*, *migration control*, and *user privacy*. Research in this theme is focused on how memory affects the human-agent relationship, how information should be shared and controlled in multi-embodied systems, and how to control agent migration.

3.6.1 Information and Memory. Memory and information recall are key characteristics required for social agents and robots, particularly for long-term interactions [5, 69]. We found 4 papers related to the information and memory challenge. Research under this topic investigated recall of conversational content [5], information disclosure [79] and information migration [81, 83]. Aylett et al. [5] investigated migrating agents that exhibited recall of personal conversational content across embodiments in a treasure hunt task and found that possessing memory improved the perceived competence of the agent. Syrdal et al. [79] explored user perceptions of multi-embodied agents that disclosed personal information between members of the same household and found that participants had differing concerns regarding the sharing of information. Tejwani et al. [81, 83] investigated user affective state when the agent identity migrated across embodiments in private and public spaces and found that users expressed more joy and surprise when both the identity and their personal information migrated between embodiments. In contrast, users were disappointed and angry when their personal information migrated without their agent's identity. **Knowledge Gap:** *Strategies and methods for enabling user control of what information is stored, recalled, or forgotten are yet to be explored.*

3.6.2 Migration Control. Agent migration can be initiated by the agent, system, or user, making migration control a design challenge for multi-embodiment systems. We found only 2 papers in the literature specifically focused on migration control. Grigore et al. [28] investigated migration triggers, comparing user-triggered and agent-triggered migration. They found that users perceived the agent as more socially present when it controlled its own migration. Koay et al. [39] found that most participants were satisfied with migrating companions who requested permission to migrate away to another location. However, some participants raised concerns about the ease of use, how long the process took, and the necessity of the agent asking permission. They also reported that some participants raised concerns about privacy and control regarding another user's personal companion migrating to their own personal computer. In other work, Reig et al. [68] reported some participants felt that the ability for agents to re-embody should be something they should control; to turn off or on as they preferred. Arent et al. [4] also identified controlling the migration process as an area for future research. **Knowledge Gap:** *There are outstanding questions in the research on who should trigger or control the migration process [4] and how migration control influences user perceptions.*

3.6.3 User Privacy. User privacy is a non-trivial research challenge for HRI. We found only 2 papers in the research that investigated user information privacy. Tejwani et al. [81, 83] investigated user affect and information migration between multi-embodied conversational agents in private and public contexts. Their results suggest that users prefer both the identity of the agent and their personal information to migrate together. They found users expressed more disappointment and anger when their information was migrated without their agent, and was used by other agent identities. **Knowledge Gap:** *There is limited research on user-customised privacy control for multi-embodiment systems.*

4 DISCUSSION

We mapped the existing work on multi-embodiment through a scoping review and identified the research themes, challenges, and opportunities. We found 6 research themes. Most of the papers reviewed addressed the feasibility of developing **multi-embodied systems** (15; 26.8%) and **identity design** for multi-embodied agents (15; 26.8%). We also identified research topics of **human-agent interaction** (8; 14.3%), **environment and context** (8; 14.3%), **information and control** (6; 10.7%), and **trust** (4; 7.1%).

Against the research themes, we identified a total of 16 research challenges for the design of multi-embodied agents. Research challenges include the design of *(1) system architecture, (2) migration cues, (3) identity cues, (4) identity performance, (5) models of social presence, (6) dynamic appearance, (7) forming relationships, (8) relationship maintenance, (9) customisation and personalisation, (10) contexts, tasks, and roles, (11) environment, (12) trust in body and identity, (13) trust repair and recovery strategies, (14) information and memory, (15) migration control*, and *(16) user privacy.* These challenges provide an initial taxonomy of design considerations examined within the research body for the development of multi-embodiment systems. However, many gaps in the research still limit multi-embodied agents from being realised in real-world systems.

4.1 Research Opportunities

In light of the knowledge gaps that emerged from this review, we identified 12 research opportunities for future work in HRI. These opportunities range from design guidelines for migration cues, identity cues, identity performance, and user personalisation to system architecture, trust, cybersecurity, and user privacy. We have formulated potential research questions for each opportunity area to guide future research in multi-embodiment and robot identity.

There is an overall lack of guidelines for designing safe and effective multi-embodiment systems for real-world applications. **Research Questions (RQ):** *What are appropriate technical architectures and system designs to support multi-embodied agents in real-world applications? How might we safely transition and scale from initial conceptual prototypes to real-world applications?* There is also a need for a systematic evaluation of migration cues. As users could find it disconcerting for an agent to change embodiments without warning, further research into migration cues is required before migration can be implemented safely in real-world systems. **RQ:** *How effective are the migration cues proposed by the existing research? How do migration cues influence user mental models of multi-embodied agents and user perceptions of agent identity?*

We found no clear design guidelines for identity cues. Recognition is a key cognitive process that enables people to identify others. Human recognition involves a complex interplay of cognitive processes, combining information from perception, memory, and semantic knowledge [7]. People can identify others using cues from a person's face, voice, name, body, smell, apparel, gait, body motion, and other behaviour, including handwriting [1, 7, 12]. However, how people recognise robots and virtual agents is poorly understood, and retention of identity in migrating agents has shown mixed results. In addition, identity performance is yet to be examined in experimental settings with human participants. **RQ:** *How do people recognise and identify multi-embodied agents? How effective are the identity cues proposed by the existing research? What kinds of identity performance strategies are acceptable to users?*

User perceptions of multi-embodied agents with dynamic appearance is under-researched. In virtual forms, an agent might change its appearance to enhance its communication capabilities. Robots could adopt a human-like appearance in virtual environments to provide users with social and non-verbal communication cues that are impossible in their original form. Little research has explored the suitability of multi-embodied agents that can dynamically change their appearance for real-world contexts and systems. **RQ:** *What kinds of visual changes are acceptable to users? In what ways can an agent's appearance change or be augmented?*

Beyond first impressions and encounters of migrating agents in a new embodiment, there is little knowledge of how multi-embodied agents can build rapport and form strong, lasting, and effective relationships with users. There is also little evidence on how the initial embodiment influences user perceptions and mental models. **RQ:** *How does the appearance or embodiment of multi-embodied agents affect initial user perceptions and mental models? What kinds of rapport-building strategies can multi-embodied agents use to form human-agent relationships? How can multi-embodied agents maintain user relationships over time?* User personalisation of multi-embodied agents was also under-researched in the literature. **RQ:** *What personalisations can be offered to users of multi-embodied agents? How does personalisation influence perceptions of social presence?*

Exploratory work has examined the kinds of contexts, roles and tasks where multi-embodied agents would most benefit users in real-world systems [50], but there are still many opportunities for further work. For example, there are potential roles for personal agents in stressful situations to help users feel more comfortable in unfamiliar environments [68]. Further, Reig et al. [67] reported differing results across different contexts and roles, which require further examination. ***RQ:*** *How suitable are multi-embodied agents in human-robot teams? What kinds of support roles can multi-embodied agents play in time-critical scenarios or high-risk environments?* Multi-embodiment in VR could enhance distributed human-robot teaming. Future work should examine the suitability of multi-embodied robots in VR for distributed teams. **RQ:** *What are the design considerations for multi-embodied agents in distributed teams? How do users perceive multi-embodied robots in immersive environments?*

There are many research opportunities for trust and multi-embodied systems. Future work is needed to further examine the interplay between trust in robot bodies and trust in their identities, to understand how systems with multi-embodied robots can best handle robot failure, and what kinds of recovery strategies are most effective before these systems can be introduced into real-world applications. **RQ:** *How do users perceive and trust multi-embodied agents based on their roles, tasks, and context? What kinds of trust repair strategies are most effective in multi-embodied agent systems? How does human trust differ between multi-embodied agent identities and their embodiments across different environments?*

There is a lack of evidence for how memory, forgetting and information control influence perceptions of multi-embodied agents. Further, we found no work that examined the kinds of information that multi-embodied agents should remember or forget. **RQ:** *How should information be shared and controlled in multi-embodied systems? How can users control who and what has access to their agent's data? What kinds of information should multi-embodied agents remember or forget?* We also found little work examining migration control in the research. **RQ:** *Who should control the multi-embodiment process? How does migration control influence user perceptions?*

We found no papers on cybersecurity for multi-embodiment systems. User privacy for multi-embodied agents is also under-researched. There is a significant need for further research in these areas as robotic systems are vulnerable to cyber-security issues and attacks [92]. Embodied systems have been shown to collect significantly more private and sensitive information from users than disembodied systems [85], and users can be unaware of the type of data and information collected [47]. There are also legal and ethical challenges with identity in virtual environments [52] to be considered for multi-embodiment. When an avatar can represent a human or an artificial agent, or be co-embodied by multiple entities, how do you know who you are interacting with? An inability to distinguish between humans and artificial agents could leave users, system owners, and organisations vulnerable to exploitation. Finally, there are ethical concerns around deception based on the appearance and behaviour of social agents [73] that are yet to be addressed in the multi-embodiment research. **RQ:** *How do cybersecurity and information privacy issues affect human-agent relationships with multi-embodied agents? How do perceived security and privacy risks influence system adoption and long-term interactions? What other ethical issues are still to be considered for multi-embodied agents?*

4.2 Limitations

The field of HRI is rapidly evolving, which means new trends or research are likely to emerge following our review. Although we aimed to employ a comprehensive search strategy, some relevant studies might have been inadvertently excluded due to the search terms or database limitations. Moreover, we did not assess the quality, scientific rigour, or bias of the individual studies included in this review. In this paper, we discussed and viewed robot identity through the specific lens of multi-embodied agents. Social robot identity performance research extends beyond multi-embodiment and the breadth of this work is outside the scope of this review. Finally, as we only included literature published in the English language in this review, it is possible that relevant work could exist in other languages that were not included.

5 CONCLUSIONS

We conducted a scoping review of the multi-embodiment literature and found 56 papers. Using Affinity mapping, we identified and described 6 research themes and 16 challenges for designing systems with multi-embodied agents. Furthermore, we provide 12 opportunities for future research ranging from design guidelines for migration cues, identity cues, and identity performance to research into user personalisation, trust recovery strategies, security and privacy. We further contribute potential research questions that can be addressed in future work. Multi-embodiment is a promising area for human-agent engagement in HRI, but many open questions and hurdles are still to be navigated. As ongoing research overcomes the challenges identified, a future where multi-embodied agents can benefit humans will come into clearer focus.

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