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The Emergence of Self-Awareness: Insights from Robotics

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Abstract
The ability for self-related thought is historically considered to be a uniquely human characteristic. Nonetheless, as technological knowledge advances, it comes as no surprise that the plausibility of humanoid self-awareness is not only theoretically explored but also engineered. Could the emerging behavioural and cognitive capabilities in artificial agents be comparable to humans? By employing a cross-disciplinary approach, the present essay aims to address this question by providing a comparative overview on the emergence of self-awareness as demonstrated in early childhood and robotics. It argues that developmental psychologists can gain invaluable theoretical and methodological insights by considering the relevance of artificial agents in better understanding the behavioural manifestations of human self-consciousness.

Introduction

Preoccupation with one's specular image presupposes the ability for self-related thought and action, a cardinal evolutionary landmark of human beings (Leary & Buttermore, 2003). Mirror self-recognition has traditionally been viewed as an index of understanding that what is in the mirror is "me," a particular combination of features that matches our idea of who we are, linked with the ability to establish mental representations of oneself (Rochat, 2003). The ability to reflect on the self as an object is typically attributed only to humans and few other species, notably great apes (Anderson & Gallup, 2015), and is often treated as a significant psychological milestone, opening the possibility of self-reflection in language, thought, and emotion (Rochat, 2019). Nonetheless, over the last decade, there has been burgeoning activity in the field of robotics, uncovering behavioural findings towards the idea of artificially constructed self-consciousness. If one assumes that the milestone for the development of explicit self-awareness in humans is markedly manifested by the ability to recognise one's specular image as their own,[1] what might be the implications of successful humanoid mirror self-recognition (e.g., Lanillos & Cheng, 2020)?

[1]Mirror self-recognition has been controversial with empirical literature not reaching consensus on its exact prerequisites (for both infants and animals; Brandl, 2018). Nevertheless, it has also traditionally been assumed as a milestone for the emergence of self-awareness (Anderson & Gallup, 2015). Notwithstanding its implementation in the field of robotics, the mirror mark test still plays a prominent role in animal research, being recommended as a promising experimental paradigm for investigating dimensions of animal self-consciousness (Birch et al., 2020). For this reason, the present essay starts by introducing cross-disciplinary ideas relevant to mirror self-recognition and, subsequently, shifts focus to contemporary arguments on the minimal self, which better reflect approaches in the current literature on the emergence of early self-awareness.

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As technological knowledge advances, it comes as no surprise that the plausibility of humanoid self-awareness is not only theoretically explored but also engineered. These developments attempt to simulate the unique and complex architecture of human cognition, aiming to get closer to the creation of an artificial sense of self in robots. Establishing that human self-consciousness emerges on the condition of the activity of varied self-processes instantiated by both brain and body, artificial systems have started to become synthesized with cognitive modelling similar to humans (Prescott & Camillieri, 2019). Notably, researchers have not focused so much on the complexity and functional sophistication of adult self-processing but, rather strikingly, on child development. In the early days of computer science, Alan Turing (1950, p. 456) famously suggested: "Instead of trying to produce a programme to simulate the adult mind, why not rather try to produce one which simulates the child's? If this were then subjected to an appropriate course of education, one would obtain the adult brain." It has now become well established in artificial intelligence research to adopt knowledge from the developmental principles of self-awareness and the mental mechanisms existing in cognitive systems of children (Cangelosi & Asada, 2022; Cangelosi & Schlesinger, 2015). Having the long-term goal of emulating human self-processing abilities, current approaches in robotics follow Turing's (1950) direction with ultimate aim to synthesize artificially constructed manifestations of self-awareness that will be directly informed by findings in developmental psychology through reverse engineering (Prescott & Camillieri, 2019).

Although researchers in the field of robotics show notable appreciation of the empirical insights of the early emergence of self-awareness (e.g., Cangelosi & Schlesinger, 2015), developmental psychology has not yet considered the relevance of artificial agents in better understanding human self-consciousness. This is unfortunate as attempts in elucidating artificially constructed manifestations of self-awareness have important implications for infant development since they could provide novel pathways of methodological evaluation and theoretical advancement of existing empirical evidence. Could the emerging behavioural and cognitive capabilities in artificial agents be comparable to humans? Before answering this question, it is imperative to provide a comparative overview on the behavioural manifestations of self-awareness as demonstrated in early childhood and robotics. Viewing comparisons between empirical findings from robotics and infancy as a promising approach, there is an exciting opportunity to employ artificial agents in bringing better empirical specificity to the mechanisms underlying the early emergence of self-awareness (Asada et al., 2001). This collaboration could ultimately result in more robust theories of self-awareness guiding empirical work while enabling rigorous interpretations of behavioural data and the development of novel experimental paradigms, leading towards a cross-disciplinary "regimen of theory-testing" (Seth & Bayne, 2022, p. 439).

The aim of this essay was to present an overview of the potential value of adopting comparative lenses from the field of robotics to refine our understanding, as developmental psychologists, of the early emergence of human self-awareness. Starting with a critical summary of mirror self-recognition (as a case example), recent empirical findings in the field of robotics will be then introduced to illustrate key issues with a presumption that explicit self-identification constitutes the milestone of the emergence of self-awareness. After presenting the concept of minimal self in humans, insights from robotics will be briefly explored to illustrate their potential relevance to advance developmental research. The present essay does not seek to provide an epistemological criticism of gaps in the existing literature, nor a concrete suggestion for the future of cross-disciplinary research, but rather to illustrate the relevance of comparative insights in reconsidering existing experimental paradigms (e.g., mirror mark test) and providing future avenues into developmental mechanisms of the early emergence self-awareness.

Self-Recognition as the Milestone of Explicit Self-Awareness?

In developmental psychology, the most well-established evidence about the emergence of explicit self-awareness has been traditionally demonstrated using the mirror mark test (Rochat, 2003). Originally developed to assess self-recognition in chimpanzees (Gallup, 1970) and later adopted to explore the development of self-awareness in children (Amsterdam, 1972), this test involves subjects being surreptitiously marked on the face with paint or rouge before being placed in front of a mirror and shown their specular image. Touching of the marked area is seen as a clear index of successful physical self-recognition, as it has been suggested that children are able to recognise something unusual in their appearance (Bulgarelli et al., 2019). Self-directed actions are then interpreted as an index of an established mental representation of the self as the object of one's awareness since one's face cannot be viewed without a mirror (Rochat et al., 2012).

Mirror self-recognition has been a key topic of inquiry in developmental psychology, and there is extensive empirical research showing that, despite cross-cultural differences in the speed of onset (Cebioglu & Broesch, 2021; Keller et al., 2004; Ross et al., 2017), most children pass the mirror mark test by 24 months (cf. Broesch et al., 2011). Nevertheless, the cognitive mechanisms behind successful self-recognition remain largely unknown (Hoffmann et al., 2021). Different factors have been suggested to motivate self-identification of one's specular image (e.g., mental representation of one's features, reliance on contingency cues, socially motivated self-exploration), albeit none of these alternative assumptions has been widely accepted (Brandl, 2018; Rochat & Zahavi, 2011). According to Rochat (2003), self-awareness might not suddenly appear when children successfully identify their own specular image but develop gradually; early perceptual experiences, proprioceptive learning, and social exchanges are likely to form the basis for progressive awareness of self-other differentiation and ultimate self-identification. Human self-awareness then does not only imply the capacity of directing attention to oneself but also to perceive oneself through "the evaluative eyes of other individuals" (Rochat, 2019, p. 345). Indeed, the onset of visual self-recognition is closely related with the emergence of differential self-relevant behaviours, including personal pronoun use, self-conscious emotions (e.g., pride, shame, guilt), pretence play, and empathy (see Lewis, 2019; Ross, 2017). From this perspective, one might not think of the mirror mark test as an "all-or-nothing phenomenon" but rather as something that develops gradually (Brandl, 2018).

Nonetheless, when it comes to animal research, according to de Waal (2019, p. 1), there is often the assumption of a "Bing Bang" theory to the capacity of self-awareness with some species possessing it while others do not (e.g., Anderson & Gallup, 2015; Gallup, 1970). Although attempts for studying mirror self-recognition have been unsuccessful to the majority of species beyond great apes, there are exceptions (de Waal, 2019). Over the last years, Asian elephants (Plotnik et al., 2006), bottlenose dolphins (Reiss & Marino, 2001), magpies (Prior et al., 2008), and recently, the cleaner wrasse fish (Kohda et al., 2019, 2022) appear to be able to self-identify in mirrors, as indicated by movements directed towards the mark (e.g., touching of the marked area) or behavioural changes (e.g., decrease of aggressive social responses and increase in self-explorative actions). Repeating Kohda and colleagues' (2019, p. 11) final question, "can passing the mark test be taken as evidence of self-awareness in one taxon and not another"? In other words, does this mean that all other species are simply not self-aware? Arguing in favour of the gradualist view of mirror self-recognition, this conclusion would seem unfair. The fact that a given species fails the mirror mark test does not necessarily indicate a total absence of self-awareness. After all, different animals are likely to have fundamentally different dimensions of self-conscious experience, without a necessity for exact parallels in behavioural manifestations (Birch et al., 2020; cf. LeDoux et al., 2023). This entails that the binary view of the capacity for self-awareness deduced simply by the mirror mark test is highly problematic.

Comparative Insights on Differential Mechanisms of Passing the Mirror Mark Test

Robotics research can provide an excellent illustration of the issues surrounding the validity of the mirror mark test. The exploration of self-processing abilities in artificial agents has gained increased popularity, with studies showing successful humanoid mirror self-recognition. For instance, in the paper of Lanillos and colleagues (2020), a humanoid robot self-recognized without being directly programmed to automatically identify itself in front of a mirror. Rather, self-recognition was achieved as a result of the accumulation of experiences of the robot's causal impact in the world through self-initiated movements and perfect sensorimotor contingency. Thus, it was non-reflective body perception and acquired contingency learning within the observed reality that provided the foundation for robotic mirror self-recognition (Lanillos & Cheng, 2020), not significantly different to animal studies employing training trials of mirror familiarization before the mirror mark test was administered (e.g., Gallup, 1970). Nevertheless, the robot here self-identified by making predictions on a sensorimotor level (e.g., whether arm movements perfectly matched the specular image, and in the case of perfect contingency, it is deduced that the figure in the mirror must be "me"), reflecting self-recognition based on contingency cues, as opposing to a cognitive framework requiring the subject to be self-aware and think about the self and one's appearance reflectively (Lanillos & Cheng, 2020).

Expanding these findings, Hoffmann and colleagues (2021) explored the low-level sensorimotor aspects of the mirror mark test, moving beyond an engineered approach of mirror self-recognition (e.g., Lanillos & Cheng, 2020) to the conceptualization of an embodied computational approach of spontaneous responses and novelty detection. Two humanoid robots passed the test through

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the following sequences: initial visual kinaesthetic matching (i.e., based on perfect contingency) in front of a mirror to identify the self in the mirror and subsequently to acquire knowledge of how their specular image looks like (i.e., store information about their visual features and make predictions), and finally novelty detection (i.e., mark should not be on the face). Although self-awareness of the complexity shown in humans is far from being achieved in artificial agents, there is still some common ground with self-recognition in animal studies as well as infancy. Thinking of the theoretical implications of this study, the researchers argued that by exploring behavioural manifestations of successfully passing the mirror mark test, we could gain insight into the mechanisms required for mirror self-recognition in animals and, ultimately, children (Hoffmann et al., 2021). Although failing the mirror mark test is unlikely to imply total absence of self-awareness, does passing it reflect self-conscious thought?

According to Anderson and Gallup (2015, p. 20), "merely simulating certain features of self-recognition through training/programming does not mean that the underlying mechanisms are the same, similar, or even remotely related." In humanoid robots, processes linked with self-awareness, notably mirror self-recognition, are predominately simulated rather than realized (Smith & Schillaci, 2021). In other words, currently, artificial agents have not demonstrated the unambiguous self-processing capacities of humans or great apes, and no direct comparison is possible as robotics research on mirror self-recognition is at this point "quite far from the biological plausibility" (Lanillos & Cheng, 2020). On a rudimentary level, human perception implies the complex functioning of living systems (e.g., sensory organs, biochemical information exchange, neural activity) towards constant maintenance and monitoring of internal physical states in the interaction with the external world (Nicholson, 2018). Such complex, recursively self-maintenance functioning (Bickhard, 2009) is not present in the perceptual process of a robot consisting of a digital signal processed by an algorithm. A biological organism not only is perpetually embedded in the physical world but also it is "made from its environment," and this interaction is a direct implication of open system thermodynamics (see Nicholson, 2018, p. 155). The "distinctive thermodynamic character" of living systems, grounding interoception, constitutes starting conditions for ultimately enabling manifestations of self-awareness (Nicholson, 2018, p. 145). This is radically different from the starting conditions of artificial agents, which lack somatic proprioception and bodily perceptions "from the inside" (Legrand, 2006; Longuenesse, 2012, p. 84).

Although there is indeed direct modelling of self-processing abilities in robotics, there is also an artificial cognitive system within which a set of (pre-reflective) principles guides real-time interaction between the body, brain, and environment (Cangelosi & Schlesinger, 2018). When artificial agents become embedded in their surrounding environment through an embodied physical structure (with sensors and actuators), they can actively respond and adapt to a dynamic external world through reciprocal exchanges (Asada et al., 2001; Cangelosi & Asada, 2022). Only by being "physically situated in the real world" (Cangelosi & Asada, 2022, p. 3) could humanoid robots potentially start to autonomously acquire the early sensorimotor abilities and learning towards the manifestation of self-relevant behaviours (see Asada & Cangelosi, 2022). It is this interaction (i.e., towards a simulated system of body-environment physical dynamics) that could realize the proposition of building computational models underlying cognitive self-processing (Nagai, 2022). It is to be noted that such prospect presupposes behavioural manifestations directed to a particular object of perception that "happens" to be the robot's physical body (Legrand, 2006, p. 91). Phenomenal subjectivity is not just "anchored in some physical substrate" (Legrand, p. 90), and thus, humanoid robots profoundly lack the first-person experience of bodily consciousness (Legrand, 2006; Longuenesse, 2012).

What robotics research demonstrates is that the mechanisms of successful mirror self-recognition are not univocal (Brandl, 2018); humans have an integration of more sophisticated processes, including interoceptive input, mental representations, and socially acquired knowledge, while some animals and artificial agents rely mostly on spatiotemporal abilities. Cross-disciplinary insights have shown that, concerning mirror self-recognition, the next step forward would be to resist overreliance on the mark test as the ultimate indicator of self-awareness. Shifting focus towards more foundational aspects of self-experience, the emergence of self-awareness can be further elucidated. Exploring self-awareness using experimental paradigms beyond the mirror mark test is often proposed as a key empirical direction, a notion especially relevant to animal research (de Waal, 2019). By employing a set of diverse methods assessing pre-reflective self-processing abilities, a more nuanced understanding of "how other species position the self in the world" (de Waal, 2019, p. 7) and how the development of self-reflection changes human cognition (Ross, 2017; Ross et al., 2011, 2020) can be gained. It is such integrative approach, incorporating ideas from cross-disciplinary contexts, through which the different dimensions of self-awareness can be established. A successful example of this approach is provided by research concerning the "minimal self," defined as "a consciousness of oneself as an immediate subject of experience, unextended in time" (Gallagher, 2000, p. 15).

The Minimal Self

The behavioural manifestations of explicit self-awareness in early childhood reflect the, often intuitively justified, approach of conceptualising the self in terms of self-conscious reflection upon one's mental experiences (Ciaunica & Crucianelli, 2019). Exploring our specular image involves the reflective experience of the body as an object in the physical world. Nonetheless, there is growing appreciation of the idea that the origins of self-awareness do not involve such a familiar perception of the self that we all are so well accustomed with by acquaintance but rather something more conceptually intrinsic. A primitive awareness does not necessitate a direct understanding of the self as the object of one's attention but a pre-reflective bodily sense that renders one's experiences implicitly subjective (Ciaunica et al., 2021; Legrand, 2006). It is an experiencing pre-reflective level of self-awareness known as the minimal self (Gallagher, 2000). In fact, such pre-reflective subjectivity should not be interpreted as an additional aspect of self-awareness, for "it essentially constitutes the very mode of being of any conscious experience" (Sartre, 1943, as cited in Ciaunica et al., 2021, p. 4). The minimal self then fundamentally underlies every "first-personal subjective experience" (Ciaunica & Crucianelli, 2019, p. 3).

Even if all the elements that we intuitively think as constituting self-awareness are removed, there is still something rather primitive that can be phenomenologically perceived as a subjective self-experience (e.g., Gallagher, 2000). Contrary to empirical findings in developmental psychology that view the self as the object of experience, the minimal self-concerns experiential states without any subject-object composition (Ciaunica & Crucianelli, 2019). Based on these theoretical approaches, the minimal self is seen as the immediate subject of experience, without a temporal extension, rendering reflective capacities not necessary for manifestations of self-consciousness (Gallagher, 2000). This relates to the sensorimotor "awareness of oneself as a subject [or agent] of experience" (Hafner et al., 2022, p. 1); it is an agent's phenomenal experience grounded in perception and action at the "here and now" that constitutes the foundation for the minimal self (Hafner et al., 2022). Defined as "systems" that act and perceive, processing incoming sensory data from varied perceptual modalities and subsequently acting upon these data through motor control, only agents are thought to develop self-processing abilities (Liesner & Kunde, 2021, p. 1). These experiential manifestations of self-awareness do not rely on complex (high-order) cognitive processing and, thus, seem to exist at the beginning of life, demonstrated behaviourally through empirical data in infancy.

The idea of the minimal self, as reflected in the above sensorimotor approaches, is in line with recent frameworks of embodied cognition, which emphasise the importance of the interaction between the physical body of an agent and the environment for the development of cognitive processes (Farina, 2021). Accordingly, it has been suggested that first-person subjectivity is not existentially predisposed but rather emerges through perceptual experience and sensorimotor learning (Hafner et al., 2022). Primitive modalities of perception arising in the womb are likely to provide the basis upon which prelinguistic and pre-reflective information relating to the self is acquired through sensorimotor input from the external world (see Ciaunica et al., 2021). Therefore, agents develop a minimal self-contingent on two learning processes occurring. Firstly, having a sense that their body provides the vehicle of the perceptual experience, being unique and differentiated from other entities in the environment, ultimately perceived as a "spatially extended part of the perceptual world" (Liesner & Kunde, 2021, p. 1). Secondly, being able to perceive the causal impact of their actions, as well as the perceived outcome, on the external world (Liesner & Kunde, 2021). These two properties, defined as sense of ownership and sense of agency, respectively, constitute key components of what is also referred to as the "ecological self" by Neisser (1988).[2]

Non-conceptual self-awareness is likely to be present at the beginning of life, with behavioural manifestations of the minimal self in infancy being "rooted in intermodal perception and action" (Rochat & Striano, 2000, p. 513). This idea was traditionally demonstrated in neonatal imitation studies where newborn infants were shown to imitate facial gestures (i.e., tongue protrusion) of adults in ways that could not easily be attributed to reflexes,

[2]The "ecological self" (Neisser, 1988) refers to knowledge of the self in relation to the physical environment, which is developed through perceptual information of children's own body acquired via self-exploration, contingent proprioception, and, ultimately, self-other differentiation (Rochat & Striano, 2000).

suggesting a capacity to match one's body with the observed gestures (Meltzoff & Moore, 1983; Nagy et al., 2013; see also Meltzoff et al., 2018). Nonetheless, more recent findings have challenged an innate ability for imitation (e.g., Oostenbroek et al., 2016). Alternative accounts argue that neonatal imitation does not really exist, with exhibited behaviour simply relying on basic cognitive processes, such as sensorimotor learning (Heyes, 2021; Slaughter, 2021). Although notions of infant imitation are still contested (Davis et al., 2021), a capacity to imitate based on learning does not undermine its role in cognitive development (Heyes, 2016). On the contrary, it is rather helpful to think about the centrality of self-observation within these associative learning models (Slaughter, 2021). Supporting theoretical frameworks of the minimal self, early behavioural manifestations of what appear to be infant imitation (irrespective of being inborn or learned) seem to initially require an ability to situate and use bodily parts proprioceptively, which ultimately provides the basis for the discrimination between self and other (Gallagher, 2000).

During the first months of life, infants continually move their bodies, bringing their hands on their faces and, notably, their mouths, ultimately beginning to explore their physical presence in increasingly deliberate ways. Through the perfectly contingent proprioception underlying these experiences, infants start to acquire perceptual information about their body as a unique and differentiated entity in the environment (Rochat & Striano, 2000). It is the unique perceptual experience of one's body that renders bodily actions and sensations exclusive to oneself (i.e., sense of ownership; Ciaunica & Crucianelli, 2019). Instantiated by motor babbling in the womb, body perception is progressively built by initially random movements that facilitate the exploration and discovery of one's body and its parts (DiMercurio et al., 2018; Prescott & Camilleri, 2019). As the infant touches itself, the experience of "skin-on-own-skin" (also known as double touch; Rochat & Hespos, 1997) is unique to the bodily self, being fundamentally differentiated by the sensory experience of touching other entities and enabling the infant to subjectively "learn the extension and limits of its own body" (Prescott & Camilleri, 2019, p. 92). It is through the contingency of sensorimotor information during self-exploration that infants understand what constitutes their physical body, likely resulting in the attribution of one's bodily self through feelings of ownership (Filippetti et al., 2013; Tsakiris et al., 2010).

In a classic study, newborn and 4-week-old infants could differentiate between internal and external stimulation after being touched by an experimenter or after spontaneous self-touch on the face, adaptively orienting their face towards the experimenter when externally stimulated (Rochat & Hespos, 1997). The evidence of the double touch shows that infants have an implicit body schema from birth, recognizing their own body as unique, long before they acquire a "conceptual and objectified sense of their embodied self" (Rochat, 2021, p. 383). Filippetti and colleagues (2013) have also found that when newborns are touched on the cheek with a brush, they show a visual preference for videos of a peer's face touched by a brush synchronously, rather than asynchronously, to their own face. It should be noted that this preference disappeared when newborns saw videos of a peer's face in an inverted presentation, showing the ability to detect multisensory synchrony specifically in relation to their body (Filippetti et al., 2013). Through the incremental sophistication of motor skills, which enables for increased exploration of the external world, infants soon learn to perform self-directed actions, demonstrated by reaching behaviours and purposeful touching (Musculus et al., 2021). Facilitated by a more sophisticated sense of ownership, these emerging motor abilities provide the foundation for the increased control the infant acquires over its body as it starts to distinguish self-initiated from other-initiated actions. This, in turn, provides the basis for understanding the perceptual consequences of self-produced actions (i.e., sense of agency; Rochat, 2019; Prescott & Camilleri, 2019).

Behavioural expressions of agency in infancy are likely to arise from the coordination between the infant's (initially spontaneous) movements and the sensory feedback they produce, further supported by the multiple opportunities for action and exploration inherently present in the physical world (Kelso, 2016). Once infants have acquired an understanding of their own agency, they behaviourally explore whether they can cause specific effects through changing and adapting their actions towards specific goals (Kelso, 2016). For instance, research exploring early understanding of one's body as motivated agent has often used the classic mobile paradigm, in which a ribbon connects the infant's limb with a mobile above its head, so that the mobile's movement can be directly controlled by one's self-movements (Kelso, 2016; Watanabe & Taga, 2011; Watson & Ramey, 1972). Infants aged 2–4 months have been found to increase the frequency of their movements when connected to the mobile compared to the baseline condition (i.e., no ribbon attached) (e.g., Watanabe & Taga, 2011). They also exhibit significantly more positive affect and smile, showing enjoyment over their own agency (Lewis et al., 1985).

Infants do not enter a physical world decontextualized from social interaction; self-awareness and intersubjectivity are deeply intertwined (Kyselo, 2016; Neisser, 1988). Facilitated by consistent face-to-face interaction with caregivers, by 2 months, infants develop social expectations and become active participants in the social environment as they appreciate their causal impact on their interaction partners and anticipate reciprocal responses (Rochat & Striano, 2000). For instance, this has been demonstrated using the still-face paradigm, in which the adult-infant reciprocal interaction suddenly becomes unresponsive, with the adult freezing in the middle of the interaction and demonstrating a "still-face" (Cohn & Tronick, 1983). Increased distress to the still-face response has been found in human neonates 3–96 h after birth (Nagy, 2008). As Neisser (1991) argued, early self-awareness is not solely contingent on body perception and interaction with a physical world but also on "ongoing worldly and interpersonal relational processes" (Kyselo, 2016, p. 1062).

First Steps towards a Cross-Disciplinary Understanding of the Minimal Self

In the last decades, empirical research on the early manifestations of the minimal self radically changed historical assumptions of viewing infants as entering the world in a state of "booming, buzzing, confusion between the self and the world" (Rochat, 2018, p. 345). From birth, infants demonstrate a pre-reflective level of self-awareness accompanied by a perceptual understanding of their own body as a unique and differentiated from other entities in the world as well as a rudimentary appreciation of their agency. These early experiences provide support for the idea that, from infancy, we are already equipped with "a minimal self that is embodied, enactive, and ecologically tuned" (Gallagher, 2000, p. 17). However, the mechanisms underlying manifestations of early self-awareness are complex, as infant behaviour is not univocal (Zaadnoordijk et al., 2018). Consequently, the origins and determinants of the human minimal self still remain mostly unknown (Rochat, 2018). In the field of psychology, behavioural patterns observed in infancy often constitute the basis for theories on the emergence of self-awareness. Nonetheless, such theories often lack an in-depth conceptualization of the mechanisms involved, which would ultimately enable insightful predictions and inferences to be made both on a conceptual and pragmatic level (Morse & Cangelosi, 2017). It is true that different computational models exist in cognitive sciences exploring the mechanisms involved in the emergence of the minimal self from birth, albeit in a potentially abstract level mostly concerned with isolated cognitive subsystems (Hoffmann et al., 2010). Still, it is challenging to make definite conclusions without a clear understanding of the interaction between the brain, body, and the external world, which characterises human self-awareness (Hoffmann et al., 2010).

Providing a "bridge between theory and experimental data," research in robotics has the potential to contribute invaluable insights to the study of the minimal self (Morse & Cangelosi, 2017, p. 36). Being inspired by empirical insights in developmental psychology, current robotic models use the same experimental setup aiming to replicate well-established behavioural findings while also proposing perhaps more robust and detailed conceptual frameworks underlying observed manifestations of self-processing abilities (Morse & Cangelosi, 2017). Humanoid robots, equipped with sensors and actuators, can interact with their physical and social environment to demonstrate self-related abilities, while their internal states and "perceptions" are logged and analysed to allow for insights into what the robots see and perceive when completing the given task (Hafner et al., 2020). It is this integration "from sensory stimuli to complex behaviour output" that renders artificial modelling of increased relevance for the field of developmental psychology as it necessitates an explicit and detailed theoretical stance about the exact computational processes required for the implementation of the observed findings (Morse & Cangelosi, 2017, p. 37).

These ideas can be illustrated in a study of humanoid imitation skills. Given that the necessary conditions involved in infant imitation are likely to involve sensorimotor learning (Heyes, 2021), robots need to be engineered with pre-conditions that would facilitate real-time perception and interaction with the world (Cangelosi & Schlesinger, 2015; Demiris & Meltzoff, 2008). For instance, a comparative analysis between child and robotic imitation showed that imitation skills "do not remain static but rather improve over time and with experience" (Demiris & Meltzoff, 2008, p. 47), highlighting the importance of sequential trajectories (which, incidentally, also supports the gradualist approach to infant imitation suggested by (Piaget, 1962, as cited in Slaughter, 2021). During imitation, the comparison between the current state of the body and the imitated movement elicits subsequent motor commands and accompanied input from the proprioceptive and visual consequences of the attempt to self-adapt the body to meet the goal (Demiris & Meltzoff, 2008, p. 45; see also Heyes, 2021).

This attempt becomes progressively more targeted and successful, initially involving simple movements, such as imitation of vocalizations and progressively facial expressions (based on a rudimentary sense of body ownership) and later more complex goal-oriented actions (facilitated by the developing sense of agency).

Before the acquisition of the necessary motivation and perceptual abilities to achieve imitation, a fundamental prerequisite for the emergence of the behavioural manifestations of the minimal self is the ability for self-other differentiation (Cangelosi & Schlesinger, 2015). It is the intimate interaction not only with the environment but also with one's body that underlies the unfolding of prereflective self-processing. Indeed, from the beginning of life, somatosensory processing contributes to the learning of what constitutes one's body and its boundaries, progressively building a mental representation of the bodily self as a unique and differentiated entity in the physical world (Cangelosi & Schlesinger, 2015). Such transition is likely to be underpinned by different mechanisms, with self-touch having a prominent role (Marcel et al., 2022). Spontaneous touching to the body involves the unique experience of 'skin-on-own-skin' which is fundamentally different from the sensory experience of touching other entities. Beyond the acknowledgement of the perfectly contingent proprioception of such distinctive sensory experience through tactile perceptions, self-touch underlies a felt first-person experience of the body as one's own (see Bermudez, 2018). By implication, self-touch enables for the progressive grounding of intermodal perceptual experiences centred around the body, such as tactile sensing, vision, and motor control (DiMercurio et al., 2018). Embodied computational models, directly implemented in artificial agents, might provide useful tools to test hypotheses as the behaviours derived from such efforts could be juxtaposed with empirical knowledge from infants (Hoffman et al., 2010; Marcel et al., 2022). For instance, the study of Roncone and colleagues (2014) aimed to better understand how self-touch contributes to the development of a body schema in early childhood. Through spontaneous self-exploratory behaviours, a humanoid robot formed representations of its own body as demonstrated by the higher precision of its self-touch after receiving sensory stimulation to an area on its arm equipped with sensors and tactile receptors (Roncone et al., 2014).

Further expanding these results, Hoffmann and colleagues (2017) compared infants' responses to bodily stimulation with computational modelling of these responses to a humanoid robot with artificial skin. Firstly, to test how infants learn their body, a vibrating buzzer was attached to different bodily parts in infants aged 3–21 months, and their movement patterns towards stimulation were assessed (Hoffmann et al., 2017). It was found that the youngest infants responded to the stimulation by moving their whole body in a seemingly undifferentiated way, with more targeted reaching responses developing between 4 and 12 months (Hoffmann et al., 2017). Although these results complement existing findings showing a developmental progression from generalized to more targeted body movements in early childhood, how do cognitive/neural networks determine which body part has been stimulated? The researchers suggested for an intrinsically motivated neural system that guides motor activity by generating random movements with self-touch occurring spontaneously. Modelling on the humanoid robot could not reveal the functioning of such sensorimotor mechanism; nonetheless, it still provided some insights for the direction of future research. For instance, in addition to the neural maps, which receive, process, and transmit this somatosensory input, a direct link must be formed between sensory and motor information, enabled by the mechanism known as sensorimotor contingencies (Hoffmann et al., 2017). It is hypothesized that sensorimotor contingencies could allow for the early creation (and progressive sophistication) of neural maps linking body and environment, a necessary condition for the emergence of more targeted self-exploratory actions (Hoffmann et al., 2017).

Conclusion

By employing a cross-disciplinary approach, the present essay provided a comparative overview on the emergence of self-awareness as demonstrated in early childhood and robotics. As research has shown, the emerging behavioural and cognitive capabilities in artificial agents are not identical to human development since the implemented algorithms are the result of a model, a simplification, of the human mechanism in question. As Forch and Hamker (2021, p. 6) argued, "it appears unlikely that an algorithm that is only constrained by a single computational goal could fully capture human behaviour and experience." Without the spontaneous interaction with the world, lifelong learning, and non-engineered motivation for performing self-relevant behaviours, integrating different dimensions of self-awareness, it is challenging to claim the potential of humanoid abilities underlying awareness of the self as the subject of experience (Hafner et al., 2020; Smith & Schillaci, 2021). Even though behavioural manifestations of self-awareness in robots are far from the phenomenal complexity inherent in living organisms (Nicholson, 2018), uncovering the reasons why humanoid self-processing is qualitatively different still contributes towards the advancement of developmental research by adopting a more critical stance to existing empirical paradigms.

Empirical research on the emergence of self-awareness in humans has demonstrated that cross-disciplinary efforts can be informative to addressing existing questions, gaining more insights into the mechanisms underlying early self-processing. Although artificial behaviour cannot be considered a proof of the functioning of a human mechanism, robotics research has potential to offer insights into developmental mechanisms not only focussing on a given behavioural output but more crucially on the "integration between or across phenomena" (Morse & Cangelosi, 2017, p. 37). Indeed, the corporeality underling early manifestations of self-consciousness involves the complex consolidation of multisensory inputs (e.g., proprioceptive, tactile, visceral) that constitute the foundations of the "transparent experiential background" of the origins of self-consciousness (Ciaunica et al., 2021, p. 4). It is this dialogue between artificial architectures and the prerequisites of self-awareness foregrounding the everlasting interaction between the body, brain, and environment, which could shape the direction of future research (Smith & Schillaci, 2021).

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Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Aikaterini Mentzou: conceptualization, writing – original draft, and writing – review and editing. Josephine Ross: writing – review and editing and supervision.

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