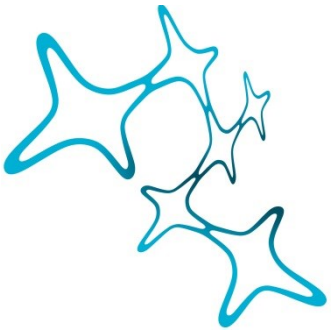
THE IMPLICIT SELF IN INFANCY — WHEN, HOW AND WHY?

Nina-Alisa Maria Kollakowski, née Hinz



Graduate School of
Systemic Neurosciences

LMU Munich

Dissertation at the
Graduate School of Systemic Neurosciences
Ludwig-Maximilians-Universität München

March, 2024

Supervisor:
Prof. Dr. Markus Paulus
Chair of Developmental Psychology and Educational Psychology,
Department of Psychology,
Faculty of Psychology and Educational Sciences.
Ludwig-Maximilians-Universität München

First Reviewer: Prof. Dr. Markus Paulus
Second Reviewer: Prof. Dr. Simone Schütz-Bosbach
External Reviewer Prof. Dr. Jeremy Carpendale

Date of Submission: 28.03.2024
Date of Defense : 23.07.2024

Table of Contents

Abstract

The nature of the self has been a topic of extensive debate. Current approaches divide the self into two aspects — the explicit self, which is based on reflection, and the implicit self, which is embedded in experience. There is no consensus on what the implicit self in infancy is nor on when or how it develops. This thesis addresses these issues. **Chapter 2** analyzes current theories on the implicit self in infancy, highlighting metatheoretical influences and advocating for enhanced conceptual precision. In **Chapter 3** a novel paradigm is employed to explore the presence of a sense of agency, a proposed aspect of the implicit self, in 9-month-old infants. The study does not provide evidence for the existence of a sense of agency at this age. **Chapter 4** examines the ontogenetic origins of the implicit self to contribute to the ongoing theoretical discourse on whether the self is inherently social. The results indicate that attributes of mother-infant interaction influence measures of the implicit self during infancy. Integrating these investigations, the present thesis concludes that there is insufficient evidence to posit the existence of an implicit self in infancy. The self may rather be considered a linguistic and social construct. The idea of an "implicit self" during infancy may be construed as a categorization of perceptual information, that has not yet been linked to the self. This thesis highlights the influence of social interactions on this categorization process, and proposes its continued development beyond the first 9 months of life.

1 General Introduction

For centuries philosophers have contemplated the concept of the self (Kitcher, 2021). In the first millennium, ideas about the self were largely inspired by Plato. Neoplatonists such as Plotinus defined the self as located in the human soul and based on reflective thought, while also including sensations and activities in their definition. In contrast, Ibn Sina, although also a Neoplatonist, claimed that the self can exist without any reflection, sensations, or thought. Ibn Sina acknowledged that the self is present in thought, but only because it serves as the basis for thought. Descartes (1641) built on the Neoplatonist idea with his infamous statement "Cogito ergo sum": asserting that only thinking beings possess a self. Consequently, according to his view, the self exists only in the mind, detached from the body and any activities (although see Lähteenmäki, 2021 for a different interpretation). With the rise of empiricism, philosophers focused more on the importance of sensations rather than the existence of a separate entity like the human soul, also for definitions of the self (Paulus, 2022b). For instance, Locke believed that people had the sensation of a continuous self based on autobiographical memory. They felt like the same person because they could remember their past experiences (Deroy & Battich, 2022). In contrast Hume believed that, the self was not continuous at all, and was instead constructed in every moment based on different sensations (known as "the bundle theory of the self"; Deroy & Battich, 2022; Paulus, 2022b). Kant also rejected the idea of the self as a concrete entity but instead believed that it was not the solely result of pure sensation. According to Kant, the self was influenced by categorical and linguistic thinking. Without a pre-existing concept of the self, individuals would not be able to experience it (Kitcher, 2021). Based on ideas of Ibn Sina (Aminrazavi, 2003), the phenomenological tradition, exemplified by Heidegger and Sartre

redefined the self as intrinsic to each perception and action, rather than reflective (Kitcher, 2021).

As this short outline of historical views about the self shows, there were two major theoretical streams: those who see the self as based on reflective thought and language, and those who see the self as based on perception and action. This distinction will be encountered throughout the thesis as various researchers adopted it. For example, James (1890) distinguished the "Me", the reflective and objective self, from the "I", the phenomenological self. Mead (1934) expanded on James' idea of two types of self. Like James, he considers the "I" to represent an active type of self. In contrast, the "Me" mainly represents a social type of self that contains the internalized view of others on the self. Consequently, according to Mead, large parts of the self emerge in and through social interactions.

1.1 What is the Implicit Self?

Developmental research was largely inspired by James' and Mead's view on the self as it provides a way to assign a self (the "Me") to verbal children as well as pre-verbal children (the "I"). Therefore, I will describe both aspects in more detail.

The "Me" is considered as the reflective and objective self. It consists of a collection of beliefs that individuals hold about themselves. Beliefs about what abilities they master and do not master, about character traits they possess, and about their look, but also thoughts about others' opinions on themselves, and moral norms they follow. Depending on which specific belief (set) is to be researched, scientists refer to it as the self-concept, the moral self and the like. Developmental research has primarily focused on this aspect of the self (for reviews see e.g. Damon & Hart, 1982; Harter, 2012). Children's ability to recognize themselves in the mirror is

often considered the onset of this self (Amsterdam, 1972). By being able to identify themselves in the mirror, children are assumed to possess a reflective view of themselves as they know how they look and how others see them. Reflectivity, or thinking about oneself, is a common ability in all different definitions of this self-aspect. Within this thesis, the term *explicit self* will be used to refer to this type of self that individuals can verbally express.

In contrast, the "I" lacks exactly this reflectivity but rather refers to subjective experiences. In developmental research, definitions of the "I" vary but they agree on a non-conceptual distinction between self and others. This means that infants do not yet have a concept about what the self is or what other people are, but they can distinguish sensory information coming from themselves and information coming from other sources. Within this thesis, the term *implicit self* will be used to refer to this self-aspect, as a type of self that individuals cannot verbally express. This self-aspect is instead implicit to sensations or actions.

The variety of theories on the implicit self makes it impossible to generally define the construct further. **Chapter 2** will discuss theories on the implicit self in infancy and explicate their assumptions on what the implicit self in infancy is. So far, these assumptions have been mostly implicit to the theories, preventing a direct comparison of theories. Assumptions about the nature of the implicit self, however, have implications for its assumed development, and also its measurement. Consequently, it is necessary to conceptually investigate theories on the implicit self in infancy to advance research on this construct.

1.2 How is the Implicit Self Measured?

Recent research on the implicit self in adults as well as children has been inspired by a theory from Gallagher (2000). He picked up James' ideas on the self and further developed it to differentiate between an explicit ("*narrative*") self and an implicit ("*minimal*") self. The minimal self is defined as the experience people have about themselves in every moment. It refers to an experience that is not extended in time and does not require awareness. Gallagher further defines two aspects of the minimal self that have largely shaped measures of the implicit self: the sense of agency, which is the experience of control over own actions, and the sense of ownership, the experience of body parts belonging to one's own body.

One example of paradigm investigating the sense of ownership in adults is the Rubber Hand Illusion (RHI; Botvinick & Cohen, 1998). In this paradigm, participants hide one of their arms behind a barrier or under the table. A rubber hand is placed in front of them and both the rubber hand and the participant's real hand are stroked with a brush, either synchronously or asynchronously. In the synchronous condition, participants appear to incorporate the rubber hand into their body representation. This phenomenon can be demonstrated by measuring a proprioceptive drift, which occurs when participants misplace the location of their real hand towards the position of the rubber hand. Additionally, increased skin conductance after threats posed to the rubber hand and questionnaires have also been used to demonstrate this phenomenon. A plethora of studies until now has demonstrated that the illusion depends on the contingency of visual, tactile, and proprioceptive information (see Tsakiris, 2017 for a review). The rubber hand is perceived as a part of the participant's body only when all sensory information is temporally contingent.

Variants of the illusion such as the enfacement illusion using another person's face instead of a rubber hand (Tsakiris, 2008) or the full body illusion using manipulated visual input of one's own body (see Pyasik et al., 2022 for a review), have demonstrated the crucial role of multisensory integration in the location and identity of the body. However, some researchers argue that in addition to multisensory integration, top-down expectations regarding the appearance of body parts or spatial configuration also affect the illusion (e.g. Tsakiris, 2010).

The RHI and other body illusions have been studied in children as well (for a review on RHI studies in children see Lee et al., 2021; for an example of a full body illusion in children see Cowie et al., 2018; for an example of an enfacement illusion in children see Steinmaßl & Paulus, 2024). Generally, children as young as 4 years old experience a similar sense of ownership over the illusion object as adults when measured with questionnaires and also show proprioceptive drift, although there is less clear evidence for this measure. There has been limited research on whether the children's sense of ownership is also influenced by top-down expectations. In a study testing children in the RHI with differently sized rubber hands (child-sized or adult-sized), no impact of size on the illusion was present (Filippetti & Crucianelli, 2019). This suggests that expectations about the appearance do not seem to influence children's implicit self to the same extent as adults.

Studies exploring infants' sensitivity to visual-tactile or visual-proprioceptive contingencies follow the logic of the RHI. In these studies, the contingency of multisensory information is varied to check infant's ability to detecting sensorimotor contingencies, which is considered an important precursor to the sense of ownership. Sensory information produced by an individual always is perfectly

contingent. For example, when infants move their arm towards their mouth, they receive visual and proprioceptive information about this movement that is contingent in space and time. Most measures of the implicit self in infancy are based on the assumption that infants recognize that some sensory information is contingent on the movement, while other sensory inputs are not. Once infants realize this, they can categorize information based on contingency. This categorization forms the basis for developing a body representation (de Klerk et al., 2021), which in turn is assumed to form the basis for an implicit self (Berlucchi & Aglioti, 1997).

Consequently, measures of the implicit self in infancy aim to demonstrate infants' ability to distinguish between contingent and non-contingent information as a step towards developing an implicit self. A seminal study that used such a measure is that of Bahrick and Watson (1985). They investigated the sensitivity of 5-month-old infants to sensorimotor contingencies by presenting them with two videos of infant legs. One of the videos was a live video of the infant's own legs, which was contingent on the infant's movements, while the other was a pre-recorded video of another infant, which was non-contingent. Bahrick and Watson measured infants' looking time to both displays, and discovered a preference for the non-contingent display. The authors concluded that infants were familiar with the contingent display because they recognized the contingency of the visual information to their own movements. As a result, they preferred the new and surprising non-contingent display. Since then, many studies have used similar approaches (see Bednarski et al., 2022 for a review) to demonstrate that infants also show sensitivity to spatial (e.g.

Rochat & Morgan, 1995) and visual-tactile contingencies (e.g. Zmyj et al., 2011). Even newborns seem to possess these abilities (Filippetti et al., 2013).

However, the interpretation of these studies has recently been challenged (Bednarski et al., 2022; Paulus, 2022a). While some studies demonstrate a preference for the non-contingent displays (e.g. Bahrick & Watson, 1985; Rochat & Morgan, 1995), others show preferences for the contingent display (e.g. Filippetti et al., 2013; Zmyj & Marcinkowski, 2017) with no clear developmental timeline. As the rationale between looking preference paradigms is that infants prefer the new stimulus over familiar stimuli, preferences for the contingent display in these studies would actually indicate that infants do not yet understand that information from their own body is contingent. Consequently, they would have a less developed implicit self than infants that favor the non-contingent display. However, also studies in which infants show a preference for the contingent display are interpreted as showing infant's existing implicit self. Given these ambiguities in interpretation it is unclear whether infants actually possess an implicit self or not.

Measurements of the other proposed aspect of the implicit self, the sense of agency, faces similar issues. In adult research it is commonly measured using two paradigms: intentional binding paradigms and sensory attenuation paradigms (for a review see J. W. Moore & Obhi, 2012). In intentional binding paradigms, participants perform an action that evokes a sensory effect, such as a tone. and then estimate the onset of the action and of the sound. For voluntary actions, participants judge the action onset to be later and the sound onset to be earlier than they actually occurred. This suggests that participants bind action and effect together in time.

In sensory attenuation paradigms, participants also execute an action that evokes a sensory effect. In another condition, the same sensory effect is presented without a preceding action by the participant, i.e. it is externally generated. In this paradigm, the measure is the perceived intensity of the sensory effect. This can be assessed by asking for perceptual judgments or by measuring neural responses, e.g. with electro-encephalography (EEG). Participants perceive the sensory effect to be less intense and show less neural response when they produce it themselves compared to when it is externally generated.

Research has shown that a sense of agency is experienced when the predicted sensory effects of an action match the actual sensory effects, particularly in terms of timing but also identity (for a review, see Hughes et al., 2013b). Models of sense agency suggest that action representations include the potential effects this action evokes. For example, pressing the light switch will be associated with the light flashing. Once an action is executed, a representation of predicted effects is activated. The predicted effects are then compared with incoming sensory information from the action. Some models of the sense of agency also suggest that top-down factors, such as expectations about causality or intentions play a role (Wegner & Wheatley, 1999). Similarly, it has been suggested that beliefs about one's own efficacy may influence the sense of agency (Synofzik et al., 2008). These beliefs are thought to develop during caregiver-infant interactions, as infants learn how effective they are in eliciting the necessary care from their caregivers (Sokol et al., 2015; Sroufe, 1994).

Although experiences from infancy are potentially important for the development of sense of agency in infants, so far no conclusive measure has been

developed to measure the sense of agency in infancy (Bednarski et al., 2022). Until recently, it was claimed that a sense of agency develops very early in infancy, and may even be present from birth (e.g. Rochat, 2003). This assumption was based on variants of the mobile paradigm, which was originally used by Rovee and Rovee (1969). The study demonstrated the ability of infants to detect sensorimotor contingencies. Specifically, 2-month-old infants were placed in a crib under a mobile that was attached to their foot with a string. Whenever the infants moved their foot, the mobile would move as well. Over time, infants moved the attached foot more often than other limbs and displayed joy presumably due to the control they could exert over the mobile. This movement pattern was interpreted as infants comprehending their ability to control the mobile, enjoying the feeling of control, and subsequently increasing their movements. This paradigm has been used in various forms (for a review, see Bednarski et al., 2022) to demonstrate that young infants understand the relation between their movements and the resulting effects, indicating a sense of agency. However, there has been recent criticism about these paradigms and their interpretation regarding a sense of agency (Bednarski et al., 2022; Zaadnoordijk et al., 2018). Through theoretical analyses and computational modeling Bednarski et al. (2022) and Zaadnoordijk et al. (2018) demonstrated that behavioral sensitivity to contingencies alone is not sufficient to indicate a sense of agency. Zaadnoordijk et al. (2018) found that classical conditioning can account for the increase in activity of effect-producing actions as seen in the mobile paradigm. However, the authors argue that this is not enough to conclude that infants possess a sense of agency, as this would also require causal understanding (i.e., “I caused the effect”; Zaadnoordijk et al., 2019) or agentic control (i.e., “I controlled the movement

that led to the effect"; Bednarski et al., 2022). To date, no studies have investigated these mechanisms, and therefore, it is unclear whether infants possess a sense of agency. In children, the intentional binding paradigm has been successfully applied, demonstrating that children as young as 4 years old exhibit temporal binding effects, although not specifically for self-produced actions (Blakey et al., 2019). Consequently, we know that a sense of agency exists in early childhood, but it is unclear when it emerges.

Zaadnoordijk et al. (2019) and Bednarski et al. (2022) agree that adding neural markers to behavioral data would improve our understanding of the implicit self in infancy (but see Coltheart, 2013 for a critical take on the usefulness of neural measures for theorizing). Neurophysiological data can provide information about implicit processing without the need for advanced language or motoric abilities. For instance, within the mobile paradigm, utilizing a recognized neural indicator of violations of expectation (known as the mismatch negativity), which is measured with EEG, could offer insights into the expectations that infants have regarding their ability to initiate movements of the mobile (Zaadnoordijk et al., 2020). Also, the sensory attenuation paradigm could be applied to infant research using EEG. Meyer and Hunnius (2021) presented a variant of the sensory attenuation paradigm in 3-month-olds, but did not discover conclusive evidence for sensory attenuation effects in this age group. **Chapter 3** implements a sensory attenuation paradigm with 9-month-old infants to investigate when a sense of agency emerges.

1.3 What Influences the Development of the Implicit Self?

Due to the theoretical variety and methodological challenges for investigation the implicit self in infancy, there is no consensus about the timing and process of

implicit self-development. Some researchers claim that the implicit self is present from birth (e.g. Rochat, 2004b), although there is disagreement on whether it is a genetic predisposition (e.g. Meltzoff & Moore, 1977) or if basic abilities develop in utero (e.g. Ciaunica et al., 2021). Similar debates exist regarding the necessity of social interactions for implicit self-development (e.g. Butterworth, 1994; Fotopoulou & Tsakiris, 2017a; Sroufe, 1994; Verschoor & Hommel, 2017). **Chapter 2** will discuss different theories about basic assumptions regarding the implicit self and their proposed line of development.

The work in this thesis is based on the assumption that social interactions during infancy influence the development of the implicit self. Attachment theory is one such theory that postulates this assumption (Bowlby, 1969). In essence, attachment theory suggests that infants develop a working model of social interactions and themselves through interactions with their caregivers. This model represents how effectively an infant can elicit necessary care from their caregivers, and how supportive those caregivers are, particularly during times of distress (Thompson et al., 2004). Infants perceive themselves as efficient and their caregivers as supportive (secure attachment) or not (insecure attachment types) based on the predictability and consistency of care provided. It is commonly assumed that attachment is established by the end of the first year of life (Ainsworth, 1978). However, Sroufe (1994) claims that even before the establishment, well-organized and predictable interactions between caregiver and infant influence the implicit self.

Next to attachment theory, various theoretical approaches (Bigelow, 2001; Fotopoulou & Tsakiris, 2017a; Montirosso & McGlone, 2020) have been developed to elaborate on sensorimotor information from the caregiver-infant interaction that are

not the main focus of attachment theory but are assumed to aid in the formation of an implicit self nevertheless. An example of such sensorimotor information is social touch. Social touch is assumed to provide contingent sensory information that can help children learn detecting sensorimotor contingencies, that is assumed to be a crucial factor in the development of the implicit self (de Klerk et al., 2021). However, so far there is little empirical evidence for a social basis of the implicit self but only the explicit self (see Harter, 2012; Thompson, 2008 for reviews on the social basis of the explicit self). **Chapter 4** will investigate whether the characteristics of the caregiver-infant interaction have an impact on the implicit self during infancy, providing insights into the potential basis of the implicit self.

1.4 The Current Thesis

After outlining both conceptual and empirical confusion surrounding the implicit self in infancy, the question arises: why is it worth investigating the implicit self in infancy? A crucial reason is that many socio-cognitive abilities are hypothesized to be based on an infant's self-understanding. The most obvious ability is the capacity to differentiate between the mental states of others and of oneself, such as thoughts or feelings. This distinction is considered necessary for empathy, for example (Bischof-Köhler & Bischof, 2017). According to this definition of empathy, individuals must share an emotional state with another person while also recognizing that the emotional state belongs to the other person and not themselves. However, distinguishing between one's own feelings and those of another requires a differentiation between oneself and the other person. It was previously believed that empathy could only develop after the second year of life, once children have developed an explicit self. Recently, researchers have claimed that infants can have

empathy because they possess an implicit self (e.g. Hoffman, 2007). Similar claims have been made about theory of mind, perspective taking (C. Moore, 1996, 2007), and imitation (Asendorpf & Baudonnière, 1993). Therefore, assumptions about the development of the self have a significant impact on various research areas. Gaining a more precise understanding of the self will advance developmental research in general.

Therefore, the purpose of this thesis is to investigate the implicit self in infancy. Previous research on the topic has been plagued by conceptual confusions and methodological challenges, leaving much unknown about the development of the implicit self. **Chapter 2** will clarify conceptual assumptions on the implicit self intrinsic to different theories. We discuss theories that propose a unified implicit self, which vary in the importance they ascribe to social interactions. We also discuss theories that assume multiple implicit selves as well as theories that question the existence of an implicit self in infancy.

In the second step, we address the methodological challenge of identifying conclusive measures of sense of agency in infants. Recent reviews have shown that most measures proposed to assess the sense of agency in infancy have been inconclusive regarding their aim. Therefore, new measures need to be developed. One measure that is considered a relatively reliable indicator of sense of agency in adults is sensory attenuation (Hughes et al., 2013b), which could also be implemented in infancy research. A previous study (Meyer & Hunnius, 2021) created a paradigm that closely resembles the one used with adults but produced inconclusive results regarding whether 3-month-old infants can differentiate neuronally between self-produced and externally-produced effects. In **Chapter 3**, we

developed an infant-friendly version of the sensory attenuation paradigm commonly used in adult research and investigated whether 9-month-old infants exhibited similar effects as adults, providing insight into the development of sense of agency in infancy.

After clarifying the theoretical grounding, and addressing methodological issues, we tested a theoretical framework on the implicit self. Specifically, we investigated whether caregiver-infant interactions influence the developing self in infancy. In **Chapter 4** we analyzed maternal sensitivity, maternal touch, and maternal contingency as possible predictors of a neurocognitive measure of the implicit self, in the context of attachment theory and other theories proposing a social influence of the self.

Chapter 5 will conclude the thesis with a discussion of the results of each chapter in light of their theoretical contributions and how they can inform future research.

2 What is the Implicit Self in Infancy? A Classification and Evaluation of Current Theories

This chapter was published in

Kollakowski, N. A., Mammen, M., & Paulus, M. (2023). What is the implicit self in infancy? A classification and evaluation of current theories on the early self. *Cognitive Development, 68*, 101394. https://doi.org/10.1016/j.cogdev.2023.101394

2.1 Abstract

Developmental science is increasingly interested in investigating the early ontogeny of the so-called implicit self. It is supposed to be a non-conceptual form of self including the experiences of agency and bodily ownership. Several theories have been proposed to account for the development of an implicit self and have inspired lines of empirical investigations. However, comparing these theories is difficult because the extent to which they rely on similar concepts is unclear, which in turn prevents systematic evaluation. This paper aims to provide an overview of currently influential theories on the development of the implicit self. It advances the debate by classifying the theories as either positing a unified implicit self, multiple implicit selves, or no self at all. The core assumptions of each theory are derived based on a comprehensive set of criteria, and evaluated using current empirical research. This overview proposes research directions that would enable further theoretical understanding of the ontogeny of the implicit self.

2.2 Introduction

The study of the self has a long-standing history in psychology. Already in 1890, James theorized about the self and divided it into two elements: the “Me”, which represents an objective and representative view of the self, and the “I”, which is a subjective and experiential version of the self. Mead (1934) further developed James’ ideas, emphasizing that a child’s perception of themselves is formed through social interactions (for review see Carpendale et al., 2018). Following these considerations, various psychological theories on the emerging self were developed. Yet, the various theories introduced different terms and partly described different phenomena, creating conceptual confusion.

For example, referring closely to James' (1890) "Me" scholars referred to this aspect of the self also *conceptual* (e.g., M. Lewis, 1979), *narrative* (e.g., Gallagher, 2000), *categorical* (e.g., Butterworth, 1992) or *objective* (e.g., Bates, 1994) self or *self-concept* (e.g. Gecas, 1982). The different terms conceptualize slightly different views on the explicit self, sometimes encompassing a temporal aspect of the self, i.e., the ability to imagine the self in the future (e.g., Povinelli et al., 1996; Suddendorf & Corballis, 1997) or remembering the self's past (Prebble et al., 2013). The concepts nonetheless overlap in their proposal that the self is described as a consciously accessible, usually verbalizable view that individuals have of themselves, such as a representation of their own bodies, their appearance, character, abilities, and so forth. The development of the self is closely related to children's ability to represent others (Carpendale & Lewis, 2004) and supports the emergence of self-regulation (Hammond et al., 2010). Within this article, we will refer to this concept as the *explicit self*.

In contrast, leaning on James' (1890) "I", current theories (e.g., Gallagher, 2000; Hommel, 2018) emphasize an additional aspect of the self, which we will refer to as the *implicit self*. The primary distinguishing feature between the implicit self and the explicit self is that the former it is proposed to involve a non-conceptual access to the self. The implicit self is proposed to be grounded in the perceptual properties of the body and its movements over a brief time frame, although past experiences may also have a top-down influence. However, also for the implicit self, theories vary to a great extent in their definitions. Some studies have attempted to identify the fundamental elements that define the implicit self. For instance, Gallagher (2000) proposes two indicators of an implicit self: the sense of agency and

the sense of ownership. The sense of agency refers to the feeling of being the one who performs an action and therefore also controls its corresponding effects (see also Sokol et al., 2015). For instance, when pushing a light switch and turning on the light, the feeling of being in control over the light arises. On the other hand, the sense of ownership refers to the feeling of possessing one's body or its parts. For instance, one feels as if the own hand belongs to one's own body. Blanke (2012) contributes another aspect to the sense of ownership for an implicit self, that is, self-location/first-person perspective, which implies the capacity to locate oneself in space and receive the impression of perceiving the world from that specific position.

The explicit self in early childhood has been thoroughly examined (for reviews see e.g., Damon & Hart, 1982; Harter, 2012; Kagan et al., 1981; Kim Koh & Wang, 2012). For this, developmental psychology has long focused on children's ability to recognize themselves in a mirror as an indicator of the explicit self. In a seminal study, Amsterdam (1972) investigated infants' ability to identify a red spot on their nose while standing in front of a mirror. At around 18 months, infants began demonstrating self-recognizing behaviors such as touching their nose or saying their names. Since then, these findings have been replicated by various studies (e.g., Brownell et al., 2010; Nielsen & Dissanayake, 2004; Nielsen et al., 2006). Despite some criticism (e.g., Kohda et al., 2022; Mitchell, 1997; Veer & van den Bos, 1999), mirror self-recognition is still recognized as a first indicator of the development of the explicit self. This is further supported by findings that around the same time children start to use their own name and personal pronouns (I, me, my) when referring to themselves (E. Lewis & Ramsay, 2004). This process lays the basis for a self that extends over time (for a review see C. Moore & Lemmon, 2001) and allows

for generalized descriptions of the self (Cimpian et al., 2017). As a result, a verbal, multidimensional self-concept emerges.

Recent developments in cognitive science have emphasized that features of the implicit self, such as body ownership in the rubber hand illusion (Botvinick & Cohen, 1998), can be altered and subsequently assessed. These advancements have resulted in a renewed interest in the early development of the implicit self from infancy (e.g., Filippetti et al., 2013; Filippetti et al., 2015; Maister et al., 2017; Zmyj et al., 2011) to early childhood (Filippetti & Crucianelli, 2019; Gottwald et al., 2021; Nava et al., 2017; Nava & Tajadura-Jiménez, 2020). Consequently, also new theories of the development of an implicit self in infancy have been proposed. These are helpful in comprehending empirical findings and directing future research.

However, the theories are somewhat disconnected from another, making it hard to compare and evaluate them. Moreover, the usage of different labels or concepts to describe the same phenomena, dampens critical analysis and empirical assessment. To address these challenges, this paper aims to give a structured overview of the central theories regarding the development of the implicit self. Several theories are only represented by single authors, and maybe even single publications, and have not been updated in years. Nevertheless, these theories are essential to the discussion since they receive broad attention in literature related to the implicit self. Despite the fact that numerous developmental theories, such as in Meltzoff's "Like me"-theory (Meltzoff, 2007a, 2007b) implicitly assume the existence of self-experiences, we will only consider theories that make explicit claims regarding the nature and development of an implicit self. Whenever an important theoretical

approach has not been adapted to infancy studies, we resort to general considerations of the implicit self and relate them to infant studies.

Our aim is to provide a systematic classification and description of how the theories interrelate, thereby creating new research avenues for testing various theories against one another. In the following paragraphs, we evaluate each theory based on: i) how it explains the previously formulated aspects of an implicit self; ii) how it incorporates the inanimate and the social worlds in its model of the emergence of the implicit self; iii) where it places the ontogenetic origins of the self;, and iv) how it explains the transition to an explicit self (see Table 1). We consider these evaluation points crucial as they enable us to compare the extensiveness and limitations of the theories and to clarify the differing views on the psychological basis of the implicit self. We choose to evaluate the theories based on the implicit self-definitions of Gallagher (2000) and Blanke (2012) since, to our knowledge, these are the only explicit definitions of an implicit self at present. Moreover, clarifying the degree to which the theories emphasize perceptual-motor and/or social processes as foundation of the self aids in comprehending the categorization of the theories. Grasping the theoretical commitments to innate processes of self-perception provides insights into the flexibility of the self and higher-level constructs derived from this foundation. The connection between explicit and implicit self has crucial consequences on whether the explicit and implicit selves are viewed as a continuum or independent constructs. Assessing the implications of each theory on animal consciousness could inform us about the phylogenetic source of self-consciousness (Barron & Klein, 2016; Boly et al., 2013) provided that a theory does not attribute the

same levels of self-consciousness to animals. However, since we focus on the ontogeny of the implicit self, this is beyond the scope of this overview.

The main difference between the theories is whether and in what form they assume the existence of an implicit self during infancy. Therefore, we classify the theories into three categories: those that assume a unified implicit self during infancy, those that suggest multiple implicit selves during infancy and those that acknowledge particular phenomena without attributing them to an implicit self during infancy.

2.3 Theories Assuming a Unified Implicit Self

The theories presented in this section assume the existence of a unified implicit self in infancy. These theories can be classified on a spectrum from theories emphasizing the perceptuo-motor nature of self development (hereafter referred to as perceptuo-motor theories) to theories emphasizing the role of the infant's social interactions in the emergence of the self (hereafter referred to as social theories). Predictive theories, as presented here, are a distinct set of theories located in the middle of this spectrum as they assign distinct and necessary roles to both the infant's social environment and interactions with the inanimate environment (e.g., object-directed activities).

2.3.1 Perceptuo-Motor Theories

Perceptuo-motor theories hypothesize the development of an implicit self in the context of action and perception, for example through an infant's exploration of objects and their own body. While these theories acknowledge the crucial role of social interaction for the basic functions of the infant, they do not assign necessary and specific roles to these interactions in the development of an implicit self.

Instead, the implicit self is believed to emerge from (subjective) experiences of an infants' physical interactions with the inanimate environment. Firstly, we will present ecological theories, which describe the implicit self as directly perceivable, followed by sensorimotor theories, which portray the implicit self as constructed through action.

2.3.1.1 Ecological Theories

2.3.1.1.1 Key Assumptions. Ecological theories regarding the implicit self are founded on Gibson's (1979) ecological perception theory. According to the ecological perception theory, perception includes two forms of information: objective, invariant information and subjective, variant information. Perception of invariant properties of the environment is objective and independent of the observer. As an illustration, consider a blue object. Regardless of the viewpoint, the object will always appear blue, albeit potentially varying in intensity depending on the lighting conditions. Hence, in this example, the object's color constitutes invariant information. Secondly, the variant properties of the environment are subjectively perceived as these properties change depending on the observer's position. In the case of the blue object, the size of the object will appear different depending on the observer's position relative to the object. If the observer is close to it, the object appears bigger; whereas if the observer is far from it, the object appears smaller. Gibson (1979) argues that this variant information always includes some information about the self, including the observer's position in the relation to the object. As a result, the implicit self can be perceived directly. According to the ecological theory perception does not require mental representation (Richardson et al., 2008); therefore also the implicit self is non-representational as well.

Butterworth (1992, 1994) applied Gibson's theory to infants and suggested that infants utilize the bi-informational nature of perception from early stages of development, and therefore have an implicit self. This perspective is supported by several experiments that demonstrate how infants use optic flow to stabilize their posture. Optic flow refers to the visual pattern that arises when moving the body through the environment. In a study involving 2-month-old infants, optic flow was generated by moving the walls of a room. Infants compensated for the movement by either falling or altering their head position (Pope, 1984). This indicates that infants were utilizing perceptual information to gain insight into their environment and to inform themselves about their subjective position and, according to Butterworth (1992, 1994), therefore about themselves. Later in development, by about 15 months, the infants continued to adjust their position in response to the optic flow However, their behavior also reveals they were wondering about the cause of the room's movement (Butterworth & Cicchetti, 1978). Such behavior has been interpreted as indicating their ability to differentiate between their own movement and that of the environment, which implies a sense of agency (Butterworth, 1992, 1994).

Furthermore, it has been suggested that infants have an innate body schema that forms the foundation for the development of an explicit self. As Butterworth (1992, 1994) explains, newborns and young infants demonstrate this body schema through their tactile exploration patterns. They mostly explore their mouth or eyes, which indicates their ability to coordinate their arm- or hand-movements to specific body parts. Therefore, it appears that some understanding of the body schema is present from an early age.

Butterworth (1994) proposes that the explicit self develops in a step-wise manner from the early implicit self by constantly reorganizing sensory information. Since birth, the sensory information has been encoded in a sensory code that incorporates the fundamental information involved in sensation. When an infant is 3 months old, the sensory code transforms into a perceptual code that represents the sensory code, and since it is a representational code – it can be stored in memory as well. At the age of 9 months, these perceptual codes get associated with each other, leading to the creation of relational representations. At this stage infants perceive themselves as permanent objects and show fundamental self-other differentiation. Although infants use mirrors to locate others in space in this stage, they recognize themselves only at 18 months as they can create symbolic representations at this age. Following this, infants develop a concept of causality and acquire a reflective self-concept that can be verbalized. However, Butterworth (1992, 1994) does not provide any further explanation on how the developmental emergence of an appreciation of causality relates to symbolic representations.

2.3.1.1.2 Evaluation and Implications. According to ecological theories, the self is experienced through subjective perception, implying two implicit self aspects: first-person perspective and self-location. From their viewpoint, perception is always subjective, and as it provides information about the self, the self is experienced from a first-person perspective. Secondly, a central claim is that any variant perceptual information involves location information relative to perceived objects. Therefore, perception relates to self-location since it allows locating the self in space. Butterworth (1992, 1994) claims that there is an innate body schema, which he does not define further, that serves as the foundation for the sense of ownership

(Tsakiris, 2010). Despite the fact that Butterworth (1992, 1994) mentions the sense of agency in noting that 15-month-old infants can differentiate between whether the room or they themselves moved in the optic flow experiments, he does not clarify the psychological mechanism underpinning this distinction. Therefore, the development of a sense of agency remains unexplained.

The ecological theory does not explicitly acknowledge the significance of the social environment for the infant's self-development, suggesting that it does not have a distinctive impact. As per the theory, when the infant is touched by another person, it presumably provides subjective and objective information akin to when the infant is touched by an inanimate object while moving through the environment. Therefore, studies showing relations between social interactions and implicit self-recognition (Zmyj & Marcinkowski, 2017) can be integrated into the theory. However, comparable non-social "touches" (e.g., a stroke of a branch) could elicit similar outcomes as well.

Ecological theories would suggest that the implicit self is present at birth, as Gibson (1979) claimed that direct perception does not require experience to be functional (Slater, 2004). Findings showing that newborns and very young infants can discriminate between self-related contingent and non-contingent information (Bahrick & Moss, 1996; Bahrick & Watson, 1985; Filippetti et al., 2013; Rochat & Morgan, 1995; Rochat & Striano, 2000; Schmuckler & Fairhall, 2001) or show differential rooting responses when touching themselves compared to when being touched by someone else (Rochat & Hespos, 1997) are used to confirm Gibson's (1979) assumption that self-perception is present at birth (Rochat, 2010, 2011). Critically, however, it could also be argued that these findings only show that infants

discriminate between different types of perceptual information and do not directly confirm that this information is self-specific, i.e. that infants use this information to perceive themselves.

The relationship between the implicit and explicit self, as defined previously, is uncertain in ecological theorizing. Although the self described by ecological theories can account for all aspects of the self that are directly perceivable, such as self-recognition, it does not constitute a reflective and narrative self. Butterworth (1992, 1994) proposed that constant reorganizing of sensory information plays an important role and eventually reaches symbolic representation. However, the transitions between the individual stages of reorganization are unspecified. Additionally, there are doubts on how a process of reorganizing sensory information can explain the emergence of conscious self-reflection and a verbal self-concept.

One important consideration pertains to the empirical basis of Butterworth's (1992, 1994) claims. The primary assertions are based on optic flow experiments with infants. It is worth noting that they rely on two assumptions. Firstly, it is assumed that infants' stabilization behavior is goal-directed. In his argument, Butterworth's (1992, 1994) claims that postural stabilization is directed towards the goal of maintaining a stable posture. This is said to be evident from the behavior being adaptable to the particular optic flow, and the behavior ceasing only after a stable posture is attained. Under this assumption, the behavior can be interpreted as self-controlled. However, this is debatable since postural stabilization is widely interpreted as reflexive rather than genuinely intentional behavior (Baloh, 2011). In fact, the American Psychological Association specifies in their dictionary that a reflex is "any of a number of automatic, unlearned, relatively fixed responses to stimuli that

do not require conscious effort […]". This definition does not exclude some degree of adaptiveness of the behavior to the circumstances. Secondly, when a behavior is goal-directed, it implies a sense of self, not the other way around (for criticism on this take see Verschoor & Hommel, 2017). Therefore, one might argue that ecological theories' view of the implicit self lacks empirical grounding.

In conclusion, ecological theories presuppose the self without explaining its origin. These theories assume that perception delivering self-specifying information is functional from birth, but the connection to the explicit self is unclear. Thus, there is no actual statement how the implicit self develops. As a result, it is challenging to generate testable predictions from the theory.

2.3.1.2 Sensorimotor Theories

2.3.1.2.1 Key Assumptions. Theories emphasizing the role of action and perception in human development, i.e., sensorimotor theories (e.g., Adolph & Hoch, 2019; Hommel, 2021; Lockman & Kahrs, 2017; O'Regan & Noë, 2001) propose that newborns do not have an implicit self that is present at birth. Rather it develops through active interaction with and exploration of the environment. According to Piaget (1970) infants begin as adualistic, i.e. they do not see the self as distinct from the environment in the beginning. It is only through sensorimotor development that infants learn about objects, and therefore about themselves (the subject). The "self-by-doing" approach by Verschoor and Hommel (2017) is related to this idea by stating that the implicit self can only be assumed to have developed once infants demonstrate goal-directed behavior.

According to Verschoor and Hommel's (2017) review, evidence suggests that goal-directed behavior can only be demonstrated by infants from the age of 9

months. Infants at this age acquire bidirectional action-effect-associations that serve as the basis for intentional action (Hommel, 2009). Upon acquisition, infants can use the action-effect-associations to guide their action selection. Before this age, infants may predict the effects of their actions, although it is unclear whether these predictions are directly used to select their actions or not. According to Verschoor and Hommel (2017) the utilization of effects to guide the action selection process represents an essential feature of goal-directed actions. Neurocognitive studies have provided evidence that 9-month-old infants exhibit motor activation when perceiving the effects of an action (Paulus et al., 2012) and demonstrated the facilitating impact of an effect on the subsequent execution of an action (Verschoor et al., 2010). Thus, it can be assumed that infants develop bidirectional action-effect-associations, and thus an implicit self, around the age of 9 months. Due to the time required to acquire action-effect-associations Verschoor and Hommel (2017) conclude that an implicit self is not present at an earlier age. Ideomotor theory proposes that these associations are acquired through sensorimotor exploration of the environment as whenever an action is performed, even unintentionally, the resulting effects become associated with the action (Hommel, 2015). Constructing a database of action-effect-associations adequate for choosing the appropriate action requires considerable familiarity with actions and their consequences, which infants gain in their first months of life. According to Verschoor and Hommel (2017), the late acquisition of goal-directed actions might additionally depend on the development of the frontal lobe or requirement for infants to learn intentional action selection through social interactions – a proposal introduced by Prinz (2012).

The development of the sense of ownership is briefly discussed by Verschoor and Hommel (2017). According to the "self-by-doing" framework, in infancy, the sense of ownership and the sense of agency are not yet dissociable constructs. The differences between both implicit self aspects are assumed to be very subtle, as they largely rely on similar information, such as movements and resulting sensory information. Further development leads to the dissociation between the two aspects of the implicit self. Additionally Verschoor and Hommel (2017) suggest that for infants, the dissociation between the senses of ownership and agency might not be beneficial. Infants may learn action-effect-associations not only through their own exploration of the environment but also from observing actions in others. Inability to differentiate between one's body and another's body and thus representing the actions of others as their own, may benefit the learning of infants.

While the dissociation between the sense of ownership and the sense of agency may develop only later in life, Verschoor and Hommel (2017) propose that the sense of ownership develops only after the sense of agency. They propose that the computation of the sense of ownership is cognitively more taxing than that of the sense of agency based on the information that is necessary for each. While the sense of agency is based on exteroceptive information (e.g., vision, audition, and proprioception) the sense of ownership requires the integration of exteroceptive and interoceptive information. Because studies indicate that children are able to recognize themselves earlier in dynamic visualizations than in static ones (e.g., Bigelow, 1981), Verschoor and Hommel (2017) conclude that the prediction of the sensory effects of infants' movements (which is part of the sense of agency) develops earlier than the experience of ownership over one's own body.

2.3.1.2.2 Evaluation and Implications. Verschoor and Hommel's (2017) "self-by-doing"-approach, as one example of sensorimotor theories, concentrates on two implicit self-aspects: the sense of agency and the sense of ownership. Their primary argument is that the sense of agency requires goal-directed actions as a necessary prerequisite. It is important to note that within the sensorimotor framework, theories vary in their assumptions about whether effect prediction is sufficient for agency, or if agency emerges from action execution. As mentioned earlier, Verschoor and Hommel (2017) propose that goal-directed action execution is essential for the emergence of agency–an assumption shared by others (J. W. Moore & Fletcher, 2012; Wegner & Wheatley, 1999). In contrast, the comparator model theory (Frith, 2005; Frith et al., 2000) assumes that predicting the effects of an action and comparing them to the actual effects is sufficient for a feeling of control to emerge. Empirical evidence for Verschoor and Hommel's (2017) assumption predominantly arises from studies conducted with adults. Studies have suggested that individuals only experience a sense of agency when performing voluntary actions and not when involuntarily triggered through methods such as transcranial magnetic stimulation (Haggard et al., 2002). Furthermore, the fluency in action selection can significantly impact the perceived sense of agency (Chambon & Haggard, 2012). Such findings corroborate the notion that the sense of agency is influenced by action selection. As the implicit self in adults could be considerably impacted by their acquisition of top-down cognitions about themselves (e.g., Tsakiris, 2010), it would be important to provide direct empirical evidence from studies with infants. As a result, future research conducted on infants will need to separate the

involvement of action evaluation and action selection in the formation of the sense of agency.

It is important to note that the developmental timeline proposed by Verschoor and Hommel (2017) is subject to debate. Their theory is based on their definition of goal-directed actions (a clear differentiation of goal and action, as well as prediction of the effects) that are assumed to develop around 9 months. However, other studies demonstrated earlier action prediction (for a review see Hauf, 2007), others showed that infants use the information about effects at rather later ages (for a review see Elsner, 2007). Consequently, future research should try to investigate sense of agency measures in infancy to see if their development matches the timeline proposed.

According to Verschoor and Hommel's (2017) assumptions, the sense of ownership develops later in life and can still be "confused" with a sense of agency during infancy. However, the necessary conditions for distinguishing both aspects and their developmental pathways are not explained. Verschoor and Hommel (2017) exclusively adhere to Gallagher's (2000) framework and concentrate on the senses of agency and ownership as fundamental elements of the implicit self. Unlike other theories (Blanke, 2012; Gallagher & Zahavi, 2010), Verschoor and Hommel's (2017) approach omits the phenomenological experiences related to self-location and a first-person perspective. These experiences may either be presupposed or not considered as indicators of an implicit self.

Sensorimotor theorizing suggests that infants can learn action-effect-associations by observing others performing actions (Paulus, 2014). However, the most prominent way in which infants learn action-effect-associations is through their

own exploration of the environment. While there may be some action-effect-associations that infants could learn faster from observation than from exploration (e.g., opening the lid of a screw top jar), there are very few action-effect-associations that can only be learned by observation. Thus, while the presence of another being in this theory could provide a *possible* learning environment for infants, it is not a *necessary* learning environment. Therefore, the development of an implicit self does not necessarily require a social environment although there are reasons to assume that the social environment supports the acquisition.

Sensorimotor theories propose that the origins of the self are based on experiences during development. To develop the implicit self, acquiring relevant information - particularly action-effect-association – through experiences within the environment is necessary and sufficient. If this assumption holds, it would suggest that the amount of experience with action-effect-associations would be related to measures of self-development. Despite this possibility holding promise for valuable research, it has received minimal investigation so far. Interestingly, specific motor developments (like grasping, e.g., Ambrosini et al., 2013, or crawling and walking, Stapel et al., 2016) have been shown to advance infants' action understanding. Therefore, motor development could be used as an approximation of infant's action-effect-experience and related to agency measures, such as adapted mobile-paradigms (Zaadnoordijk et al., 2018) or other recently developed paradigms (Bednarski et al., 2022). Another way to approximate experience with action-effect-associations would be to measure the interaction qualities of infant-caregiver interactions. If caregivers structure infants' environment in a way that is appropriate to advance infants' learning, infants will develop a better understanding of actions

than infants whose caregivers structure the environment less efficiently (e.g., Licata et al., 2014). Research on scaffolding demonstrated that appropriately structuring the infant's learning environment benefits the infant's language acquisitions, executive functions, and overall cognitive abilities (for a review see Mermelshtine, 2017). Relatedly, a recent study showed that maternal sensitivity and maternal imitation of infant behavior predicts the development of infant action imitation (Essler et al., 2023) supporting the view that social learning of action-effect associations supports action development. Therefore, caregiver's ability to structure the environment could also be beneficial for the development of the implicit self in infancy, a claim that should be investigated in future research.

Hommel (2018) proposes that the sensorimotor experiences of one's own actions become associated with higher-level constructs such as psychological characteristics of the self and societal expectations throughout life. In essence, every perception related to oneself, either through observing of one's own (typical) behavior or comments others make, gradually forms memory traces which become associated with oneself. According to Hommel (2004), all this information is stored in an "event file". In ideomotor theory, event files encompass all sensorimotor information, concepts, and perceptions related to a particular event. However, Hommel (2018) suggests that event files can also represent individuals such as oneself. Thus, the implicit self forms the basis of the event file, with which the explicit self is later associated.

2.3.2 Predictive Theories

2.3.2.1 Key Assumptions

The predictive coding framework is founded on the assumption that every organism aims to minimize surprise by means of creating predictions about the world until all incoming sensory information is perfectly predictable. In practice, this point is never achieved, but it is the ultimate target. Predictions are adjusted through prediction errors. If the predictions do not align with the real sensory input, an error arises and that is utilized to adjust the predictions for future events. These assumptions are established on the free energy principle by Friston (2005). In the recent years, researchers have applied the framework to the implicit self (Apps & Tsakiris, 2014; Limanowski & Blankenburg, 2013). These theories suggest that the self is a mental model arising from the process of explaining most of the sensory input that one receives.

When considering the self, bodily movements create various exteroceptive sensory inputs, that is information that comes from the world outside of one's body. As an example, reaching out for a bottle of water on a table generates proprioceptive, visual, and tactile information simultaneously. The information is contingent in space and time. A model that assumes this information originates from the self would provide most accurate predictions of the sensory information. Over time a (common) cause is inferred from the perceptual information - a process called perceptual inference. The inferred common cause or the mental model corresponds to the individual's body.

Predictive theories were applied to the emergence of the self in infancy by Fotopoulou and colleagues (Ciaunica & Crucianelli, 2019; Ciaunica & Fotopoulou,

2017; Fotopoulou & Tsakiris, 2017a). According to their predictive model, the implicit self includes both exteroceptive and interoceptive information, i.e., information coming from outside and inside the body. This is an expansion of earlier predictive theories about the implicit self, which exclusively focused on exteroceptive information (e.g., Apps & Tsakiris, 2014). The theory states that infants can make inferences about exteroceptive information on their own, but they require their caregiver for inferences about interoceptive information. Infants are born with motoric immaturity, which necessitates caregivers to ensure their biological functioning. Consider a scenario where a newborn is hungry. They are not yet able to identify this specific (negative) emotion as hunger (Sroufe, 1996). Instead, they may feel generally uncomfortable and respond by crying. When caregivers provide food (something the infant cannot yet provide themselves with), the infant feels relieved. Through this association, infants learn to associate the specific feeling of discomfort with food. If the caregiver does not respond appropriately, the infant may not be able to make this association, therefore not being able to identify the feeling as hunger when it comes up again (Filippetti, 2021). Even in the case of an established association between the feeling and hunger, infants have no means to test their prediction – a process called active inference in the free energy framework – as they are motorically incapable of organizing food themselves. Infants rely on the help of their caregivers to confirm their interoceptive predictions and develop important aspects of their self (e.g., Ciaunica & Crucianelli, 2019).

Due to the close embodied interaction between caregiver and infant and the abundance of sensory information in such interactions, it is difficult for the infant to distinguish between self-generated information and that coming from the caregiver

(Fotopoulou & Tsakiris, 2017a), as both types of information are highly contingent on the infant's actions. The infant can only detect that self-related information has perfect contingency and that information from the caregiver has less contingency when closely monitoring the contingency of this information over a long time. However, these differences may be minute and challenging to detect. Thus, Fotopoulou and colleagues suggest that during infancy, the infant's implicit self may also involve the caregiver, leading to blurred self-other boundaries between infant and caregiver. Over time, the distinction between the infant and the caregiver becomes more apparent.

2.3.2.2 Evaluation and Implications

Predictive coding theories propose that perceptual input is matched with predictions from the self-model, which predicts temporally and spatially congruent sensory information to originate from the own body. If the incoming sensory information matches these predictions, an individual may experience a sense of ownership or locates themselves to a specific location in space. This phenomenon has been demonstrated in paradigms that manipulate the sensory input received by participants. For example, in the Rubber Hand Illusion, participants can mistakenly believe that a rubber hand is a part of their body due to the synchronous tactile stimulation provided to their real hand and the visible rubber hand (Botvinick & Cohen, 1998). As the self-model predicts tactile and visual feedback originating from the participant's body, they perceive the rubber hand as a part of their body. This is demonstrated by explicit questionnaires and implicit measures such as the mislocalization of their own hand towards the rubber hand (proprioceptive drift). Similar paradigms have been utilized to manipulate the first-person perspective or

self-location: by presenting manipulated visual input to the participants, they perceive themselves as if they are looking at their bodies from behind (Blanke, 2012).

Since measures of the sense of ownership in adults' research are not suitable for infants, research in infancy has mainly focused on infant's use of multisensory integration to differentiate sensory information. Typically, these studies use a looking preference paradigm to present infants with visual information that is synchronous or asynchronous to the tactile or proprioceptive information they receive. Researchers determine which stimuli infants prefer by measuring their looking time. Infants' preference for the asynchronous stimulus is commonly considered as a sign of familiarity with the synchronous stimulus, which is then taken as evidence of their ability to perceive the contingency of sensory inputs. Studies using this method demonstrate that infants already utilize multisensory integration to differentiate self-produced and other-produced inputs (e.g., Bahrick & Watson, 1985; Zmyj & Marcinkowski, 2017), particularly for bodily stimuli (Filippetti et al., 2013).

The predictive theory explains the sense of agency in a similar way. The sense of agency is assumed to arise from matching the predicted sensory effects of an action to the actual sensory effects (see also Sensorimotor Theories). Meyer and Hunnius (2021) demonstrated that 3-month-old infants differentiate between predictable and unpredictable sensory effects, with self-produced effects being similarly processed as predictable external effects. This study indicates that predictive processes are present early in infancy. However, according to the predictive theory, self-produced stimuli should be even more predictable than predictable external events (although still debated in the field, see for example Kaiser & Schütz-Bosbach, 2018). Thus, the ability to distinguish between those two

types of predictability would be another milestone in an infant's self-development. Future studies could investigate the age at which infants achieve that milestone.

The role of the social environment in predictive theories is not completely consistent: While it is considered an essential aspect for interoceptive prediction (Fotopoulou & Tsakiris, 2017a), it not a requirement for exteroceptive prediction. According to the theory, the implicit self is reliant on the integration of exteroceptive and interoceptive information. Therefore, the social environment seems necessary. However, Fotopoulou and Tsakiris (2017b) state that social interactions are not a necessary requirement for infants' self-development, in a way that infants would not develop a self without caregiver-infant interactions. However, as infants are born with immature motor abilities, they are dependent on caregivers for survival, which makes their environment necessarily social and important for their development in general.

The predictive framework is distinct from social constructivist theories. Social constructivist theories require the caregiver to engage in cognitive processes such as theory of mind to think about what the infant might need in the specific situation. They require the social interaction partner to represent the infant as an individual being with a mind (termed as "cognitive mentalization" by Ciaunica & Fotopoulou, 2017). In contrast, the predictive coding framework is based on pure embodied interaction without the requirement of cognitive mentalization. The embodied interaction between two partners is sufficient information for the infant to construct the self. This process is referred to as "embodied mentalization" (see also Montirosso & McGlone, 2020). It is important to note that if the infant only requires an accurate processing of bodily signals and the appropriate response to them (such

as providing food), and not a higher-level cognitive understanding of the infant as an individual, then the interaction partner does not necessarily need to possess higher cognitive functions. It is simply necessary to have a way to process the infant's signals and to be able to react to them. Consequently, these requirements could also be met by an animal or even non-sentient machines with good learning algorithms.

Recent empirical work provides evidence of the influence of caregiver-infant interactions on self-perception. Following the theory, young infants are predicted to show self-other overlap with their caregiver. A recent study (Maister et al., 2020) found a relationship between the amount of self-other overlap of 6-to-8-month-old infants and their caregiver, and their dyadic coordination. More specifically, the study found that less alignment in affective states between the mother and infant resulted in more self-other overlap between the infant and the mother. The findings of this study support the view that contingent information from the caregiver can assist the infant in developing an implicit self that is separate from the caregiver (Fotopoulou & Tsakiris, 2017a). However, this finding is also consistent with attachment theory (see below). In another study, Della Longa et al. (2019) observed that 5-month-old infants responded to visual-tactile synchrony of stroking only when it was administered at a slow pace, but not at a fast pace. A slow pace of stroking is suggested to convey affective touch, which is an essential aspect of embodied caregiver-infant interactions (see Morrison et al., 2010 for a review).

The predictive coding framework refrains from making any claims about the ontogenetic origins of the self. According to Fotopoulou and Tsakiris (2017b), the theory combines both nature and nurture aspects, by proposing the existence of a phylogenetic disposition for the self and an ontogenetic development. They argue

against a simplistic dichotomy between nature and nurture. Given the central assumptions of the theory, it is reasonable to suggests that infants require a certain amount of learning experiences to develop a predictive self-model. Recent accounts even propose that model building already begins in utero (Ciaunica et al., 2021). From our perspective, predictive coding theories place a greater emphasis on experience rather than innateness, However, these theories do not provide a timeline for the development of the self-model. The self-model is believed to remain plastic throughout one's life, never reaching a "fully-finished" state. The absence of specific developmental predictions makes it difficult to test the theory.

According to predictive coding theories, the self-model is assumed to be unconscious (Limanowski & Blankenburg, 2013) with no explanations on the emergence of the explicit, conscious self and its relation to the implicit self. This is a significant flaw of predictive theories, as they do not provide testable and specific predictions. This makes it challenging to falsify the basic predictive theory in general (Kogo & Trengove, 2015). Therefore, the predictive account should be viewed as a general framework or paradigm that can generate specific theories instead of being a theory itself. Considerable research has been conducted on specific aspects of the predictive coding framework, such as the predictive nature of perception and hierarchical structuring. However, convincing evidence on the representation of the prediction error, which is also difficult to test empirically, is still missing (Heilbron & Chait, 2018; Walsh et al., 2020).

2.3.3 Social Theories

The theories discussed in this section are social constructivist, meaning that they view an infant's interaction with their social environment as a necessary

requirement for the development of the implicit self. In the following section, we will discuss two theories that are at the center of current debates; the affective-engagement approach by Reddy (2004, 2008) which defines the implicit self as directly perceivable through the attention of others, and the attachment theoretical framework (Sroufe, 1994; Thompson et al., 2004), which defines the implicit self as a process from dyadic to individual coordination.

2.3.3.1 Affective-Engagement Theory

2.3.3.1.1 Key Assumptions. The affective-engagement theory employs self-conscious emotions such as shame and pride - emotions that arise with the recognition that the self is being evaluated and attended by others - to make inferences about self-development (Reddy, 2003, 2004, 2008). Consequently, self-perception is believed to arise from the interactions with other social beings, mostly in the affective domain. This theory postulates that even in the first months of life infants exhibit self-conscious emotions. Thus, it is contended that infants possess an implicit self. This presents a new approach because the previously established developmental timeline assumed that self-conscious emotions develop during the second year of life, when children demonstrate mirror self-recognition, and thus an explicit self-concept (e.g., M. Lewis et al., 1989). In particular, the theory postulates that expressions of coyness (as a forerunner to shame) are already apparent in 2-month-old infants (Reddy, 2000). Similarly, behaviors that may be construed as showing-off, that is, repeating certain actions that were recognized and praised by others, emerge during the second half of the first year. These behaviors are considered precursors to pride.

This set of phenomena is interpreted as an indication that infants are aware of another person's attention directed towards themselves. Thus, infants in the six months of life demonstrate some form of self (Reddy, 2003). A fundamental idea is that the attention of others can be directly perceived without requiring an explicit or conceptual understanding of the other person's mind (Reddy, 2003). Therefore, displaying self-conscious emotions does not require a representation of oneself or the other person. Considering a developmental perspective, the theory reviews the differences between infants' emotional expressions and the later displays of shame and pride in childhood. Infants below 18 months appear to have little control over their coyness reactions, making it difficult for them to hide their smile. Hiding the smile, however, is a defining trait of shyness observed in adults. According to the theory, this is due to limited motor control during infancy. Moreover, the coyness reaction in infants predominantly arises during the initial interactions when the other person directs their attention towards the infant. Hence, coyness is believed to be the result of the infant's direct perception of another person's attention rather than their evaluation. While the coyness seen in infancy differs from emotional display of coyness in later childhood, these differences suggest that the self develops through infancy. As children grow older, their self becomes more complex and their emotional reactions become more pronounced and adult-like. Despite this, the basic aspects are already apparent in early infancy.

Self-conscious emotions require awareness of other's awareness. For instance, shame arises as a consequence of anticipating others' evaluations. Therefore, the development of self-conscious emotions corresponds with awareness of others' presence (Reddy, 2004). Reddy regards self-awareness and other-

awareness as inseparable concepts. Therefore, it is suggested that increasing complexity in other-awareness leads to increased complexity in self-awareness during development. By the age of 2 months, infants begin to experience other's attention as directed toward themselves and subsequently begin to develop self-conscious affects. At around 7 months, infants begin to exhibit "showing-off" behavior and repeat actions that have been previously appraised by others as they become aware of others focusing on certain aspects of the self, such as their actions. By around 9 months, the ability for joint attention demonstrates that infants experience the attention of others directed towards other objects. By the age of 12 months, infants can represent the others' representation of the world. With a gradual increase in complexity of these representations, infants begin to develop an explicit self by 18 months.

2.3.3.1.2 Evaluation and Implications. Reddy (2003, 2004, 2008) does not explicitly mention any of aspects of an implicit self. The theory implies both some level of self-location and a first-person perspective. For instance, when infants perceive that others direct their attention to themselves, they gain knowledge about the relation between their body and the other person; however, this does not necessarily apply to other objects in the environment. The first-person perspective has been implicated much like in the ecological approach. Infants need to know that their perceptions are related to themselves to perceive attention as being directed towards themselves. The sense of ownership might be implicated in the assumption that infants can perceive attention directed towards themselves which necessitates an ability to represent their body parts. This might suggest that the sense of ownership for all body parts, or at least a body schema, is present in infants from an

early stage. The onset of “showing-off” behavior may coincide with the emergence of the sense of agency. As per the theory, the infant chooses specific actions to attain certain effects which enables them to control attention directed towards themselves. The infant specifically chooses an action that garnered appreciation in the past to elicit further admiration. This process closely resembles the conditions for the sense of agency where actions are selected based on the anticipated effect. However, Reddy does not explicitly mention any implications for the bodily aspects of the self.

When considering the role of the social environment, it is important to note that the definition of the self in the affective-engagement theory differs significantly from the previously presented accounts. According to the affective-engagement theory, the implicit self is defined as being completely relational, where the implicit self can only be conceptualized in relation to others (Reddy, 2008). As a result, the implicit self only develops in relationships and can vary depending on the specific relationship. This statement raises a question about whether and how the self ever separates from specific relationships with others. Does the implicit self exist even in moments of loneliness? If so, at what stage and through which mechanisms does this detachment-process occur? Social-interactional (e.g. Mead, 1934) and cognitive social-historical theories (e.g., Vygotsky, 1934) provide frameworks for how individuals’ minds separate from social interactions. However, it is uncertain which process Reddy endorses and how.

The theory does not explicitly claim the early emergence or innate nature of the implicit self. However, based on the perception of attentional direction being directed towards the self, the theory supposes that the implicit self can be perceived directly. This argument bears similarity to the presented ecological theories. Hence,

Reddy assumes that some implicit self is present at birth. Since the implicit self then appears to be a prerequisite for processing self-directed social information, it cannot be considered a consequence of social processes itself. Thus, this suggests that some aspects of the self are not rooted in social processes. Nevertheless, further development of the self eventually occurs through social interactions.

The theory provides a pathway by which the implicit self develops into an explicit self. Children's other-awareness (i.e., awareness of the others' direction of attention) becomes increasingly complex, including more objects to which the other's attention can be directed. Eventually, children can represent the other's representations by 12 months and even extend their understanding of other's representations to past events by 15 to 20 months. A key tenet is that self-awareness and other-awareness develop in relation to each other, leading to the self-understanding becoming complex enough to represent oneself as an object to others (i.e., as an explicit self). However, the theory does not provide a more detailed view on how a comprehensive representation of the other emerges from an understanding of other's direction of attention. Typically, understanding others involves an assessment of their emotional and mental states (e.g., C. Moore, 2006), and this seems to be more than mere sharing of foci of attention (C. Moore & Paulus, 2013). More importantly, it remains unclear exactly how emergent other-awareness relates to an understanding of the self. That is, central parts of the theory remain at the level of postulates without being grounded in a sufficiently detailed explanatory model.

Although coyness smiles have been demonstrated in other studies (e.g., Colonnesi et al., 2013), the evidence for other behaviors the theory is based on

seems mostly anecdotal. The presence of showing-off behavior is only demonstrated in case studies (Bates, 1976; Trevarthen & Hubley, 1978) and qualitative interviews (Reddy, 2004). Additional empirical support is necessary to demonstrate the presence of behaviors that can be interpreted as self-conscious emotions before the age of 2 years. Alternatively, it needs to be considered whether coyness smiles in infants are true emotional reactions or simply reflexive behaviors. It is important to note that they could be indicative of inborn behavioral reactions that evoke attachment behavior in the caregiver (Gergely, 2003). According to the theory, only true emotional reactions would imply that the infant is aware of the attention of the other and therefore has an implicit self. The theory states that the behavior shows individual and situational variability, and that different stimuli are differentially successful in evoking the smiling response. Thus, it is believed to be non-reflexive (Reddy, 2004). This argument assumes that reflexive behavior is not capable of demonstrating situational differences or being specific to a particular stimulus. However, studies suggest that reflexes can exhibit situational differences and variable success rates in response to various stimuli (e.g., Zehr & Stein, 1999). Furthermore, it is arguable that showing-off behavior is a result of learning action-routines rather than a separate awareness of the attention of others. In conclusion, the significance of these early behaviors and their connection to the emerging self appears to be an interesting avenue for future research. For example, an investigation into the extent to which these behaviors are within the agentive control of infants (Bednarski et al., 2022) will provide evidence to support the conclusion that these behaviors represent self-conscious emotions. Moreover, to substantiate the assertion that self-conscious emotions in infancy contribute to a developing self,

future research should relate the demonstrations of these emotions to measurements of the self in a longitudinal study.

2.3.3.2 Attachment Theories

2.3.3.2.1 Key Assumptions. Attachment theory concerns the nature and psychological significance of infants' relationship with their primary caregiver(s) (Bowlby, 1969). It is suggested that this relationship plays a central role in the development of the self (Sroufe, 1994; Thompson et al., 2004).

According to the attachment framework, the self is defined as an organization of attitudes, expectations, and feelings (Sroufe, 1994) - a capacity that newborns lack. Instead, such organization develops within the context of significant relationships. Affective regulation of the infant lies at the core of the emergent self. The basis for infants' emotional regulation is the infant's attachment to the primary caregiver and the caregiver's sensitivity. Attachment theory posits that the caregiver's and infant's sense of self are closely connected. The development of the infant's self is linked to achieving independence from the caregiver, developed through several phases (Sroufe, 1994): from birth to 3 months, caregiver-infant interaction is primarily focused on regulating the infants' basic needs. To achieve this goal, the caregiver-infant-interaction must first synchronize. Once synchronization occurs, coordinated interaction sequences begin to emerge during the following 3 months. These are the initial indicator of interaction organization. The infant exhibits responses to the caregiver only in fixed and predetermined patterns. When the caregiver performs A, the infant consistently performs B. However, the infant does not perform B in any other circumstances even though they are capable of doing so. These phases are thought to demonstrate the basic aspects of the self ("pre-

intentional self") as infants begin to develop self-regulatory abilities. Subsequently, an implicit self, which is called "intentional self" by Sroufe, starts. By the age of 6 to 9 months, infants start to internalize the reactions of their caregivers. Within the specific relationship between the caregiver and the infant, the flexibility of actions and reactions is possible. The infant can initiate interactions on their own. However, in other contexts without the caregiver, these abilities diminish. The caregiver cannot be substituted by others. From 9 to 12 months, infants exhibit more observable self-organization. At this point, the infant becomes capable of self-regulating their emotions and displaying goal-directed behavior, revealing a certain degree of organization. Nevertheless, the infant remains reliant on the caregiver as high arousal due to negative stressors or strong positive emotions requires the caregiver's assistance for regulation. The second year marks the fifth phase where infants begin to physically and psychologically separate from the caregiver and engage in more autonomous exploration. However, their behavior is also balanced with reaching out for the caregiver's involvement. Individual differences depending on the attachment style emerge here. Both types of insecurely attached children (insecure-avoidant and insecure-anxious) demonstrate less autonomy than securely attached children. Children with both types of insecure attachment styles experience less agency within the interaction with the caregiver. Inconsistently sensitive caregivers (proposed to be leading to insecure-resistant attachment) do not consistently react to the infant's signals, while unavailable caregivers (proposed to be leading to insecure-avoidant attachment) do not react to the infant's signals at all. Both types of caregivers therefore show that the infant is not effective in eliciting care. According to Sroufe (1994), the seeming autonomy displayed by children with insecure-avoidant

attachment in the strange-situation procedure is actually a lack of dyadic regulation. In fact, in later years, preschool teachers perceive insecure-avoidantly attached children as being more emotionally-dependent than securely attached children (Sroufe et al., 1983), indicating that only secure attachment leads to the establishment of an independent self. According to Sroufe (1994) this phase of self-development is called “separate (aware) self”. The sixth and last phase of self-organization begins between 18 and 36 months of age. Infants experience other humans as distinct from themselves, and they perceive their own self as consistent. In addition, infants exhibit behaviors associated with the explicit self, such as self-recognition and the use of personal pronouns at this phase, which indicates that it is a phase of explicit self rather implicit self.

Attachment theory proposes that, though the self emerges as individually organized at around 3 years, it is never entirely independent from the experiences with the primary caregiver or other significant individuals. This is because the history of emotional and behavioral regulation during the first 2 years of life is reflected in how individuals perceive themselves and others (e.g., Hesse, 2008), thus being a fundamental component of the self. In this regard, the self is dependent on and shaped by the history of the social relationship shared with the primary caregiver.

2.3.3.2.2 Evaluation and Implications. Attachment theories explicitly consider the sense of agency as one of the self-aspects. During the interaction with the caregiver, the infant notes their own effectiveness in eliciting care-behavior which leads to a sense of agency. Manifold experiences with one’s own effectiveness in interactions with significant others can result in more generalized expectations of one’s own agency (Thompson et al., 2004). Traditional attachment theory does not

discuss the first-person perspective, self-location, and the sense of ownership. Attachment theory has not explicitly reflected on the role of the body (Fonagy & Target, 2007). Considering how important the body is to the implicit self, this is a blind spot of the theory. However, it is important to note attachment theory was not developed to give a comprehensive account on the implicit self. A recent account by Montirosso and McGlone (2020) defined parental sensitivity, a significant concept in attachment theory, through embodied interactions during infancy, even though they do not explicitly refer to attachment theory. As per this theory, the infant builds a bodily self through sensitive embodied interactions with the caregiver, primarily in the interoceptive domain. Oldroyd et al. (2019) demonstrated a correlation between attachment quality and interoceptive awareness. The study found that individuals with insecure-avoidant attachment style were less aware of their interoception compared to those with insecure-anxious attachment style. Combining the theory proposed by Montirosso and McGlone (2020) with attachment theory could bridge the gap between bodily aspects of the self and the attachment account of the self.

Attachment theory posits that the social environment plays a crucial role in shaping an individual's self-development. Yet, different caregiving styles have varying degrees of impact on promoting the development of an independent self. Children with secure attachment typically develop an autonomous self, and see themselves as competent in handling relationships and pursuing their own goals. On the other hand, both types of insecurely attached children are less free and autonomous. Insecure-avoidantly attached children pretend to be very autonomous and strong while they are not truly free in their expressions. Insecure-anxiously attached children are overly dependent on others and display heavy and intense emotions

from which they are easily overwhelmed. Children with disorganized attachment may not have developed a stable internal organization (however see Duschinsky & Solomon, 2017, for a debate on the general validity of this classification). Empirical investigations have indicated that attachment style influences self-understanding, such as mirror self-recognition (M. Lewis et al., 1985). Contrary to predictions of the presented attachment theory here, insecurely attached children showed earlier self-recognition than securely attached children. In contrast, previous studies by Pipp and colleagues (Pipp et al., 1993; Pipp et al., 1992; Pipp-Siegel et al., 1995), operationalized self-understanding as the complexity of self-knowledge and self-oriented actions. These studies reported that 1- to 3-year-old children with secure attachment exhibit more complex self-knowledge than their insecurely attached counterparts, supporting the theory. A recent study by Maister et al. (2020) examined the implicit self in infants aged 6 to 8 months and revealed that infants preferred synchronous visual-tactile stimulation over asynchronous stimulation when there was a low correlation between infants' and mothers' affective states. The authors concluded that less coordinated interactions between mothers and infants could result in greater self-other overlap of infants with their mothers. Thus, the study demonstrates that more coordinated interactions, which could be a pre-requisite for developing secure attachment, lead to earlier self-other distinction and subsequent self-development, supporting the theory. In conclusion, while the findings about whether specific attachment style leads to earlier self-development are mixed, the results consistently report the relationship between attachment style and early self-development.

Attachment theory does not advocate for any innate aspect of the self (Sroufe, 1994). However, attachment theory posits that the need for attachment is innate. All infants form an attachment relationship with someone (Bowlby, 1969). Thus, the emergence of the self is a universal feature of humans, but it only develops when close social relationships occur in the months post-birth.

The implicit and explicit self both are based on the same experiences that give rise to the internal working model (Sroufe, 1994), indicating a certain degree of continuity in development. The explicit self is based on the ability to hold beliefs and attitudes about oneself and others, in addition to the affective regulation that forms the core, implicit self. Attachment theory assign a central role to the acquisition of mental state language (Becker Razuri et al., 2017; Mcquaid et al., 2008). Verbal interactions between children and caregivers lead to the formation of an explicit representation of the self (Bretherton, 1993). Development continues until adolescence when a self-reflective self emerges (Sroufe, 1994) which can, for example, be assessed in the Adult Attachment Interview (Hesse, 2008).

2.4 Theories Assuming Multiple Implicit Selves

Theories that assume the existence of multiple independent implicit selves are concerned with the tension between categorizing the self on the basis of actions and perceptions or social interactions. According to these theories both types of information - information from interactions with the inanimate world and from interactions with the social world - give rise to different kinds of selves.

2.4.1 Key Assumptions

Neisser (1988) proposed the existence of multiple forms of self. These comprise the ecological self which is the perception of oneself in relation to the

environment, the interpersonal self which arises in human interactions, the extended self which is based on personal memories, the private self that pertains to the knowledge of experiences not shared with others, and the conceptual self that includes knowledge about the social roles, characteristics, and traits of the self. However, Neisser postulated that only the ecological and interpersonal selves emerge in infancy and from implicit knowledge and are therefore relevant to consider in this context.

Neisser (1991) posits that infants perceive two dominant types of stimuli: immediate environmental situations that form the basis of the "ecological self", and social interactions that form the "interpersonal self". Neisser (1988, 1991) defines the ecological and interpersonal self also by drawing on Gibson's (1979) theory of ecological perception. According to Neisser (1988, 1991), the ecological self is grounded in the subjective information implicated in every perception. This definition corresponds with previously reviewed ecological theories. Similarly, the interpersonal self is directly perceivable from the structure of social interaction in a Gibsonian manner. Infants can perceive that their actions produce a temporally and spatially contingent response from their interaction partners. This perception of contingent responses leads infants to believe that they have the ability to control their partners, providing the infants with a sense of agency during interpersonal interactions.

According to Neisser (1991), the two types of self are differently active in different contexts. In an individual context, the ecological self is active, while the interpersonal self can only be experienced in social interactions. Conversely, in social interactions, the dominance of social perception may result in no experience of an

ecological self. Psychopathology can differentially affect both types of self. Neisser views autism as a disorder of the interpersonal self, whereas the ecological self remains unaltered.

Rochat (1998, 2003, 2009, 2011) developed these consideration further in his theory. Rochat also contends that from birth, human newborns perceive their own experience as unique because they experience perfect contingency between visual and proprioceptive information only through their own movements. Rochat (2003) classifies this as the first level of self-awareness ("differentiation"), equivalent to Neisser's (1988, 1991) "ecological self". Infants actively and systematically explore the contingencies between action and perception from about 2 months of age. The self can be situated in the environment, an achievement marking Rochat's (2003) second level of self-awareness ("situation"). Rochat (2003) posits three further levels of the (explicit) self. The third level, "identification", pertains to explicit self-recognition and is achieved within the second year of life. The fourth level, "permanence", refers to the understanding that the self remains constant over time and it is reached around age 3 to 4. The fifth level 5, "self-consciousness", involves the emergence of self-conscious emotions and theory of mind and is achieved by the age of 4.

Rochat (2004b) also proposes an interpersonal self. This self develops at 2 months of age when the infant starts exhibiting social smiles and engage in affective reciprocity with the caregiver. The caregiver's social mirroring helps the infant distinguish their own emotions, as mirrored in the caregiver, from the caregiver's emotions that receive less accentuation. This process helps the infant learn to differentiate themselves from the caregiver.

Unlike Neisser (1988, 1991), Rochat (2004b) argues that the ecological self is a necessary requirement for developing an interpersonal self. According to Rochat (2004b) the interpersonal self is where further self-development begins, as the self is entirely social. Rochat (2004b) suggests that the ecological self and interpersonal self are not independent parts of the self, but become intertwined during the self-development.

2.4.2 Evaluation and Implications

Since the accounts presented here mainly rely on the self-definition proposed by the ecological theories, the assessment of the implied self-aspects significantly overlaps (see Ecological Theories). To recap, the theories presume that self-location and the first-person perspective are inherent in the variant information of the infant's perceptions. According to Neisser (1988) everything that moves in accordance with the infant's intentions is presumed to be a part of the body, hence defining the sense of ownership and the sense of agency.

The social environment is significant and necessary for both theories, but only for the interpersonal self and not for the ecological self. The ecological self is entirely independent of social interactions, whereas the interpersonal self only develops in social interactions and is present solely within these interactions.

These accounts share the same stance as the ecological theories on the ontogenetic origin of the ecological self and assume self-other differentiation to be present at birth. According to Neisser (1988, 1991) the perception of interpersonal interactions, including the interpersonal self, is also present at birth. Rochat (2004b) asserts that the need for social affiliation is innate. As a result, infants attempt to interact with other humans which facilitates their development of an interpersonal

self. There is empirical evidence that suggest even very young infants, including newborns, can distinguish between self-related and other-related information (e.g., Filippetti et al., 2013; Rochat & Morgan, 1995; Schmuckler & Fairhall, 2001), supporting the assertion of self-other differentiation being present at birth. Nonetheless, Rochat (2004a) recognizes that the ecological self may arise already from prenatal learning, thereby making self-other differentiation not necessarily a genetic predisposition.

According to Rochat (2009), the social environment is necessary for further self-development. An explicit self can only develop based on the interpersonal self within social interactions. Developing an explicit self requires affective reciprocity and social mirroring, which aid the infant in differentiating between self and other (Rochat, 2003). According to this claim, infants raised by caregivers who exhibit more social mirroring, e.g. measured through imitation, should demonstrate earlier self-development, e.g. measured through mirror self-recognition, compared to those children raised by less mirroring caregivers. A study by Kristen-Antonow et al. (2015) found that infants' preference for a stranger who imitated them (compared to a stranger who did not) at 12 months was positively related to delayed self-recognition at 4 years. Moreover, a study by Zmyj and Marcinkowski (2017) indicated that the level of contingent feedback provided by the caregiver, seen as a component of social mirroring, was linked to the infant's preference for real-time visual feedback of their own actions.

Unlike Rochat, Neisser's (1988) explicit selves are dependent on the individual's cognitive development such as memory development for the extended self and verbal abilities for the conceptual self. The study by Kristen-Antonow et al.

(2015) also partly provides evidence supporting this claim since some variation in self-recognition was attributed to verbal intelligence.

A potential objection to theories proposing multiple selves is how these selves interact to form a unified phenomenological experience of oneself. According to Neisser (1988), the various selves he proposes are cognitively distinct but ultimately perceived as components of the same individual. Neisser suggests that the conceptual self is particularly responsible for the unified self-experience. If the different selves are ultimately perceived as one single self, then why differentiate them at all? Do we consider the various selves as distinct entities, or rather as different facets of a singular concept? Furthermore, if the conceptual self plays a crucial role in unifying the various selves into a singular experience, could it be inferred that infants lacking this concept do not have a unified self-experience but perceive two separate entities that later merge together during development?

Rochat (2003) overcomes this objection by suggesting that the various self-levels he defines are not distinct selves, but instead represent different hierarchical levels of the same self. He states that even adults can transition between these self-levels depending on the context and circumstances. Furthermore, the ecological and interpersonal self appear to be different developmental stages that are not independent from one another (Rochat, 2001). Thus, strictly speaking, his theory does not posit the existence of differentiated selves. This approach represents an elegant method of integrating various kinds of information and different levels of abstraction into a singular coherent concept.

2.5 Theories Questioning the Usefulness of the "Implicit Self" Concept (in Infancy)

Previous accounts have affirmed the existence and nature of the implicit self during infancy and toddlerhood. The final section of this overview will discuss a theoretical standpoint opposing the notion of discussing an implicit self. This position begins with meta-theoretical considerations regarding the nature and utility of scientific concepts (e.g., Carpendale, 2018). This perspective acknowledges the existence of certain phenomena that structure actions and perceptions during infancy (e.g., acquiring a body image). However, they argue that these phenomena do not necessarily indicate that an implicit self exists. In other words, the use of the term "implicit self" does not contribute anything to our understanding of these phenomena and it can rather lead to confusion.

2.5.1 Key Assumptions

The most prominent account is that of Bennett and Hacker (2003). They argue that the self is a phenomenon that emerges through the use of language: through the capacity for reflective thought, which is inherently based on the use of propositional language, comes the capacity to attribute thoughts, behaviors, and characteristics to something. This creates the need for an entity to which these thoughts can be ascribed – this entity is called the self. This self, they describe, is more like the narrative self as it plays a role in our narratives (e.g., clarifying to whom to a thought should be attributed: "Was it his idea?" – "No, it was my idea."). This in itself is not problematic as long as we do not make further claims based on this narrative role. However, Bennett and Hacker (2003), following the tradition of Wittgenstein (1953), argue that the use of the word "self" erroneously leads scholars

to assume that a true measurable and separable entity must exist. This leads scholars to search for the nature of the self, how it evolves, how it is manifests neuronally, and so on; when there is nothing beyond the reported phenomena. In other words, phenomena such as multisensory contingency detection, which many scholars use as evidence for the existence of an implicit self in infancy, are mislabeled as "self" because of this linguistic confusion (Bennett & Hacker, 2003). Once adults have acquired the ability to verbalize a self, they may tend to apply this label to perceptual phenomena that are just that and nothing else: perceptual phenomena. This illustrates how an unreflective use of language can obscure our thinking.

Kagan (1998) suggests that evidence of self-emergence before the age of 2 can be explained by more parsimonious accounts, such as biologically prepared reactions or cross-modal matching abilities. Therefore, this evidence does not require the existence of an implicit self. Kagan identifies preoccupation with societal standards, appropriate emotional reactions to mastering a task, and directing others (especially adults) to change their language that describes own actions as reliable signs of an explicit self. Kagan acknowledges that assuming the absence of a self before the age of 2 yields a developmental discontinuity which requires an explanation of how the self can emerge. Some researchers might be prompted to explore precursors to the self in infancy by this. Nonetheless, Kagan maintains the existence of these discontinuities (see also Bischof-Köhler, 2011) and asserts that the self develops based on the abilities acquired at 2 years of age, such as representational abilities and language proficiency. However, this does not necessarily require the prior identification of self-precursors. As this perspective does not presume the presence of an implicit self and instead highlights the emergence of

the explicit self, it would not assert that measures of an "implicit self" in infancy necessarily correlate with the explicit self measured in toddlerhood.

2.5.2 Evaluation and Implications

The presented theories recognize the presence of certain perceptual phenomena, like cross-modal contingency matching, but they do not consider them to be evidence of the implicit self. Specifically, the theories reject the idea of another psychological structure or process underlying the individual phenomena grouped under the concept of the "implicit self". Until now, studies on the self during infancy have not shown empirical evidence of a relation between phenomena presumed to measure the implicit self and measurements of the explicit self. Klein-Radukic and Zmyj (2020) found no correlation between contingency detection and mirror self-recognition. Nevertheless, there is limited research on the relation between implicit and explicit self. If future research (e.g. longitudinal studies starting in infancy and monitoring children until toddlerhood, when the explicit self develops) discovered such relations, the theories that contest the implicit self during infancy would require additional clarification regarding to why this relation still does not confirm the existence of an implicit self.

There appears to be dichotomy in the structure of sensory information where sensory inputs resulting from one's own actions differ from that produced by others in terms of frequency and contingency. Given the available evidence that infants use environmental statistical patterns for learning (Saffran & Kirkham, 2018), it is highly probable that they detect this dichotomy. The crucial matter to address is the significance of this dichotomy, for which theories need to provide a more thorough answer. As per the theory, it could be postulated that the acquisition of language

skills allows for the differentiation of sensory inputs as belonging to either “self” or “other”. On the other hand, a notion opposite to the theory is that even though sensory contingencies may not relate to the self-concept in infancy, they could be intricately linked in adulthood. Several studies have demonstrated that variations in sensory feedback significantly affect explicit self-attribution (e.g., Balslev et al., 2007; Burin et al., 2018), which supports this argument.

A potential area of future research could be developmental neuroscience (e.g., Meyer & Hunnius, 2021; Zaadnoordijk et al., 2020). In a review of neuro-cognitive studies on the self in adulthood, Gillihan and Farah (2005) discovered neural functional independence and anatomical specificity for the sense of ownership over body parts, and a common set of brain areas that were consistently activated in studies of the sense of agency. This suggests that there is at least one underlying cognitive substrate for these different phenomena. However, it is possible that the specificity in processing the sense of ownership and the sense of agency develops after the verbal use of these concepts. If studies conducted with preverbal infants could show the same neural patterns, this may indicate an ontogenetic predisposition for the senses of ownership and agency. This would pose the challenge for the presented theories to explain the relation between the sense of ownership and agency in infancy and the explicit self that only develops later.

The presented theories propose that proficiency in language and representational abilities are prerequisites for developing a self-concept. Zukow-Goldring (2012) claims that language development is rooted in a shared understanding of action between a caregiver and a child. During the preverbal phase of a child’s development, the caregiver teaches the child object-use by guiding their

attention to the object's affordances through demonstrations and then assisting the child in imitating this action. Learning this process may help the child learn language. This teaching process may also help the child to develop a sense of agency. Observing and performing actions are both believed to contribute to acquiring the necessary action-effect association for developing a sense of agency (Verschoor & Hommel, 2017). Zukow-Goldring (2012) suggest that the origins of self-development may be found in social interactions that form the embodied basis of action understanding and language development, potentially leading to emergence of an explicit self-concept. The aforementioned perspective is in line with Bennett and Hacker's (2003) assertion that the self is rooted in language.

2.6 Conclusion

In recent decades, many theories have been developed concerning the implicit self in infancy. Nonetheless, none of these theories have yet received a persuasive level of empirical support. Furthermore, the theoretical status of critical concepts and the limits of the concept of an implicit self are still under debate. After comparing the theories, we have identified several issues within the field that are restricting both empirical and theoretical progress.

Firstly, the field lacks conceptual clarity. On a metatheoretical level, two different streams of theories can be identified. Following Overton's (2015) classical differentiation, a line of theorizing can be described as a Cartesian-Split-Mechanistic worldview, while the other constitutes a Process-Relational worldview (for a related differentiation see also Jopling, 1994). Theories with a Cartesian background localize "the self" encapsulated in the mind. They make the organism explore a materialistic world and formulate predictions about this world. The sensorimotor and the

traditional predictive coding theories could be classified within this Cartesian-Split-Mechanistic worldview. Both theories incorporate predicting the world as a central theme in their theories, either pertaining to action effects (sensorimotor theories) or the world in general (predictive theories). The infants actively explore the world and test their predictions. Nevertheless, mind and matter are largely independent. Through making and testing predictions about the world, infants aim to approximate reality.

As a result, the conclusions drawn from both theories are similar: they both view the self as being acquired through exploration and claim that the various aspects of the self arise from matching of sensory input with predictions. Notably, recent developments within this field of theory highlight the importance of interoception and embodied interactions with the caregiver (Fotopoulou & Tsakiris, 2017b), and attempt to broaden the predictive approach beyond Cartesian dichotomies such as nature-nurture or mind-body distinctions. In fact, according to Fotopoulou and Tsakiris (2017a) the infant relies on embodied social interaction. However, this theory continues to be based on a “computational mind” approach as it suggests that embodied social interaction assists the infant in creating more accurate predictions about both the world and self, and also in testing these predictions through interaction with the caregiver. As a result, the theory appears to be inconsistent and requires further refinement to address its inherent contradictions.

Attachment theory is a relational theory. The infant’s development is shaped by the environment as much as the infant shapes the environment itself. According to Sroufe (1994), the relationship between a caregiver and a child is a self-organizing

system that develops over time. Ecological theories are less clear in their implications. Although originally developed to overcome Cartesian dichotomies (Lobo et al., 2018), the theory of the development of the implicit self in infancy lack any consideration of social interactions. The ecological theory also considers most self-processes to be present at birth, leaving it unclear how further development of the self might be facilitated by interactions with the environment. The affective-engagement theory and Rochat's theory are based on ecological theory while including the social environment as a necessary factor for self-development. Both theories propose that the implicit self develops through the caregiver's affective attention (affective-engagement theory) or affective mirroring (Rochat's theory), respectively. Thus, both theories assume the ecological self, independent of social interactions, as the basis for further social development and are subject to the same criticism as ecological theories. However, both theories share some similarities with attachment theory: For example, the concept of parental sensitivity, which involves accurately understanding and responding to the infant's signals, including affective cues, (Nicholls & Kirkland, 1996), closely resembles the parental characteristics important in Rochat's and Reddy's theories. In conclusion, both theories are difficult to categorize as either relational or Cartesian and appear to represent hybrid theories.

Examining the implications of these theories made the metatheoretical assumptions clear. This has important implications for empirical research. Theories with different metatheoretical assumptions are difficult, if not impossible, to test against each other. This calls for further theoretical work on the conceptual assumptions on the nature of the implicit self. For example, it would be valuable to

explore in more detail whether different aspects of the implicit self are more or less susceptible to social influences. Bodily aspects of the implicit self, such as the sense of ownership, seem to receive more attention in Cartesian theories, while the relational theories presented here hardly ever explicitly consider the emergence of a bodily representation. This might be the case as in Cartesian approaches the body is by definition separated from the mind. The mind thus needs to represent the body in order to relate to it and to act with it. Relational theories, on the other hand, seem to pay more attention to the sense of agency than do Cartesian theories. Further conceptual research could compare the influences on these different aspects. In addition, conceptual analysis should consider whether the different theories and worldviews use different measures of the implicit self, perhaps tapping into a separate aspect.

Additionally, this overview identifies gaps in current theories that require explanation. Due to advances in neurocomputational modeling, there is now significant potential to test theoretical predictions through computational models. Within these models allegedly necessary conditions can easily be extinguished, making it possible to test their necessity. However, accurate computational modeling requires specific predictions which are largely absent (Forch & Hamker, 2021). Computational modeling could also generate new predictions and push the theories even further. Moreover, more specific and testable predictions would also provide benefits for empirical research. This overview makes concrete suggestions within the different evaluation sections on how theories can become more specific. Thus, it paves the way for future empirical research, thereby advancing the field.

When discussing the current empirical evidence of an implicit self in infancy, it is necessary to examine the potential and the limitations of various methodological approaches. Some studies use looking preference paradigms. However, these paradigms have been conceptually criticized (Haith, 1998; Paulus, 2022a) for their far-fetched interpretations of looking patterns as cognitive, and are less conclusive than sometimes proposed. Other studies explore action contingencies and interpret increased action patterns as indications of a sense of agency, but this claim has been challenged and alternately leaner interpreted (Bednarski et al., 2022; Verschoor & Hommel, 2017; Zaadnoordijk et al., 2018). Recently, several researchers have proposed more advanced paradigms, particularly for the sense of agency (Bednarski et al., 2022; Zaadnoordijk et al., 2019). These paradigms aim to establish an action-effect association within the experiment which is subsequently dissolved. Examining the infant's behavior after dissolving associations may provide insight into their sense of agency. Even though these proposals attempt to give the infant a more active role, they lack ecological validity by focusing mainly on screen-based approaches. A study by Reddy et al. (2013) proposed that an ecologically valid method that could reveal goal-anticipation even in 3-month-old infants, which is at a younger age than previously believed. The authors call for more participatory research, in which infants are studied in familiar settings and play an active role. Although the idea of testing infants in familiar situations is not new, there are no studies on the self that we are aware of that made use of this approach. However, incorporating ecologically valid approaches may unveil critical insights into the self.

In conclusion, the field needs more conceptual clarity to advance the research on the implicit self in infancy. To enable researchers to compare their own self-

definitions to existing definitions, they need to be clear about their metatheoretical assumptions. Making comparisons instead of adding new prefixes to the term “self” and thus introducing a new definition would undoubtedly enhance the field. In addition, to gain more insight into the development of the implicit self in infancy, new methodological approaches beyond looking preference paradigms, are required.

Table 1

Evaluation of Each Theory on the Implications for the Implicit Self.

Theory	Self-Aspects			
	Ownership	Agency	Self-Location	First-Person Perspective
Ecological Theories	Innate body schema	Differentiation between own movements and externally caused movements, but no mechanism provided	Perception = self in relation to environment	Subjective perception
Sensorimotor Theories	Confused with agency in infancy	Develops out of action-effect-associations, only after goal-directed actions	No implications	No implications
Predictive Theories	If sensory input matches model predictions	If sensory input matches model predictions	If sensory input matches model predictions	If sensory input matches model predictions
Affective-Engagement Theories	Innate body schema	Active control about actions by 7 months, no mechanism provided	Given so that infant can perceive attention directed to self (location)	Subjective perception of attention
Attachment Theories	No implications	Ability to elicit appropriate care from caregiver	No implications	No implications
Multiple Selves Theories	Innate body schema	Movements in accordance with infant's intentions and ability to control interaction partner	Perception = self in relation to environment	Subjective perception

Table 1 (continued).

Theory	Social Environment	Ontogenetic Origins	Explicit Self
Ecological Theories	No influence	Present at birth	Constant reorganization of sensory information, specific link to explicit self is unclear
Sensorimotor Theories	Possible (but not necessary) learning environment	Acquired through sensorimotor exploration	One event file: sensorimotor experiences associated with other features of the self
Predictive Theories	Necessary for development of interoceptive aspects	Acquired: self-model builds through experience	No account provided
Affective-Engagement Theories	Self only exists in relation to others and develops in relationships	Ecological self is present at birth, further self-development through interaction	Increasing complexity of representations of self and other eventually lead to explicit self
Attachment Theories	Self develops out of caregiver-infant-relationship	Acquired	Both types depend on internal attachment working model
Multiple Selves Theories	Necessary for interpersonal self only	Ecological self is present at birth, interpersonal self might be acquired (Rochat)	Rochat: progression of interpersonal self Neisser: further cognitive development necessary

3 Neural Processing of Self-Produced Effects in 9-Month-Old Infants

This chapter is based on:

Kollakowski, N. A., Pletti, C., & Paulus, M. (2024). *Neural processing of self-produced effects in 9-month-old infants* [Manuscript in preparation]. Department of Psychology, LMU Munich.

3.1 Abstract

The sense of agency, the feeling to be in control of one's actions and their effects, is a central aspect of the human self. An important indicator of the sense of agency is sensory attenuation, that is, reduced neural activation for self-produced effects. Developmental theories assume the sense of agency to emerge in infancy, implying that sensory attenuation should appear by then. We measured the neural activity of 38 9- to 10-month-old infants with electroencephalography while they either pressed a button to trigger an audiovisual stimulus, passively watched the same audiovisual stimuli or pressed a button to trigger a visual stimulus. A cluster-based permutation analysis revealed that the neural activation to the self-produced stimuli was significantly larger compared to the external stimuli in fronto-central electrodes around 668 to 964 ms. Such a late effect does not correspond to commonly accepted neural indicators of sensory attenuation. Rather this effect might be indicative of infants learning about the effects of their actions.

3.2 Introduction

The development of the self has been a topic in psychology for centuries. Influential theories have proposed that a minimal self emerges in infancy (for a review see Kollakowski et al., 2023, **Chapter 2**). One important aspect of the minimal self is the sense of agency, the feeling of control over one's own actions and their effects (Gallagher, 2000). Notwithstanding the high theoretical relevance, recent reviews highlight that there is no conclusive evidence showing when the sense of agency emerges (Bednarski et al., 2022; Zaadnoordijk et al., 2019; Zaadnoordijk et al., 2018). Consequently, the ontogenetic roots of the sense of agency remained subject to speculation. However, given the recent evidence that the sense of agency

influences action selection and response inhibition (Ren et al., 2023), investigating the emergence of the sense of agency would yield important implications not only for the development of the minimal self, but also for other domains of cognition.

A widely-used indicator for the sense of agency is sensory attenuation (for a review see Hughes et al., 2013b). Sensory attenuation is usually observed in paradigms in which participants press a button to trigger a sound in the self-produced condition. In the external condition the same sound is presented by the computer. In a motor control condition, participants press a button, but no sound is triggered. Participants then show a decrease in the self-reported intensity of the stimulus when it is self-produced, compared to when the stimulus is externally triggered. The amount of decrease depends on the degree of the stimulus' predictability (e.g. Blakemore et al., 1999). These effects can also be demonstrated in neural signals as measured with EEG (for a review see Horváth, 2015). Sensory attenuation is usually observed in the auditory N1 over fronto-central electrodes (Bäss et al., 2008): even when controlling for the motor activity of the button press, the auditory N1 is attenuated in the self-produced condition compared to the external condition. Sensory attenuation is sensitive to freedom of choice (Borhani et al., 2017) and to the identity of a specific stimulus or action (Hughes et al., 2013a), which makes it the most promising implicit indicator of the sense of agency (Hughes et al., 2013b).

A necessary (but not sufficient; see Zaadnoordijk et al., 2019) pre-requisite for sensory attenuation to emerge, is the prediction of the sensory consequences of one's action (e.g. Han et al., 2022; Kaiser & Schütz-Bosbach, 2018). One model of the sense of agency and sensory attenuation, the Comparator Model (Blakemore et al.,

1999; Hommel, 2015), assumes the sense of agency to emerge out of a comparison between the predicted sensory effects of one's own action and the actual sensory effects of that action. When executing an action, an efference copy of the issued motor command makes it possible to predict the exact kinematics and sensory consequences of that action. Therefore, self-produced effects are not only predictable in their timing. Thus, even when externally-produced effects sometimes can be predictable in their timing, self-produced effects can still be differentiated from them, based on the executed action (Klaffehn et al., 2019).

Consequently, infants need to be able to predict the sensory effects of their actions to show sensory attenuation. Indeed, infants can predict the sensory effects of their actions by around 9 months given that at this age they acquire action-effect-associations (Paulus et al., 2012) and are able to act on them (Verschoor & Hommel, 2017). Using an adapted version of the sensory attenuation paradigm with 3-month-old infants, Meyer and Hunnius (2021) showed that the neural processing of self-produced effects is not yet attenuated compared to regularly timed external events. Although they showed a trend towards different neural processing of self-produced and irregularly presented external effects, this effect did not persist when controlling for motoric activity. Consequently, when in ontogeny children display sensory attenuation - and thus a sense of agency - remains an open question.

Based on previous research showing that 9-month-olds can predict the effects of their actions (Verschoor & Hommel, 2017), we hypothesized that at this age infants will show sensory attenuation, and tested this prediction in an infant-friendly paradigm. As previous studies have shown that in infants neural processing of auditory stimuli is enhanced with audiovisual displays (Hyde et al., 2010), we used

short video-animations with sound in the current study. Furthermore, the auditory event-related potentials in infancy vary substantially in latency, amplitude and topographic distribution from the ones reported in adults (Csibra & Johnson, 2007; Trainor, 2008; Wunderlich et al., 2006). Consequently, we could not predict where exactly to find sensory attenuation effects in infants, and did not restrict our analysis to a specific location or timing but rather used cluster-based permutation tests over all electrodes and the whole time range. Using cluster-based permutation tests we might detect any difference between conditions while correcting for multiple comparisons. If infants indeed would show sensory attenuation, this would imply that they differentiate between self-produced and external effects on a neural level, indicating a sense of agency.

3.3 Methods

3.3.1 Participants

57 white 9- to 10-month-old infants were invited to the lab, of whom 38 infants (17 female) were entered into the final analysis. 19 infants were excluded because of fussiness (3), technical issues (1), because they would not tolerate the cap (7) or did not contribute data of sufficient quality (8; see 3.3.4). This drop-out rate is comparable to other infant EEG studies (Stets et al., 2012). The sample was a convenience sample: invitation letters were sent out to a random group of parents with infants in the appropriate age, based on the birth register of a large German city.

The mean age of the infants included in the final data set was 9 months 18 days (*SD* = 14 days, range: 8 months 14 days-10 months 23 days). All infants were born after 37 weeks of gestation and typically developed. Parents gave informed

consent for their infants' participation in a longitudinal study, of which the reported experiment was a part. The local ethical committee gave approval for the longitudinal study. Families received compensation for travel expenses and a small gift for the infant.

3.3.2 Experimental Conditions

The stimulus presentation was controlled with OpenSesame version 3.2.8 (Mathôt et al., 2012). Three conditions (self-produced, externally-produced, motor) were presented to the infant, each up to three times. Initially, the experimenter presented a blue and a yellow button to the infant and pressed each to demonstrate the effects. Subsequently, the infant was encouraged to press the buttons four times. When the infant pressed the blue button, an audiovisual stimulus appeared on the screen, enabling the infant to acquire action-effect-associations (Hommel et al., 2001). Previous studies demonstrate that a few demonstrations of an action-effect association are sufficient for the infant to learn the association (e.g., Collie & Hayne, 1999; Hauf & Aschersleben, 2008).The stimulus was one of six 1.5-second-long cartoon animations (a stretching cat, an ape rolling over, a wiggling duck, a turning puppet, a dog moving left and right, a jumping ball), accompanied by an individual complex sound with a duration between 600 and 860 ms. Thanks to an anonymous reviewer, we discovered that the sound was presented between 330 and 740 ms (depending on the stimulus) after the onset of the visual stimulus (see an example stimulus in Figure 1). Therefore, we recoded the triggers for each individual stimulus to the onset of the sound and analyzed the EEG-activity time-locked to the sound onset. For transparency, the analysis with EEG-activity time-locked to the visual onset is reported in the Supplementary Material. The stimulus was presented against

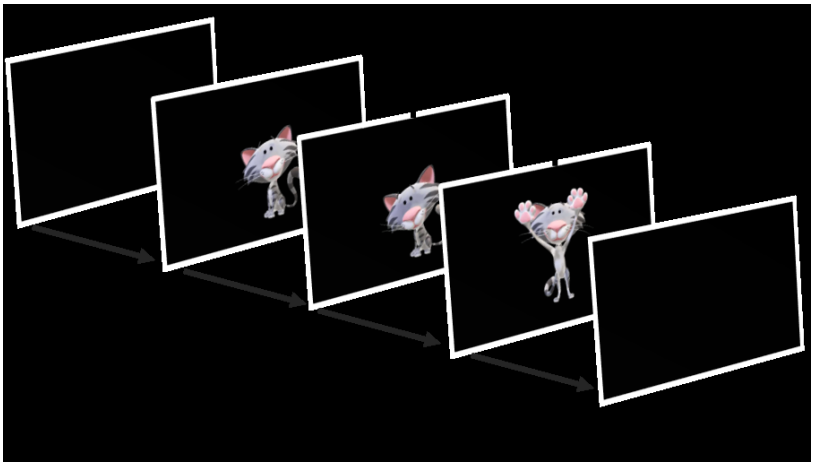
a black background. Which stimulus appeared upon the button press was random. Until the next button press of the infant, the screen remained black. After 60 seconds, the infants' next button press ended the block. When the infant pressed the yellow button, the same animations appeared on the screen but this time without sound. After 30 seconds, the next button press ended the block. In the externally-produced condition, the experimenter hid the buttons, and the infant could not control the stimuli. The same audiovisual stimuli were presented randomly after a time interval varying between 1200 and 1600ms (in steps of 50ms). Each block contained 27 trials. Thus, one block lasted approximately 78 seconds. In the motor condition, the experimenter was presenting a yellow button to the infant. The order of presentation was similar across participants: self-produced, externally-produced, motor, externally-produced, self-produced, motor, externally-produced, self-produced, motor. The presentation order was chosen to keep the infants' motivation for participation high. On average, infants completed 2.71 blocks in the self-produced condition, 2.32 blocks in the motor condition, and 2.74 blocks in the externally-produced condition.

3.3.3 Procedure

Upon arrival, parents were informed about the study procedure and EEG. Together with their infants they were then brought to a dimly lit, sound-attenuated, electrically shielded room in which the experiment took place. Infants sat on their parents' lap on a chair approximately 70 cm away from a screen that was placed on the height of the infant's face. While one

Figure 1

Example Trial in the Self-Produced Condition



Note. Upon button press the visual stimulus was presented. In this example stimulus the sound was presented after 430 ms and 870 ms long. In total the stimulus was 1500 ms long. This figure was created by myself in content and style.

experimenter played with the infant, the other experimenter placed the EEG cap onto the infants' head. Parents were instructed to remain still during the experiment and to not talk to their infants. An experimenter was sitting next to the infant throughout the recording. In the self-produced and motor blocks, the experimenter motivated the infant to press the button, e.g. by pointing on the button and talking to the infant. After each block, the experimenter decided to continue with the next block or play a video to calm the infant if they got fussy. The session was video-recorded with a webcam, time-locked to the EEG signal. The whole session lasted approximately 30 minutes, of which the recording lasted 10 minutes or until the infant became bored or fussy.

3.3.4 Electrophysiological Recordings and Pre-Processing

Infants wore infant-sized R-Net caps (Brain Products GmbH, Gilching, Germany) with 64 channels arranged in the standard 10-20 system. The impedances were ensured to be below 150 kOhm. The channels were online-referenced to FCz. The signal was amplified by the BrainAmp DC EEG Amplifier (Brain Products GmbH, Gilching, Germany) and recorded at a sampling frequency of 1000 Hz.

The EEG data was pre-processed using the standardized HAPPE+ER-pipeline (Monachino et al., 2022) from HAPPE 3.0 in MATLAB R2020a. The data was filtered between 0.5 Hz and 30 Hz with an IRR butterworth filer and electrical noise at 50 Hz was removed using the default cleanline method. The data was then resampled to 250 Hz. We used the default wavelet thresholding with a hard threshold as recommended for infant data (Monachino et al., 2022). On average, the correlation between the data before and after the wavelet thresholding was r = .25 (*SD* = .12). Three participants with $r < .1$ were excluded from further analysis. The data was segmented based on the condition. Each segment was time-locked to the onset of the auditory stimulus from 200 ms prestimulus to 1000 ms poststimulus. The baseline correction was performed using the 200 ms prestimulus period. Bad channels within each segment were interpolated. On average 2.07 channels per segment (*SD* = 0.30) were interpolated. Segments with amplitude artifacts smaller than -200µV or larger than 200 µV were rejected. On average, 3.12 % of segments (*SD* = 6.49 %) were rejected. Five participants who had less than five artifact-free trials per condition were excluded from further analysis. This resulted in a mean of 31 included trials (range: 12 - 65 trials) for the self-produced condition, 16 trials (range: 6 - 31 trials) in the motor condition and 74 trials (range: 41 - 81 trials) in the

externally-produced condition. Subsequently, the data was re-referenced to the average of all channels. Each participant's data was then averaged over all trials per condition.

3.3.5 Data Analysis

The signal differences between the self-produced condition and the externally-produced condition were compared using the cluster-based permutations test implemented in FieldTrip version 20190209 (Oostenveld et al., 2011). We restricted our analysis to the poststimulus time window (0 ms - 1000 ms) but included all channels. We used the Monte Carlo method to calculate the p-values and evaluated the effect at the cluster-level. The alpha-level-threshold for each cluster was 0.05 and we used the maximum of the cluster-level statistics as the test statistics. The alpha-level threshold of the permutation test was 0.025. We selected a two-tailed dependent-samples t-test with 1000 permutations. Effect sizes were calculated using the scripts from Meyer et al. (2021). The reported effect sizes are Cohen's *d* and represent i) the maximum effect size within the cluster, and ii) the effect size from the data that was averaged within a rectangular shape fitted around the respective cluster.

Previous studies on sensory attenuation in adults often corrected for motoric activity in the signal of the self-produced condition by subtracting the signal of the motor condition from the self-produced condition's signal. However, in our case, we investigated the signal related to the sound onset that occurred later than the button press that was time-locked to the onset of the visual stimulus. Motoric activity builds up before a movement (here the button press) and therefore can only affect the

early activity after the movement and is not time-locked to the sound onset. Still, we present this data in the Supplementary Material (**Chapter 3.7**) for transparency.

3.3.6 Data Availability

Datasets and analysis scripts can be found here: https://osf.io/umd63/?view_only=18224752c0cf418284ab8c33eb4e11f8

3.4 Results

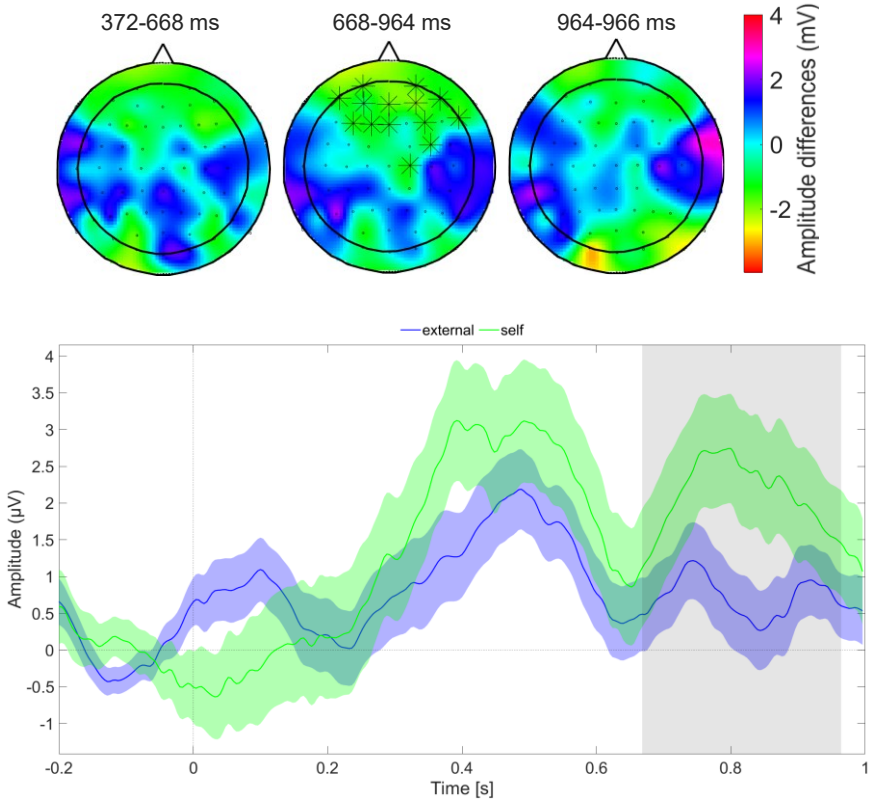
The cluster-based permutation test revealed a significant difference between the externally-produced condition and the self-produced condition (p = .02). The externally-produced condition showed a less positive amplitude than the self-produced condition between around 668 ms to 964 ms (see Figure 2). The cluster included frontal electrodes, namely, AFz, AF3, AF4, AF7, AF8, Fz, F1, F3, F4, F8, FC4, C2, Fp1, and Fp2. The mean amplitude over this cluster was 0.72 µV (SE = 0.51) in the externally-produced condition and 2.12 µV (SE = 0.77) in the self-produced condition. The maximum effect size within the cluster was d = -0.37 channel AF4 and 964 ms. The average effect size within a rectangular shape fitted around the cluster including only the electrodes within the cluster was d = -0.52.

3.5 Discussion

The development of a sense of agency is a significant topic in psychological research (Bednarski et al., 2022; Kollakowski et al., 2023; Zaadnoordijk et al., 2019). In this study we investigated sensory attenuation, a well-known indicator of sense of agency (Horváth, 2015), in 9-month-old infants. Our findings suggest no clear sensory attenuation effect in infants. Significant differences between the self-produced and the externally-produced condition were only detected after 600 ms, while sensory attenuation effects in adults are commonly visible in the auditory N1, which

Figure 2

Topographic Distribution and Grand Average of the Negative Cluster Between Externally-Produced and Self-Produced Condition at Auditory Onset



Note. (Top) The topographic distribution of the amplitude difference between the externally-produced condition and self-produced condition for a time window before (left), during (middle) and after the significant negative cluster (right). Channels within the significant cluster are indicated by a black asterisk. (Bottom) The grand averages for each condition, averaged over all electrodes included in the cluster. Shaded areas around the waveform indicate one standard error. The grey shaded area indicates the time range of the significant cluster. Zero indicates the onset of the auditory stimulus. This figure was created by myself in content and style.

shows a latency around 100 ms after the stimulus presentation (Horváth, 2015).

In our study significant differences were found between the self-produced and externally-produced condition at 600 to 900 ms post sound onset. The ERP component visible in the self-produced condition might be a positive slow wave (PSW) that is usually found around 700 to 1000 ms after stimulus onset and is supposed to represent memory updating (Haan, 2007; Kayhan et al., 2019). This PSW is assumed to be a precursor to the adult P3 (Haan, 2007; Marinović et al., 2014) that has shown sensory attenuation effects in previous studies (Goldberg et al., 2017; Kühn et al., 2011). However, in our study the activity in the self-produced condition unexpectedly displayed a larger amplitude than in the externally-produced condition, and therefore the PSW shows no sensory attenuation effect. Typically, infants exhibit a larger PSW in oddball paradigms for the infrequent stimuli in a train of frequent stimuli (Kushnerenko et al., 2002; C. Piazza et al., 2016; Trainor et al., 2001). Therefore, the greater PSW is regarded as an indicator of attention capture (Trainor et al., 2001) or stimulus encoding (Haan, 2007).

In our study, the larger PSW in the self-produced condition suggests that infants are still learning about the connection between their own action and the resulting effects. It is crucial to note that the precise sound produced was predictable from the onset of the visual stimulus and identical in the externally-produced condition. Therefore, the activations would have been similar in both conditions, and the effect seen in the self-produced cannot be attributed to learning about the exact effect. The one thing that was different between both conditions and therefore still required learning was the relation between the infants' movement and the consequences. Previous research utilizing predictive gaze measures in the context of

action prediction found that infants were able to anticipate the endpoint of actions after just a few trials (Adam et al., 2016). Thus, infants have the ability to acquire observed action-effect associations quickly. Indeed, also neurocognitive studies provide evidence that 9-month-old infants acquire action-effect-associations by observing others' actions (Paulus et al., 2013). Yet, in that study, infants observed the action for several days, giving them ample time for learning. Potentially, the learning process for *self-produced* effects seems to require more time. Importantly, infants must complete the learning process regarding the association between their action and the resulting effect in order for sensory attenuation to occur for self-produced effects. However, it could also be the case that the infants were more captivated by the effects they produced themselves, thereby producing a larger PSW. Self-generated effects are more salient and carry more information about the causal structure between the action and the effect. To disentangle these two possibilities, future studies should extend the learning phase of the investigated action-effect association, such as by implementing a training phase at home and utilizing a manipulation check to ensure infants acquire the association.

One could argue that a possible reason for the absence of a sensory attenuation effect in our study is that the design of our stimuli made the sound onset predictable in both conditions. Regardless of whether the infants triggered the stimulus through their button press or not, the visual part of the stimuli preceded the onset of the auditory stimulus by a few hundred milliseconds, thereby potentially acting as a predictive cue. Therefore, the difference between both conditions did not involve temporal predictability of the stimulus but solely whether the stimulus was self-produced or not. Interestingly, maintaining consistent temporal predictability

between the externally-produced and self-produced condition led to the elimination of sensory attenuation effects in the auditory N1 in experiments with adults (Egan et al., 2023; Kaiser & Schütz-Bosbach, 2018). Additionally, a study conducted with infants (Meyer & Hunnius, 2021) found evidence of sensory attenuation only in instances where a non-predictable externally-produced condition was compared with the self-produced condition but not when the externally-produced stimuli were predictable. Meyer and Hunnius (2021) hypothesized that the predictions stemming from the infants' still immature motor system may lack the necessary precision to distinguish self-produced effects from predictable externally-produced effects. Considerations on adults' sense of agency assume that the early sensory attenuation effects represented in the auditory N1 are associated with general predictive processes, whereas the later effects as depicted by the P2 and P3 are linked to more high-level cognitive processes such as the processing of complex sounds (Korka et al., 2022) or temporal discrimination (Aytemur et al., 2021). Therefore, they might be less influenced by the predictability of the stimulus. Indeed, a recent study that controlled for temporal predictability in both conditions found attenuation effects in the P2 but not in the N1 (Egan et al., 2023)

A limitation of the study is the variability in the sound onset. It might have been the case that for stimuli with late sound onsets infants did not consider them as contingent on their action anymore, which would reduce sense of agency (Blakemore et al., 1999). However, little is known about the temporal integration window for action-effect contingencies in infancy. Generally, they seem to be larger than for adults (Lewkowicz, 1996). Previous studies with adults showed that sensory attenuation effects can still be found for with long and variable delays between

action and effect (Bäss et al., 2008). Consequently, it is probable that infants considered the effect contingent on their actions. Nevertheless, future research should systematically vary the delay between action and effect to test our assumption.

As this study represents the first implementation of an infant-friendly version of the classical sensory attenuation paradigm, several conclusions can be drawn for future studies. To ensure visual input is consistent across conditions and minimize head movements, future studies should directly present the visual stimulus on the button, given that infants primarily fixate on the button while pressing it. In our design there were also considerably more trials in the externally-produced condition. To account for differences in subject-to-subject variability between the conditions, the externally-produced condition could present the recorded button presses of the same infant in the self-produced condition. This way, an equal amount of trials would be presented to each child in both conditions. Including a motor condition in the paradigm without presenting any effects did not engage the infants. Presenting a visual effect in this condition, however, poses other challenges since the infants also self-produce an effect in the motor condition. Future studies should explore other control options for motor activity in the self-produced condition, as for example demonstrated by Meyer and Hunnius (2021).

3.6 Conclusion

No evidence was found for sensory attenuation to self-produced sounds in 9-month-old infants when compared to externally-produced sounds. Therefore, infants at this age might not exhibit the same sense of agency as adults do in similar paradigms. Nevertheless, they show different neural processing of self-produced

sounds, indicating that a necessary prerequisite for sensory attenuation is provided around 9 months of age.

3.7 Supplementary Material

3.7.1 Additional EEG Analysis and Results

To control for the motor activity in the self-produced condition's signal, we computed a difference wave for each participant by subtracting the motor condition average from the average of the self-produced condition. The signal differences between this corrected self-produced condition and the externally-produced condition were compared using the cluster-based permutations test implemented in FieldTrip version 20190209 (Oostenveld et al., 2011). We restricted our analysis to the poststimulus time window (0 ms - 1000 ms) but included all channels. We used the Monte Carlo method to calculate p-values and evaluated the effect at the cluster-level. The alpha-level-threshold for each cluster was 0.05 and we used the maximum of the cluster-level statistics as test statistics. The alpha-level threshold of the permutation test was 0.025. We selected a two-tailed dependent-samples t-test with 1000 permutations. Effect sizes were calculated using scripts from Meyer et al. (2021). The reported effect size is Cohen's *d* and represents the effect size from the data that was averaged within a rectangular shape fitted around the respective cluster.

3.7.1.1 Visual Onset

The cluster-based permutation test revealed a significant difference between the externally-produced condition and a difference wave between the self-produced and motor condition (corrected self-produced condition; $p = .006$) when time-locked to the visual onset. The external condition showed a more positive amplitude than the

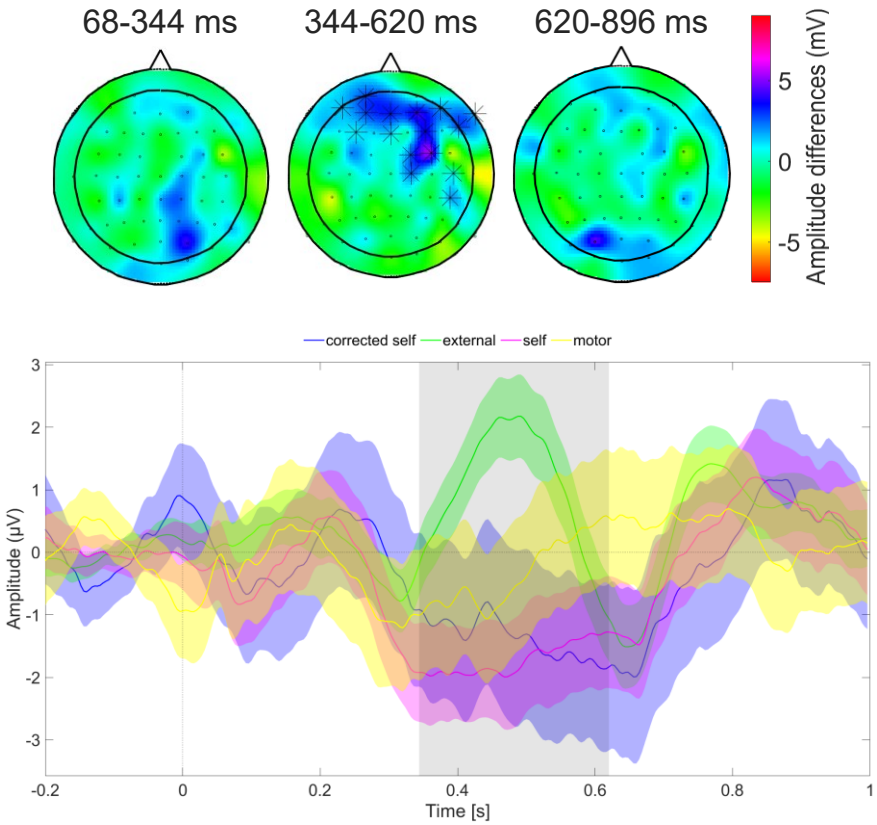
corrected self-produced condition at fronto-central electrodes, namely AFz, AF3, AF4, AF7, AF8, Fz, F3, F4, F8, F10, FC2, FC4, C2, C6, Fp1, CP6 around 344 ms to 620 ms (see Figure 3). The mean amplitude over the positive cluster was 1.03 µV (*SE* = 0.63) in the externally-produced condition and -1.37 µV (*SE* = 1.32) in the corrected self-produced condition. The maximum effect size within the cluster was *d* = 0.41 channel FC4 and 560 ms. The average effect size within a rectangular shape fitted around the cluster including the only cluster electrodes was *d* = 0.65.

3.7.1.2 Auditory Onset

The cluster-based permutation test revealed no significant differences between the externally-produced condition and the corrected self-produced condition when time-locked to the auditory onset (all $p > .028$).

Figure 3.

Topographic Distribution and Grand Average of the Positive Cluster Between Externally-Produced and Corrected Self-Produced Condition at Visual Onset



Note. (Top) The topographic distribution of amplitude differences between the externally-produced condition and the corrected self-produced condition for a time window before (left), during (middle) and after the significant positive cluster (right). Channels within the significant cluster are indicated by a black asterisk. (Bottom) Grand averages for each condition, averaged over all electrodes included in the cluster. Shaded areas around the waveform indicate one standard error. The grey shaded area indicates the time range of the significant cluster. Zero indicates the onset of the visual stimulus. This figure was created by myself in content and style..

4 Social Origins of the Self in Infancy — Maternal Interaction Shapes Neural Processing of Self in 5-Month-Olds

This chapter is based on:

Kollakowski, N. A., Pletti, C., & Paulus, M. (2024). *Social origins of the self in infancy: Maternal interaction shapes neural processing of self in 5-month-olds* [Manuscript submitted for publication]. Department of Psychology, LMU Munich.

4.1 Abstract

The ontogenetic origin of the self in infancy is a topic of ongoing debate. While influential developmental and neurocognitive theories propose that caregiver-infant interactions play an important role in infants' self-development, little is known on the specific mechanisms involved. Some theories highlight the importance of caregiver sensitivity and touch, while others propose that caregiver contingency plays a central role. The study aimed to investigate infants' self-perception by measuring brain activation in the posterior superior temporal sulcus (pSTS), a region previously associated with self-related processing. A total of 118 mother-infant dyads participated in a free-play interaction, during which maternal sensitivity and touch were measured. Additionally, a face-to-face interaction was conducted to measure maternal contingency. Infants' brain activation was measured using functional near-infrared spectroscopy (fNIRS) while they watched a live video of themselves being stroked by a brush (contingent) or a delayed video of the same content (non-contingent). The results showed that infants exhibited more HbO-activation in the right pSTS in the non-contingent condition. Importantly, the more sensitive the mothers were and the more they touched infants during free play, the less differential activation the infants showed in response to both conditions. This effect was driven by infants showing less activation to the non-contingent condition when their mothers exhibit more care, maybe because of a smaller prediction error for non-contingent self-related multisensory information. Overall, the study deepens our knowledge on how early social interactions relate to the emergence of the self in infancy.

4.2 Introduction

Based on a renewed interest in the development of the self in infancy (e.g. Ciaunica & Crucianelli, 2019; Fotopoulou & Tsakiris, 2017a; Montirosso & McGlone, 2020), the psychological mechanisms subserving the emergence of the self have become subject to intense debate. One central topic of the theoretical debate concerns whether or not the self develops through social interactions (for recent review see Kollakowski et al., 2023; **Chapter 2**). While some theories, for example attachment theory (Sroufe, 1994) and the theory of mentalizing homeostasis (Fotopoulou & Tsakiris, 2017a) propose that the social environment is necessary for the infant's self, as it develops out of caregiver-infant interaction, other theories put less emphasis on social interactions (e.g. sensorimotor theories; Verschoor & Hommel, 2017). Previous work on the relation between the caregiver-child relationship and self-development focused on the self-concept and self-esteem which emerge after the age of 2 (for a review see Harter, 2012). However, it has been proposed that an implicit self, that, in contrast to self-concept and self-esteem, describes an unreflective, immediate experience of the self, develops earlier, namely in infancy (Rochat, 2009). Little research so far has investigated the extent to which caregiver-child-interactions support the development of the implicit self in infancy. This question is particularly interesting given the close relationship between infants and their caregivers. Indeed, developmental theories highlight the existential dependence of infants on their caregivers (e.g., Bowlby, 1969), implicating a central role for caregivers in early social and cognitive development. Research on the social basis of the implicit self in these early years is limited though. Therefore, the current study aims at deepening our knowledge on the psychological processes subserving the emergence of the implicit

self by investigating relations between the caregiver-infant interaction and neurocognitive measures of the infant's developing self.

Attachment theory proposes that the caregiver-infant relationship plays a crucial role in self-development (Bowlby, 1969). More precisely, it posits that self-development is a process of organization (Sroufe, 1994). Initially, the infant initially is dependent on their caregiver. Then the infant progressively constructs an internal working model of the caregiver-infant-interaction, becoming ever more capable of organizing themselves independently, which results in increasing psychological and physical separation from the caregiver. This whole process is supposed to lead to the development of the infant's self. The theory posits that infants with a secure attachment exhibit the most stable explicit self, as these infants experienced well-organized interactions with their caregivers leading to a well-organized self (Sroufe, 1994). Most empirical investigations of attachment security have primarily focused on the association with self-esteem, rather than the implicit self, with the majority of the results substantiating the theory (for a review see Thompson, 2008). Yet, it remains an open question to which extent this also holds for the implicit self.

Attachment can only be reliably measured by the end of the first year of life, despite crucial phases of the implicit self occurring earlier (A. J. Bremner & Spence, 2017). Hence, studying early influences of the caregiver-infant relationship on an infant's implicit self requires different means of investigation, such as predictors of attachment. Caregiver sensitivity, which involves the prompt and accurate identification and response to the infant's signals is a primary predictor of secure attachment (Wolff & van IJzendoorn, 1997). Similar to studies on attachment measures, maternal sensitivity measures have been shown to predict self-esteem

and the self-concept in toddlers (Harel et al., 2002; Harel et al., 1999) and preschool children (Paulus et al., 2018). In a study involving infants, Maister et al. (2020) demonstrated that decreased coordination in mother-infant interactions resulted in higher levels of self-other overlap for the infant and their mother. Although the authors did not directly measure maternal sensitivity, highly sensitive mothers are assumed to have more well-coordinated interactions with their infants, as the mother recognize the infant's signals and adapt to them. The results from Maister et al.'s study suggest that an infant's development of an independent self might be hindered when there is a lack of caregiver sensitivity, which is in line with attachment theory. However, Maister et al. presented infants with pictures of their or others' mothers, potentially triggering a social component of the infant's self. It is unclear whether the relation would persist when the stimuli presented are self-related. That is, it remains open and an intriguing question to which extent caregiver sensitivity relates to infants' developing self. The current study aims at filling his gap.

A different line of developmental theorizing proposes that further caregiver characteristics support infant's self-development. Specifically, Bigelow (2001) proposed that contingent interactions between caregivers and infants – defined as the prompt reaction to signals of the infant – train infants to detect contingencies in the environment. This in turn helps the infants perceive themselves as detecting contingencies of sensory information is a crucial aspect of the implicit self (Botvinick & Cohen, 1998; Tsakiris, 2008; Weijs et al., 2021). Notably, although caregiver contingency is part of the definition of caregiver sensitivity, it is an independent component of caregiving behavior (Keller et al., 1999). The importance of contingent caregiver-infant interaction is supported by empirical evidence which demonstrates

that an increased number of maternal contingent responses is associated with the infant looking longer at a live video of their own legs, compared to a delayed video (Zmyj & Marcinkowski, 2017). Also, maternal contingency is a predictor of mirror self-recognition by the child (Keller et al., 2005). Consequently, also caregiver contingency seems to help infants to develop an implicit self.

Recent developmental theorizing has offered alternative perspectives on the impact of caregiver-infant interactions on an infant's implicit self that focus specifically on interpersonal touch (Ciaunica & Fotopoulou, 2017; Fotopoulou & Tsakiris, 2017a; Montirosso & McGlone, 2020). Precisely, it has been proposed that tactile interactions between caregivers and infants aid caregivers in adapting to their infant's needs, consequently increasing the caregiver's sensitivity (Montirosso & McGlone, 2020). Furthermore tactile interactions are assumed to contribute to the development of an implicit self in infants by providing sensory information about their bodies (Ciaunica & Fotopoulou, 2017). Although this line of theorizing considers all physical contact to be contributing to self-development, they highlight the role of affective touch, which has a stroking or caress-like quality. as it also communicates emotional information. Studies with adults have shown that affective touch can enhance self-perception (Crucianelli et al., 2013; Lloyd et al., 2013; van Stralen et al., 2014). Furthermore, affective touch is a significant predictor of attachment (Woodhouse et al., 2020), indicating that it might be especially important for the infant's developing self. Notwithstanding increased interest in the role of touch, there is little empirical evidence on whether caregiver touch affects the development of an infant's self (see Della Longa et al., 2019 for preliminary evidence).

In summary, various theoretical approaches predict that characteristics of caregiver-infant interaction, such as sensitivity, contingency, and touch, play a significant role in infants' self-development. The infant's self has usually been investigated by measuring their looking preference to contingent or non-contingent self-related information (e.g. Bahrick & Watson, 1985; Filippetti et al., 2013; Rochat & Morgan, 1995). However, recent research has also investigated neural activation patterns during tasks involving contingent and non-contingent information (Bulgarelli et al., 2019; Filippetti et al., 2015). The basis for this research line were studies with adults that demonstrated the involvement of various brain regions, predominantly located in the right hemisphere and parietal cortices (for reviews see Blanke, 2012; Gillihan & Farah, 2005; Tsakiris, 2010). The right temporo-parietal junction (TPJ) is a brain region that frequently exhibits activity in self-related processing (Quesque & Brass, 2019). Also research with infants highlights the involvement of these brain regions in the infant's self: Bulgarelli et al. (2019) found that infants who identify themselves in mirrors at 18 months exhibit more connectivity in the right TPJ than those who do not yet show mirror self-recognition. Filippetti et al. (2015) demonstrated that 5-month-old infants had increased brain activity in the bilateral posterior superior temporal sulcus (pSTS) and left inferior frontal gyrus while viewing live-video footage of their own face brushed compared to watching a delayed recording.

Interestingly, also the caregiver characteristics presented herein are linked to the development and activation of these particular brain areas. It has been revealed that attachment style relates to the activation of a mentalization brain module, including pSTS (Long et al., 2020). STS and TPJ also exhibited greater activation

during caregiver-infant interactions that were contingent, in contrast to pre-recorded or non-contingent interactions (Hakuno et al., 2020; Hakuno et al., 2018; Lloyd-Fox et al., 2015; E. A. Piazza et al., 2020). Likewise, social touch activates a broad network of brain regions, such as the pSTS (Björnsdotter et al., 2014; Brauer et al., 2016). However, there is conflicting evidence regarding the neural distinction between affective and non-affective touch in infancy (Jönsson et al., 2018; Pirazzoli et al., 2019).

4.2.1 Current Study

This study aims to investigate the origin of the self during infancy. Specifically, we examine whether caregiver-infant interaction plays a role in forming the infant's implicit self. Various theories, like attachment theory, predict that facets of caregiver-infant interactions aid infants in developing their implicit self. Consequently, higher levels in the investigated caregiver characteristics should positively predict the measures of the infant's self.

The present study aims at providing an empirical touchstone for influential theories on the relation between caregiver-infant-interaction and infants' developing self. Based on three theoretical approaches, three different measures are considered, namely caregiver sensitivity, contingency, and touch. Measuring all of the different interaction characteristics in one study will give us the opportunity to assess whether each explains unique variance in the infant's self-development. Caregiver sensitivity will be measured using the Emotional Availability Scales (Biringen, 2008). Within the Emotional Availability Scales sensitivity is defined as a dyadic construct, in which caregiver and infant exert bidirectional influences on each other. Therefore, the measure gives a holistic picture of the caregiver-infant

interaction, from which the infant's self develops according to attachment theory. Caregiver contingency will be assessed in a face-to-face interaction, as in previous studies (e.g. Keller et al., 1999; Zmyj & Marcinkowski, 2017). Two types of caregiver touch will be assessed. Although theories emphasizing the role of interpersonal touch on the developing self, hypothesize all types of touch to be beneficial for self-formation, a special role is ascribed to affective touch, transporting also emotional information. However, so far little research confirmed a special role of affective touch over touch in general (Della Longa et al., 2019). The current study will therefore consider interpersonal touch in general, independent of the type of touch, and affective touch to investigate whether affective touch indeed plays a special role beyond general touch.

Infants' self-development will be measured with functional near-infrared spectoscropy (fNIRS). Previous research with adults demonstrated that the right pSTS is consistently activated by self-related information, and a study by Filippetti et al. (2015) confirmed a similar activation pattern in infants. According to Filippetti et al. (2015), the heightened pSTS activation while watching a live video of the infant's face being stroked by a brush indicated more integration of the contingent multisensory information. Integration of multisensory information is an integral part for self-development (de Klerk et al., 2021). Thus, the more pSTS activity infants show while watching the live video, compared to a delayed video, the more they manage to integrate the multisensory information, indicating a more pronounced self-development. Consequently, in the current study we hypothesized higher scores on the caregiver characteristics to be related to more activation to the contingent condition compared to the non-contingent condition in the pSTS.

4.3 Methods

4.3.1 Participants

118 mother-infant (54 infants female) dyads participated in the study. The mean age of the infants was 5 months and 19 days (SD = 13.69 days) at the behavioral testing session. fNIRS was measured in a separate session, on average 8 days (*SD* = 10) after the behavioral session. Mothers were on average 34 years old (SD = 3.46). One mother did not disclose her age. All infants were typically developed and born after 37 weeks of gestation. Families were recruited from a large city in Germany via public birth records, therefore the sample was mainly from middle-class white background. Mothers gave informed consent for their and their infants participation in the study and received compensation for travel expenses and a small gift for the infant. The study was approved by the department's ethical committee. Testings took place between July 2020 and April 2021.

4.3.2 Behavioral Testing Session

4.3.2.1 Procedure

Upon arrival, mothers were informed about the study procedure and infants were given some time to get accustomed with the environment. Then infants were placed into the infant seat, facing the mother. The experimenter left the room for 8 min while mother and infant were interacting face-to-face. Subsequently, mother and infant moved to the floor for the free play-situation, for which the experimenter again left the room for 10 min in total. After 5 min the experimenter shortly re-entered the room to make toys available to the dyad. At the end of the session the experimenter measured the infant's head circumference for the fNIRS session that took place at another session a few days later.

4.3.2.1.1 Maternal Contingency. The setup followed Zmyj and Marcinkowski (2017). Infants lied in an infant seat that was mounted on a table. The mother sat exactly in front of the table on a chair facing the infant. One camera was located behind the infant to record the mother's face, while the other camera was placed next to the mother to film the infant. Mothers were instructed to interact normally with the infant for 8 min but without using any objects or toys and while leaving the infant in the infant seat. Before leaving the room, the experimenter touched the infant seat as a visual cue to synchronize both videos for analysis.

Maternal Sensitivity and Maternal Touch. Mothers and infants sat on a blanket on the floor. Cameras stood at opposite sides of the blanket to film the interaction. Mothers were instructed to interact normally with the infant for 10 min – the first 5 min they were not allowed to use any objects or toys, then the experimenter made age-appropriate toys available.

4.3.2.2 Coding

All tasks were coded using Datavyu version 1.3.7 (Datavyu Team, 2014). For each task, a trained assistant coded the data of the whole sample, while a second trained and independent assistant coded 20% of the data.

4.3.2.2.1 Maternal Contingency. The coding followed Zmyj and Marcinkowski (2017). The 1st min of the interaction was considered a warm-up phase and therefore not analyzed. From then, 4 min of the interaction were coded as this decreased the drop-out rate compared to coding the entire interaction. At first, the coder identified episodes of mutual gaze, which were then inspected further. In separate passes the coder recorded the verbal and non-verbal utterances of the mother and infant. Then, the facial expressions of mother and infant were coded

separately. Three facial expressions were considered: smiling, lifting or scrunching the eyebrows, and tongue protrusion. For the mother, smiling was coded when the corners of the mouth were at least above the middle of the mouth. For the infant, smiling was coded when the corners of the mouth were at least parallel to the middle of the mouth. Tongue protrusion was coded when the tip of the tongue passed the lips. Reliability was computed using GSEQ (Generalized Sequential Querier; Bakeman et al., 2009), which computes two forms of Cohen's kappa: the time-unit kappa comparing the timing of each coder's sequences, and the event-alignment kappa comparing the event sequences of both coders. For the time-unit kappa we tolerated one second of deviation; for the event-alignment kappa two seconds of deviation were tolerated, however the events had to overlap 80% of the time. The time-unit kappa was .92-.92 (agreement: 97%-97%), the event-alignment kappa was .62 (76% agreement).

Each maternal behavior that started within 1000 ms after the onset of the infant's facial or vocal expression was considered a contingent behavior. For the infant's vocal expressions, maternal behavior was still considered contingent when it started within 1000 ms after the offset of the infant's expression, to also include mothers that did not want to interrupt their infant. If the maternal behavior started at the same time as the infant's behavior, it was not considered contingent. If two maternal behaviors fell within the latency window, only the first one was considered as contingent. If the infant produced several behaviors simultaneously, the maternal behavior was considered contingent to each of them separately.

Next, we computed a responsiveness index for maternal contingency that takes the total amount of maternal behavior into account (Keller et al., 1999;

Equation (1)). This way, the responsiveness index indicates whether the mother was contingent to the infant's behavior above chance level:

$$\frac{\text{maternal contingent behaviors}}{\text{infant behaviors}} - (1 - e^{\frac{\text{maternal behaviors}}{\text{duration of mutual gaze}} * 1000}) \quad (1)$$

The two-way mixed model ICC was 0.65 for the responsiveness index between coders. Data from 97 dyads were analyzed as 7 were excluded because of technical errors, 4 were excluded because the mother refused to take off her mask and 10 because of fuzziness of the infant.

4.3.2.2.2 Maternal Touch. From the free-play interaction, the first 5 min without toys were analyzed for this measure. The video was divided into 2 s-long segments. For each segment the coder decided for one of seven categories of touch which were derived from Crucianelli et al. (2019) and Provenzi et al. (2020): affective, harsh, playful, attention-getting, instrumental, static, and incidental touch (see Table 2 for definitions). If more than one touch category was present within the two-second-segment the category that appeared earlier in the enumeration above was coded, as we considered the more intentional and more affective touches more important. Only touches performed with the hand were coded. When no touch occurred within a segment, no touch category was coded. Cohen's Kappa for the coding was 0.78.

Subsequently, a total duration was computed for each category. We assumed that each touch occurred for the whole duration of the 2s-segment. For the general touch variable, a sum was built over all touch categories, representing the total amount of time spent with the mother touching the infant. To account for slightly different interaction lengths, the absolute time of all touch categories and affective

Table 2

Codes of Maternal Touch Used in this Study

Category	Definition
Affective	Intentional, low-energy, and slow touch that gives a sense of closeness between mother and child
Harsh	Intentional touch that is not contingent with the infant's emotional state by being too fast or intense for the infant
Playful	Intentional, fast-paced touch with the goal to make the infant smile or laugh
Attention-getting	Intentional touch with the aim to direct the infant's attention to the mother, for example by tapping on the infant
Instrumental	Intentional touch without a communicative value, intending to change or maintain the infant's position, clean the infant, or adjust the infant's clothes
Static	Mother keeping her hand in contact with the child without moving it, intending to maintain physical contact
Incidental	Mother touching the infant when actually aiming at something else

touch was divided by the total duration of the video. The ICC for these measures was 0.98. Data from 113 dyads was analyzed. Data from 4 dyads had to be excluded because of experimental errors, data of 1 dyad because of a technical error.

4.3.2.2.3 Maternal Sensitivity. Maternal sensitivity was coded according to the Emotional Availability Scales 4.0 (Biringen, 2008) using the entire 10 min of free-play interaction. According to the coding manual, sensitivity is scored on a 7-point scale, representing a holistic score for the whole session. A 7 indicates a highly sensitive caregiver, a 4 represents inconsistent sensitivity, a 3 indicates somewhat insensitive caregivers, and a 1 represents highly insensitive caregivers. To receive a

high score on this scale, caregivers need to display a warm affect, clear perceptions of the infant's signals and appropriate responses to these signals, have a good awareness of timing, flexibility in their behavior, display respect in their interaction with the child, as well as a smooth handling of conflict situations. Both coders completed the necessary training for coding and achieved acceptable reliability before coding the present dataset. Reliability on the present dataset was ICC = 0.86. 117 datasets were analyzed as 1 dyad had to be excluded due to technical issues.

4.3.3 fNIRS Session

4.3.3.1 Procedure

Upon arrival, caregivers and infants were brought to a sound-attenuated, dimly lit and electrically shielded testing booth. The caregiver was informed about the procedure and the functioning of the fNIRS system, while the infant had some time to get accustomed to the environment. The infant sat on the caregiver's lap approximately 70 cm away from a computer screen positioned on the eye-level of the infant. A webcam was positioned directly below the computer screen to film the infant's face. Caregivers were instructed to refrain from interfering with the task by avoiding movements and talking.

Two experimenters fitted the fNIRS cap on the infant while the infant was watching videos on the screen. The fNIRS was a NIRScout (NIRx Medical Technologies GmbH, Berlin, Germany) and had 8 sources and 16 detectors, measuring 30 channels in total with two continuous wavelengths at 760 and 850 nm. The channels were located temporally on the left and right of the infant's head. The optodes were placed according to the 10-5 system (Oostenveld & Praamstra, 2001) to ensure a source-detector separation between 20 and 25 mm. Sources were located at C5, C6,

TP7, TP8, CP3, CP4, P5, and P6. Detectors covered the locations FC5, FC6, FCC5h, FCC4h, FTT7h, FTT8h, T7, T8, C3, C4, CP5, CP6, P7, P8, P3, and P4. As the measured brain area lies approximately in the middle of source and detector, this results in the channels locations in Figure 4.

After calibration of the fNIRS, the testing booth door was closed. One experimenter remained within the booth, sitting on the left side of the caregiver, controlling the task and applying the brush strokes to the infant. This experimenter was the same for all infants. The other experimenter controlled the fNIRS recording outside the booth. The fNIRS was recorded with NIRStar 15.2 (NIRx Medical Technologies GmbH, Berlin, Germany).

The task followed the procedure of Filippetti et al. (2015) and consisted of two conditions with up to 10 trials each: in the contingent condition infants saw a live video of their own face on the screen. In the non-contingent condition, the video was delayed by 3 s. Each trial lasted 15 s and was preceded by a 12 s baseline, in which six different pictures of vehicles were presented with a pseudo-randomized duration of 1, 2 or 3 s. The videos and pictures were presented by OpenSesame version 3.2.8 (Mathôt et al., 2012). During the trials, the experimenter brushed the infant's left cheek maximum three times per trial (contingent: M = 2.81, SD = 0.25; non-contingent: M = 2.77, SD = 0.36; $t(81) = 0.65$, $p = 0.51$). Each brush lasted 702 ms (SD = 124) on average in the contingent condition and 674 ms (SD = 112) in the non-contingent condition ($t(81) = 3.12$, $p = 0.002$). In the non-contingent condition, the experimenter took care that the actual brushstroke did not happen at the same time as the visible brushstroke. The order of conditions followed an ABBABAAB rhythm, starting with the contingent condition.

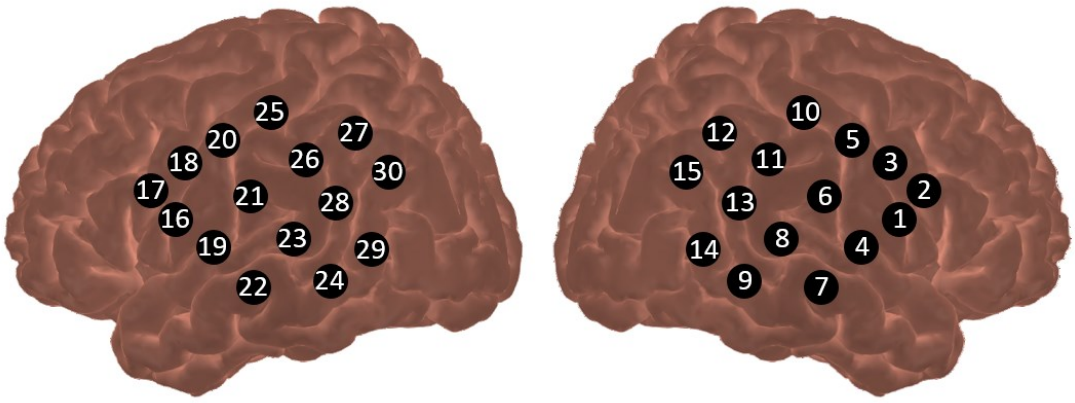
During the whole task, piano music played to calm down the infants. Whenever the infant was fussy, the experimenter could initiate a break. When the infant was too fussy to continue, the task was aborted. To draw back the infant's attention to the screen, the experimenter could play a sound in the beginning of the baseline. In these cases, the same sound was also played in the beginning of the respective trial.

4.3.3.2 Pre-Processing

Data of 13 infants had to be excluded before pre-processing because of technical issues (7) or fuzziness (6). The processing was conducted in Homer2 (Huppert et al., 2009). First, trials were rejected based on the looking time of the infant: only trials, in which the infant looked to the screen more than 50% of the time were included. A minimum of three valid trials per condition was necessary for the infant to be included in further analysis; 30 infants did not meet these criteria. The remaining infants on average completed 6.39 trials (*SD* = 1.87) in the contingent condition and 6.31 trials (*SD* = 1.83) in the non-contingent condition ($t(58) = -0.49$, $p = .62$). Data from the remaining trials were first checked for channels whose activity was outside of a range from 0.09 V to 1 V or whose signal-to-noise-ratio was smaller than 0. Data were then converted to optical density. Following recommendations from Di Lorenzo et al. (2019), we then removed motion artifacts by applying a sequence of first detecting motion artifacts by channel with a change in a channels' signal of more than 14 standard deviations or more than 0.4 optical density units in amplitude within 1s marked as motion artifacts. These motion artifacts were then corrected with wavelet filtering with an interquartile range of 0.5. Subsequently, we

Figure 4

fNIRS Channel Placement on the Left and Right Hemispheres



Note. Each number denotes a channel, lying in the middle between source and detector. This figure was created by myself in content and style.

wavelet-transformed the HbO function for each channel and visually checked the channels for a visible heartrate and motion artifacts (see Nguyen et al., 2021). Channels were excluded if they showed no heartrate or too many motion artifacts. Finally, data were again checked for remaining motion artifacts. Contaminated trials were then rejected. Afterwards data were bandpass filtered between 0.01 Hz and 1 Hz and converted to concentration using the modified Beer–Lambert law with a differential pathlength factor of 5.1. Two regions of interest (ROI) were formed, both spanning the superior temporal sulcus on both hemispheres. The ROI on the right hemisphere included channels 8, 9, 13, and 14. The ROI on the left hemisphere included channels 23, 24, 28, and 29. The signal from all channels within an ROI was averaged for subjects that had data for at least 2 channels within an ROI.

Overall, 55 subjects contributed data to the left ROI with an average of 3.24 channels (*SD* = 0.82) per subject. 52 subjects contributed data to the right ROI with an average of 3.08 channels (*SD* = 0.86) per subject.

4.3.4 Data Analysis

All analyses were conducted in RStudio. To check for relations between the maternal variables, we used Pearson product moment correlation.

For analysis of the fNIRS data, we followed de Klerk et al. (2018). Six time bins were created (3s each) of the post-stimulus time-window, in which data were averaged for each ROI and condition separately. A repeated-measures ANOVA was conducted, using time bins and conditions as within-subject factors. This way we analyzed whether there was significant change of activation over time, and whether this activation differed significantly between conditions.

For each ROI, we then computed difference scores, averaging the signal over the whole post-stimulus time range and subtracting the signal in the non-contingent condition from the signal in the contingent condition. These difference scores were then used as dependent variables in a linear regression model. Independent variables were the relative amount of time mothers touched their infants, the relative amount of time spent with affective touch, the maternal sensitivity score, the contingency responsiveness index, and the age of the child at the time of the fNIRS session.

4.4 Results

Descriptive statistics of all maternal variables, as well as correlations between maternal variables are reported in

Table 3. Only maternal touch in general and maternal affective touch were significantly correlated.

Table 3

Descriptive Statistics and Correlations of Maternal Variables

Variables	n	M	SD	1	2	3
1. Sensitivity	117	5.08	1.11	—		
2. All Touch	113	62.19%	27.12	-.02	—	
3. Affective Touch	113	10.38%	9.24	.15	.41***	—
4. Responsiveness Index	97	-0.12	0.26	.10	.07	.13

* $p < .05$. ** $p < .01$. *** $p < .001$.

4.4.1 fNIRS Analysis

The left ROI (see Figure 5) showed a significant difference in HbO-activation over time, indicated by a main effect of time bin ($F(5, 270) = 9.80$, $p < .001$). Also the interaction effect between condition and time bin was significant ($F(5, 270) = 2.73$, $p = .02$), but the main effect of condition was not significant ($F(1, 54) = 2.39$, $p = .13$). However, post-hoc t-tests on each time bin revealed no significant differences between both conditions in HbO concentration (all *p*s > .07). Analyses of HbR in the left ROI revealed significant difference in activation over time ($F(5, 270) = 4.34$, $p < .001$) but no other significant effects. The difference score for the left ROI had an average of -0.08 µV ($SD = 0.37$).

The right ROI showed a significant difference in HbO-activation over time (F(5, 255) = 11.94, p < .001) and a significant main effect of condition (F(1, 51) = 5.08, p = .03). Post-hoc t-tests (see **Chapter 4.7**, Table 5) on each time bin revealed significant differences in the first three time bins (i.e. from 0 to 9 s) and in the last time bin (i.e. from 15 to 18 s) with more activation in the non-contingent condition than in the contingent condition (see Figure 5). Analyses of the HbR in the right ROI revealed significant activation differences over time (F(5, 255) = 9.32, p < .001) and a significant interaction between time bin and condition (F(5, 255) = 2.41, p < .04). However, post-hoc t-tests on each time bin revealed no significant differences between both conditions (all p > .16). The average difference score for the right ROI was -0.14 µV (SD = 0.45).

4.4.2 Regression Models

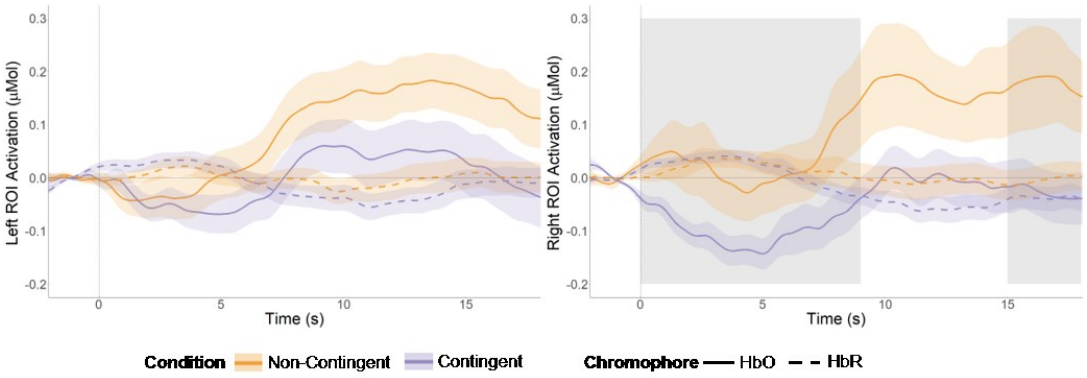
The linear regression model with the differential activation in left ROI as outcome variable was not significant (F(5, 37) = 0.81, p = .55, adjusted R^2 = -0.02). No predictor had a significant effect on the differential activation in the left ROI (see **Chapter 4.7**, Table 6).

The linear regression model with the differential activation in the right ROI activation as outcome variable was significant (F(5, 34) = 3.87, p = .007, adjusted R^2 = 0.27). Maternal sensitivity as well as the total amount of maternal touch were significant predictors (see Table 4). As the ROI difference score indicated how much more activation there was to the contingent condition (compared with the noncontingent condition), and since the difference score was negative, the positive estimates of both predictors mean that more maternal touch and more maternal sensitivity lead to less differential activation in the right ROI.

Post-hoc tests revealed that more maternal sensitivity and maternal touch lead to less activity in the non-contingent condition (see **Chapter 4.7**, Table 7), while there was no significant influence of any predictor on the activity in the contingent condition (see **Chapter 4.7**, Table 8).

Figure 5

Grand Averages of fNIRS Signal Over Both Regions of Interest



Note. Grand averages over the region of interest (ROI) on the left hemisphere (left), and on the right hemisphere (right). Averages of the contingent condition are presented in orange. Averages of the noncontingent condition are presented in purple. Solid lines represent the oxygenated hemoglobin concentration (HbO), while dashes lines indicate the concentration of deoxygenated hemoglobin (HbR). Gray shades indicate significant time windows. This figure was created by myself in content and style.

Table 4

Linear Regression Results on the Differential Activation in the Right ROI

Variable	Estimate	SE	95% CI	t-Value	p-Value
Intercept	-2.0270	0.7130	[-3.4760, -0.5780]	-2.84	.008
Affective Touch	-0.0070	0.0081	[-0.0234, 0.0095]	-0.86	.40
All Touch	**0.0059**	**0.0024**	**[0.0011, 0.0107]**	**2.49**	**.02**
Contingency	-0.1093	0.2573	[-0.6322, 0.4136]	-0.43	.67
Sensitivity	**0.1567**	**0.0577**	**[0.0394, 0.2739]**	**2.72**	**.01**
Age	0.0044	0.0039	[-0.0035, 0.0122]	1.14	.26

Note. Significant ($p < .05$) variables are presented in bold font.

4.5 Discussion

Developmental theorizing has a long-standing interest in understanding how caregiver interactional characteristics relate to an infant's developing self. Influential developmental theories propose that sensitive and contingent caregiving, as well as (affective) touch during interaction, promote the development of the self in infancy. The current study investigated theoretical claims that these characteristics would positively predict the infant's ability for multisensory integration, an important precursor to the self (de Klerk et al., 2021). Multisensory integration was measured with the infant's brain activity in the pSTS while watching contingent videos of themselves, compared to non-contingent videos. In contrast to our assumption, infants showed more activity in response to the non-contingent condition. Importantly, maternal sensitivity and maternal touch negatively predicted the

infants' brain activity to the non-contingent condition. This suggests a relation between maternal interaction characteristics and neurocognitive processes that support infants' developing self.

Interestingly, contrary to a previous study (Filippetti et al., 2015), infants in our study showed more right pSTS activity in response to the non-contingent condition than to the contingent condition. At the same time, studies with adults demonstrated similar patterns as reported in our study (e.g. Ionta et al., 2011; Kontaris et al., 2009). For instance, a study (Leube et al., 2003) manipulated the delay between participants' hand movement and the visual feedback of the movement. This study found a positive correlation between the temporal delay and the activity in the right pSTS. Typically, increased activation to non-contingent information is interpreted as a prediction error in these studies (e.g. Kontaris et al., 2009). Participants predict that visual feedback of their bodily sensations, such as touch or movement, will be temporally contingent with these sensations. If this is not the case, a prediction error arises, which is represented by higher neural activation. The existence of prediction errors in infancy has been repeatedly demonstrated (Berger & Posner, 2023). Therefore, our discovery that infants exhibit heightened neural activity in response to the non-contingent condition could be interpreted as a prediction error in relation to visual information that does not correspond to their bodily sensations. The emergence of a prediction error for non-contingent visual information suggests that infants have an expectation that visual information will match their bodily sensations. Previously, the establishment of these expectations was considered to be the beginning of the infant's implicit self (Rochat, 1998). Thus, higher neural activation to the non-contingent condition compared to the contingent

condition would indicate a more pronounced implicit self. This result supports developmental theories that highlight the impact of predictive processes for the development of the self (see Kollakowski et al., 2023; **Chapter 2** for a recent review).

It is noteworthy that increases in maternal sensitivity and touch result in less neural differentiation between conditions, indicating that the response to both conditions is more similar. This effect is primarily due to increases in maternal sensitivity and touch leading to reduced activation in the non-contingent condition, resulting in less prediction error. Both measures, however, are not correlated, indicating that they are independent of each other, although both contribute to infant attachment (Anisfeld et al., 1990; Biringen et al., 2014). Indeed, both might fulfill different functions for infants' self-development. Maternal touch as measured in this study represents the number of touches delivered to the infant, independent of the function and appropriateness of the specific touch. Thus, this measure assesses the amount of tactile (and maybe visual) information delivered to the child. According to the theory of mentalizing homeostasis (Ciaunica & Fotopoulou, 2017; Fotopoulou & Tsakiris, 2017a), this would represent a learning opportunity for multisensory integration, an important factor in self-development. While the present findings support the theory of mentalizing homeostasis in their claim that interpersonal touch plays a role in self-development, more touch leads to a less pronounced self-development. Consequently, it might be the case that the not perfectly contingent information provided by the mother rather trains the infant to have a broader time range for considering information as contingent. Therefore, they show less prediction errors within the non-contingent condition. When the mother is

providing less touch, infants might be less tuned to these imperfect contingencies, producing larger prediction errors.

Despite recent theories emphasizing the significance of affective touch in the caregiver-infant interaction (Ciaunica & Fotopoulou, 2017; Montirosso & McGlone, 2020), our findings indicate that there is no specific contribution of affective touch beyond touch in general to the infant's self. Currently, only one study has demonstrated a specific role of affective touch in behavioral measures of contingency detection in infancy (Della Longa et al., 2019). In contrast, our study examines the neural activation of infants' brains under different contingency conditions. Previous studies have shown mixed evidence regarding the differences in brain activation between affective and non-affective touch in infancy (Jönsson et al., 2018; Pirazzoli et al., 2019). Therefore, it is possible that neural and behavioral measures are differentially affected by affective touch or touch in general.

Maternal sensitivity goes beyond maternal touch in that it also provides the infant with sensory information mostly contingent to their own signals, but in this measure also the appropriateness of the reaction to the infant’s signal is considered. According to attachment theory, the implicit self results from a well-organized caregiver-infant interaction, hypothesizing that appropriate reactions to the infant’s signals result in a more organized interaction. Consequently, increases in maternal sensitivity are hypothesized to promote infant’s implicit self, which our results contradict. One possible explanation for this finding is that a more pronounced self is not beneficial for the infant, at least at this age. Verschoor and Hommel (2017) for example hypothesize that a less pronounced self and therefore less self-other differentiation is beneficial for observational learning. If the actions of another

person are considered as own actions due to a lack of differentiation between self and other, infants could incorporate these actions into their action repertoire without the need of establishing a correspondence between themselves and the other. Thus, infants should be less sensitive to imperfect contingencies of multisensory information, as sensory information produced by other people will be less contingent than self-produced sensory information, and therefore these infants should produce less prediction error when seeing non-contingent information. A similar idea has been put forward by M. Lewis et al. (1985) and Mahler et al. (1985). M. Lewis et al. (1985) demonstrated that children with insecure attachment styles showed earlier mirror self-recognition than children with secure attachment styles, Children with less aligned caregivers, resulting in insecure attachment styles, in contrast might need to develop a self earlier to be able to act on their own, compensating for a lack of care.

It is important to note that our findings may not be entirely generalizable due to the use of touch in our fNIRS task. As noted by Ciaunica and Fotopoulou (2017), touch in experimental settings is inherently interpersonal and may have activated representations of social interactions in the infant, which could explain the observed influences of social interactions on neural activation. The relations may differ when considering self-related tasks that do not involve touch, but only visual-proprioceptive contingencies. Only if these relations persist in such tasks, can we confidently conclude that social interactions have an influence on the infant's self.

Although maternal contingent responsiveness has been hypothesized to influence the infant's self (Bigelow, 2001), we did not find evidence for this relation in our study. There could be several reasons for this. Firstly, our measure of maternal

contingency was limited to facial expressions and vocal utterances of the mother and child, and did not incorporate movements of other body parts. This may have provided a too limited view of contingency. Furthermore, other theories suggest that caregiver contingency has an impact on affective self-regulation (Gergely et al., 2010) or agency (Sroufe, 1994), rather than on the multisensory integration, which was the focus of this study. Further research is needed to explore the relation between caregiver contingency and different aspects of the self.

4.6 Conclusion

Infants exhibit a neural prediction error when viewing a non-contingent video of their own face being stroked, indicating an expectation for synchronous self-related sensory information. However, infants show less of this prediction error when their mothers are more sensitive and touch them more during interactions. This suggests that, at this age, it might be beneficial for the infant to be less sensitive to imperfect contingencies, producing less prediction error in non-contingent situations, possibly to facilitate learning from observation.

4.7 Supplementary Material

Table 5

Post-Hoc Comparisons of HbO in Right ROI

Time Bin	Raw Time	*t*-Value	*p*-Value
1	**0-3 s**	**2.11**	**.04**
2	**3-6 s**	**2.62**	**.01**
3	**6-9 s**	**2.36**	**.02**
4	9-12 s	1.86	.07
5	12-15 s	1.88	.07
6	**15-18s**	**2.30**	**.03**

Note. Significant ($p < .05$) comparisons are presented in bold font.

Table 6

Linear Regression Results on the Differential Activation in the Left ROI

Variable	Estimate	SE	95% CI	t-Value	p-Value
Intercept	-0.0055	0.5500	[-1.198, 1.1087]	-0.01	.99
Affective Touch	-0.0052	0.0065	[-0.0184, 0.0080]	-0.80	.43
All Touch	-0.0020	0.0019	[-0.0040, 0.0036]	-0.11	.92
Contingency	-0.0922	0.2080	[-0.5136, 0.3292]	-0.44	.66
Sensitivity	-0.0552	0.0458	[-0.1480, 0.0377]	-1.20	.24
Age	0.0018	0.0030	[-0.0042, 0.0079]	0.62	.54

Table 7

Linear Regression Results on the Activation to the Non-Contingent Condition in the Right ROI

Variable	Estimate	SE	95% CI	t-Value	p-Value
Intercept	**1.8349**	**0.8111**	**[0.1864, 3.4834]**	**2.62**	**.03**
Affective Touch	0.0110	0.0092	[-0.0077, 0.0297]	1.19	.24
All Touch	**-0.0062**	**0.0027**	**[-0.0116, -0.0007]**	**-2.28**	**.03**
Contingency	0.0444	0.2927	[-0.5505, 0.6393]	0.15	.88
Sensitivity	**-0.1749**	**0.0656**	**[-0.3083, -0.04154]**	**-2.67**	**.01**
Age	-0.0031	0.0044	[-0.0120, 0.0059]	-0.70	.49

Table 8

Linear Regression Results on the Activation to the Contingent Condition in the Right ROI

Variable	Estimate	SE	95% CI	t-Value	p-Value
Intercept	-0.1921	0.3884	[-0.9815, 0.5973]	-0.49	.62
Affective Touch	0.0040	0.0044	[-0.0049, 0.0130]	0.92	.37
All Touch	-0.0002	0.0013	[-0.0029, 0.0024]	-0.19	.85
Contingency	-0.0649	0.1402	[-0.3498, 0.2200]	-0.46	.65
Sensitivity	-0.0182	0.0314	[-0.0821, 0.0456]	-0.58	.57
Age	0.0013	0.0021	[-0.0030, 0.0056]	0.62	.54

5 General Discussion

The concept of the implicit self in infancy has been a topic of debate for a long time. There is no clear definition of the implicit self in infancy, nor is there a conclusive way to measure it. The purpose of this thesis is to investigate the implicit self in infancy. To achieve this, three research aims were defined. **Chapter 2** examined theories about the implicit self in infancy to better understand what the implicit self in infancy actually is. As it turned out, settling on a definition of the implicit self is akin to adopting a worldview. Therefore, it might be necessary to rethink the topic of the implicit self. In **Chapter 3**, the thesis introduced a new measure of the sense of agency in infancy to investigate if this important aspect of the implicit self is present by 9 months of age. However, infants did not show any indications of a sense of agency, delaying the proposed onset even further than previously thought. In **Chapter 4**, the thesis examined potential social influences on the implicit self in infancy to determine whether the social environment is necessary for self-development. The study revealed that maternal interactional characteristics have an impact on infants' implicit self, providing preliminary evidence for a social basis of the implicit self. The following section will discuss the implications of each chapter on our understanding of the implicit self in infancy, and provide suggestions for further research.

5.1 What is the Implicit Self in Infancy?

Throughout history, researchers have proposed various ideas about the self. **Chapter 2** revealed that many of these ideas are still present in contemporary theories about the self. Ecological theories follow the ideas of Ibn Sina and the phenomenological tradition, viewing the self in perception. Hommel (2021), as a representative of sensorimotor theories, defines the self as a bundle of different

features that become associated through action, largely inspired by Hume. Predictive theories locate the self in the brain, which has replaced the soul in contemporary thought (Overton, 2015), following Descartes' ideas. The social theories discussed in **Chapter 2** are inspired by Mead (1934), and theories that challenge the usefulness of the implicit self in infancy may follow Kant's idea that language drives all of our categorical thinking.

This shows that contemporary theories still face the same debates as ancient theories regarding the self. Decades of research have not brought us any closer to solving the puzzle of what and where the self is. One reason for this may be that most theories rely on different worldviews, as explained in **Chapter 2**. It is impossible to test theories with different worldviews against each other as they rely on different basic assumptions. Therefore, it seems that the nature of the self has been more of a conceptual decision rather than an empirical question. In fact, reviewing dozens of experimental and neurocognitive studies, Gillihan and Farah (2005) demonstrated that the self is not anything special in cognitive processing. To the contrary, there are no brain regions that are specific to self-related processing. Most effects that seem to show a special role of the self in information processing can probably be explained by confounding variables or leaner explanations (Gillihan & Farah, 2005). Other researchers also conclude that there is no empirical or conceptual evidence for the existence of a self (e.g., Metzinger, 2011). The lack of conclusive evidence for a self substantiates the idea that most theories around it rather depend on conceptual ideas not empirical evidence.

Of course, it is possible that the appropriate measurement for the self has not yet been discovered, but that advances in neuroscience may lead us there.

Alternatively, we may have been searching in the wrong places for the self. However, it is also possible that we are searching for something that does not exist in the way we imagine. Research on the self may be hindered by essentialism, which attempts to identify an underlying essence to all self-related phenomena, despite the lack of evidence for such an essence (Medin & Ortony, 1989). The argument is not that there is no self at all. We talk about ourselves and attribute traits, ideas, beliefs, and actions to either "you" or "me". We use a concept of the self in communication and much of our society is built on this concept (e.g. when talking about responsibility; Sokol et al., 2015), But maybe this is all there is. Perhaps the self is merely a linguistic concept we are dealing with, rather than a measurable essence.

Several researchers have posited that the self is a linguistic concept (Bennett & Hacker, 2003; Carpendale & Lewis, 2021; Feldman Barrett, 2017). None of these researchers propose a clear developmental timeline for self-development. However, they do offer general ideas about development that can be applied to the self. Carpendale and Lewis (2021) define self-understanding as a result of social understanding. According to the authors, children learn to communicate with their caregivers through social interactions, which lays the foundation for the development of thought and social understanding. Communication involves both verbal and nonverbal interaction. In infancy, communication often takes the form of coordinated actions with caregivers, such as the use of gestures. Learning about the meaning of gestures is a bi-directional process. Caregivers interpret the gestures as meaningful and respond accordingly, even if infants are not yet aware of their communicative value. Through this process, infants learn that their actions can have an impact on others. This iterative process leads to intentional communication

between caregivers and children, resulting in mutual understanding. As a result, children learn to understand others and that others perceive them as individuals, which helps them develop a self.

Feldman Barrett (2017) argues that the self is a social construct. In a given culture there is a shared understanding of what the self represents, such as a collection of traits, attributes, actions, and beliefs. However, these attributes are not necessary nor sufficient for the self-concept. Attribute A may be related to the self in one moment, while attribute B may be related in another moment. However, neither A nor B needs to be present for the self to exist or develop. In this approach, the self-concept is multifaceted and varies depending on the situation. It is defined by the function these attributes have in the specific moment, which is to distinguish oneself from others. Feldman Barrett assumes that children learn to use this concept during social interactions by observing how caregivers use words related to the self such as "you" and "I". Once learned, children then assign meaning to their perceptions using this concept.

Both theories agree that social interactions and advances in communication drive self-development. Some theories evaluated in **Chapter 2** make similar claims. For example, attachment theory proposes that the self develops within caregiver-infant interactions. Within these interactions, infants build a working model about interactions. In a sense the working models represents a shared understanding of routines and interactions that then influence the self. This understanding of the self as being based on communication that is based on shared routines closely resembles the ideas by Carpendale and Lewis (2021). Also, in the predictive theories discussed in **Chapter 2** gradually learn about the self through shared routines. Although the

focus of these predictive theories are embodied caregiver-infant interactions, it has been proposed that embodied interactions build the basis for communication in infancy (Lipschits & Geva, 2024). The approach of Feldman Barrett leans on the predictive coding framework, expanding predictive theories discussed in **Chapter 2**. The theories questioning the usefulness of an implicit self in infancy also base their argumentation on the assumption that the self is nothing more than a linguistic construct.

However, defining the self as a linguistic construct implies that it only emerges once individuals develop language. What is it then that is measured as an "implicit self" in infancy when children are still pre-verbal? At a closer look, measures of the "implicit self" in infancy only assess whether infants can categorize information based on contingency. Assuming that this process is related to the self, again, rather seems to be a conceptual decision more than an empirical question. In fact, a recent study found no correlation between contingency detection in infancy and self-recognition measures in toddlerhood (Klein-Radukic & Zmyj, 2020), indicating that these processes are independent. Also in adults it has been repeatedly reported that "implicit self"-measures are not related to measures of the explicit self (Dewey & Knoblich, 2014; Ma et al., 2021; Saito et al., 2015). Furthermore, a sense of ownership or agency can also be found for non-corporeal objects like computer cursors (see Liesner et al., 2021 for a review). All these findings challenge the idea that these measures assess an "implicit self".

Also, conceptually it is unclear whether such a categorization process can say anything about the self. For example, Mandler (1988) argues that "[t]o categorize incoming stimuli into different types is a basic component of a perceptual

recognition device; by itself, this ability tells us nothing about the formation of accessible concepts that may be used for purposes of thought and reflection." (p. 117). Categorizing information as contingent or non-contingent is insufficient for making a distinction between "self" and "other", as external information can also be contingent. **Chapter 3** indeed shows that at least infants do not neuronally differentiate between self-produced and predictable, i.e. contingent, externally-produced information. Distinguishing between self-produced and externally-produced information may require a concept of "self" and "other" as discussed in Zaadnoordijk (2020). Individuals who possess an explicit self may assign the label "self" to contingent information and "other" to non-contingent information. Once established, the explicit self may then impact perceptual processing (Feldman Barrett, 2017; Gillihan & Farah, 2005). Indeed, models of the senses of ownership and agency acknowledge that top-down factors, such as expectations about one's own efficacy, influence implicit processing (Synofzik et al., 2008; Tsakiris, 2010).

However, even if there exists evidence that measures of the "implicit self" might not even be related to the self, there is a possibility that they are connected to self-development in infancy. Previous research has demonstrated that 12-month-old infants use perceptual object categories to learn words (Pomiechowska & Gliga, 2019). Similar mechanisms may be at play in the categorization process and its relation to the explicit self. It is possible that infants learn the categorization first and then assign the word "self" to it once it is learned. Admittedly one study investigating the relation between "implicit self"-measures and explicit self-measures did not find meaningful relations between these measures (Klein-Radukic & Zmyj, 2020). However, this study did not take the social environment of infants into account.

Theoretical approaches discussed in this chapter assume that developing an explicit self needs social interactions, in which children are taught about the self. Previous research has shown, that this type of concept-based learning is influenced by the language infants are exposed to, even before they can speak (Yin & Csibra, 2015). Therefore, the language input that infants receive from their caregivers may be a variable that needs to be included in models of infants' self-development. For example, the frequency with which caregivers refer to an infant's mental states during interactions could predict the infant's explicit self.

It is important to note that meaning is not solely conveyed through words. Gestures and structured patterns of interaction are fundamental to communication and language development (de León, 2023; Zukow-Goldring, 2012). These more embodied interactions may also impact infants' comprehension of concepts such as the self (Carpendale & Lewis, 2021; Feldman Barrett, 2017). For example, Shai and Belsky (2017) propose that mentalization, the act of caregivers treating their children as individuals with their own selves, is primarily conveyed through embodied interactions during infancy. Therefore, future research should not investigate not only the effects of verbal but also nonverbal behaviors on infants' self-development (see also Lipschits & Geva, 2024).

The theoretical approaches positing that infants learning about the self through caregiver-infant interactions, also posit that caregivers assume the existence of a self in their infants. Just like caregivers assign meaning to infant's gestures, allowing them to learn that their actions can have meanings (Carpendale & Lewis, 2021), caregivers assign a self to infants allowing them to learn that they are individuals with a self. Caregivers (and researchers) assume that infants have a self,

even though they may not develop one until they acquire language. This erroneous conclusion may result from caregivers struggling to imagine the experiential world of an infant (or anyone) without a self (Metzinger, 2011). Therefore, humans tend to treat everyone with a personality as if they have a self. In some cases, humans even treat inanimate objects like robots as if they have a self (Perez-Osorio & Wykowska, 2020; Pohl et al., 2024). Recent research has shown that simple behavioral cues, such as a robot pushing a box, can trigger self-ascriptions (Pohl et al., 2024). Similar interactions may occur when caregivers interact with infants. For example, if infants kick a mobile and laugh, caregivers may interpret the laugh as a sign of joy because the infant is perceived as understanding their own efficacy in making the mobile move. Consequently, caregivers may attribute a self to the infant and communicate with them accordingly. In this approach, self-development is the outcome of the interaction between infants' action and caregivers' attributions. **Chapter 4** showed that the embodied characteristics of mother-infant-interaction can predict an infant's categorization of contingent and non-contingent information. It is worth testing if when infants have a more developed categorization process and therefore exhibit more of such an apparent self, they prompt caregivers to use more language that refers to the infant's self, promoting further self-development.

In summary, it is possible that the self is purely linguistic and that the "implicit self" does not actually exist. The ability to distinguish between perceptual information of different contingency, that is assessed by measures of the "implicit self", may not necessarily indicate the presence of a self. However, once the explicit self is developed, it may affect measures of the "implicit self", leading people to believe that these measures indeed represent an aspect of the self (Dieguez, 2018).

Similarly, caregivers may assume that their infants possess a self based on their categorization abilities, and consequently address them as if they had one. This in turn, lays the foundation for developing an explicit self.

5.2 When Does the "Implicit Self" in Infancy Develop?

Now that it has been proposed that infants may not have a self until they develop language, the rest of this chapter will only make claims about the categorization process of contingent and non-contingent information. **Chapter 4** investigated infants' sensitivity to perceptual information that is temporally contingent on their bodily sensations. **Chapter 3** investigated whether infants differentiate self-produced information from predictable externally-produced information. Predictability goes beyond contingency as it involves assumptions about causality. Self-produced information is perfectly predictable, as predictions can be based on executed motor commands. This information is not available for predictable externally-produced information. Consequently, it was investigated in **Chapter 3** whether infants can distinguish self-produced information from predictable externally-produced information based on the fact that self-produced information is even more predictable. Both chapters aimed to determine if infants categorize information based on perceptual properties.

Chapter 4 demonstrated that 5-month-old infants can differentiate between temporally contingent and non-contingent information as they showed more brain activity in the non-contingent condition. This finding is consistent with previous research that shows young infants can differentiate information based on contingency (e.g. Bahrick & Watson, 1985; Filippetti et al., 2013; Rochat & Morgan,

1995). Consequently, the categorization process appears to be functional from a very early age, possibly even from birth (Filippetti et al., 2013).

In contrast, **Chapter 3** demonstrated that 9-month-old infants do not perceive self-produced information as more predictable than predictable externally-produced information. Specifically, in **Chapter 3,** infants did not exhibit sensory attenuation for self-produced effects compared to predictable externally-produced effects. It is possible that self-produced effects cannot yet be classified as such if they are not distinguishable from external effects in terms of predictability. Meyer and Hunnius (2021) showed that 3-month-old infants did not exhibit sensory attenuation for self-produced effects compared to externally-produced effects that were temporally regular. However, they did show a tendency for sensory attenuation compared to externally-produced effects that were temporally irregular. Meyer and Hunnius (2021) also demonstrated that 3-month-old infants distinguish between temporally regular externally-produced effects and temporally irregular externally-produced effects. This suggests that infants at this age can differentiate information based on predictability, but are not yet able to consider self-produced effects as predictable.

Recent research with adults has shown that sensory attenuation occurs even when externally-produced effects are predictable in some cases (Harrison et al., 2021; Klaffehn et al., 2019, but see Kaiser & Schütz-Bosbach, 2018). It is unclear why adults can differentiate between self-produced and predictable externally-produced effects in some cases while 9-month-old (or younger) infants cannot. It is possible that due to the motoric immaturity of infants, they cannot yet issue predictions from their actions that are precise enough to differentiate them from predictable

externally-produced effects (see **Chapter 3.5**). Additionally, as discussed in this chapter, adults may have a self-concept that influences their perceptual processing, while infants may not. Adults understand that self-produced effects are self-produced, even if the externally-produced effects are equally predictable. Infants, who may not yet have a self, lack this understanding. They may simply categorize information based on predictability, and in the case of **Chapter 3** both self-produced and externally-produced effects are equally predictable.

However, the conclusions that can be drawn from **Chapter 3** are limited. Currently, there is no research indicating that infants can differentiate self-produced effects from unpredictable externally-produced effects. Therefore, it is unknown whether self-produced effects are considered predictable at all. **Chapter 3** presents evidence that 9-month-old infants exhibit differential learning processes or attention to self-produced effects compared to externally-produced effects. Infants at this age may be in the process of learning that self-produced effects are predictable. Future research should compare sensory attenuation for self-produced effects to unpredictable externally-produced effects to determine at what age infants consider self-produced effects as predictable.

In conclusion, infants categorize information based on contingency from very early on. By 9 months, infants do not seem to consider self-produced information as particularly predictable, although they can categorize information based on predictability (Meyer & Hunnius, 2021). Although there is evidence that the contingency categorization process only works for bodily stimuli (Filippetti et al., 2013; Zmyj et al., 2011), there is no evidence connecting this process to the explicit self. In fact, there is contradictory evidence (see **Chapter 5.1**). Also, self-produced

information does not seem to be something special for infants, who do not yet have a self-concept. Consequently, this thesis does not provide evidence for the existence of an "implicit self" in infancy.

5.3 Are Social Interactions Necessary for the "Implicit Self"?

This chapter discussed the importance of social interactions for self-development. Infants learn about the self-concept through communication, which is inherently social. However, it is currently unknown whether the categorization process identified in "implicit self"-measures is related to the self in infancy, and whether social interactions are necessary for this process. Previous research showed that infant's learning about categories is better when the information is associated with words (Yin & Csibra, 2015), suggesting that communication might also influence perceptual categorization. Additionally, embodied social interactions provide infants with contingent sensory information, which can aid in their categorization of information based on contingency.

As demonstrated in **Chapter 4** social interactions do indeed have an influence on the categorization process. All measures of social interaction discussed in **Chapter 4** are related to nonverbal communication, which is the primary channel of communication during infancy. Social touch serves as a mean of communication, particularly for expressing affects (Hertenstein, 2002). Studies have shown that temporal contingency of caregiver responses to infant signals is a significant factor in the development of language skills in infants (McGillion et al., 2013; Roseberry et al., 2014). Thus, contingency, as measured in **Chapter 4** is a communicative aspect. Additionally, sensitivity holds communicative value as infants can learn about the meaning of their actions for other people when caregivers react promptly and

appropriately to infants' signals (Carpendale & Lewis, 2021). Consistent with this, Alvarenga et al. (2021) demonstrated that maternal sensitivity is associated with maternal verbal responsiveness. Higher sensitivity appears to lead to more communication between caregiver and infant. Consequently, it would be interesting for future research to investigate whether verbal measures of caregiver communication contribute to the infant's categorization process, as **Chapter 4** demonstrated that nonverbal communication does.

At first glance, it may seem surprising that the investigated maternal characteristics have a negative impact on the infant's categorization process. The proposed approach suggests that more communication should lead to better categorization processes. However, it is important to note that these assumptions are based on an adult perspective of infant development. Having an established self-concept may be beneficial in adults life, allowing us to differentiate between our own mental states and emotions and those of others. This distinction is crucial to engage in prosocial action (Bischof-Köhler & Bischof, 2017). Having an established self-concept, we are aware of the actions that we execute ourselves and those we do not. This is important to understand for what we need to be held responsible (Sokol et al., 2015). However, in the world of infants, delaying self-development may actually be beneficial. For example, Verschoor and Hommel (2017) argue that observational learning is much easier if infants cannot differentiate between their own actions and those of others. From an attachment theory perspective, it could be argued that later self-development provides the infant with more time to engage in the regulation process of the caregiver-infant dyad. As a result, infants would have more opportunities to learn emotional regulation, which would be beneficial.

A mother who is sensitive may intuitively assist in the delay of the categorization process and/or self-development by providing highly contingent information. Sensitivity is defined as the ability to respond promptly and appropriately to the infant's signals. Therefore, the sensory information provided by a highly sensitive caregiver will not be perfectly contingent on the infant's movements, but it will be close to perfect. Infants may then have difficulty categorizing information based on contingency, as there are no clearly distinguishable categories of contingent and non-contingent information. Instead, there is information that is non-contingent from most interactions with the physical world, information that is perfectly contingent from the infant's own movement, and information that is somewhere in between from interactions with the caregiver. Caregivers who are less sensitive tend to provide information that is closer to the non-contingent category, which might help infants with the categorization process. In **Chapter 4** it was found that sensitivity was not related to the amount of touch a mother provided but that also the amount of touch decreased infants' differentiation between different contingencies. However, the same mechanism as for sensitivity may explain the relation between touch and infants' categorization process. Increased tactile interactions between a caregiver and an infant increase can lead to a blurring of categorical boundaries between contingent and non-contingent information, as the caregiver's touch has a higher likelihood on being more contingent on the infant's movements.

In conclusion, social interactions have an impact on the categorization process of infants regarding contingent and non-contingent information in infants. Since it is impossible to find infants who have never experienced social interactions,

we cannot be certain whether social interactions are necessary for the categorization process. Therefore, the best evidence we can obtain to support the claim that social interactions are necessary for the categorization process is by finding meaningful relations between social interactions and the categorization process.

5.4 Directions for Future Research

The research presented in this thesis opens several directions for future research. Conclusions from **Chapter 2** indicate that further conceptual clarification is necessary to advance the field of research on the self in infancy. Future research on the self in infancy should be very clear on the assumptions they are making.

Based on the analysis in **Chapter 2**, **Chapter 5** raises the question of whether the categorization of contingent and non-contingent information commonly used to investigate the "implicit self" in infancy, is truly an implicit measure of the self or an independent process from the explicit self. Although one study found both aspects to be independent (Klein-Radukic & Zmyj, 2020), more research on this topic is necessary. Future research should investigate the relation between the categorization process in infancy and the explicit self in toddlerhood to determine if there is a meaningful connection. Finding no relation between both aspects would pose challenges for views on the self as an entity.

However, if future research found meaningful relations between the categorization process and the explicit self, it would be interesting to investigate whether the relation is mediated by social interactions. **Chapter 4** demonstrated that social interactions influence the categorization process. This categorization process may lead to behavior that could be interpreted as indicating the presence of a self in infants, such as increased interest in contingent information. This interpretation may

prompt caregivers to treat infants as if they have a self, which could enhance their explicit self-development. Therefore, the categorization process may only be indirectly linked to self-development, mediated over social interactions.

While investigating the influence of social interactions on the development of the "implicit self", it is important to note that our study was limited to a Western and highly educated sample. It is worth considering that the nature of social interactions can vary across cultures (e.g. Kärtner et al., 2012), which may result in different versions of the self between cultures. For instance, there has been a recent discussion on whether sensitivity is universal across cultures (Keller et al., 2018; Mesman, 2018; Mesman et al., 2018). While sensitivity and touch influence infant's contingency detection in a Western sample, as demonstrated in **Chapter 4,** this may not necessarily apply to other cultural contexts.

Also, cultural assumptions about the self vary across cultures (Carpendale & Lewis, 2021; Kitcher, 2021). In this thesis, reviewed definitions of the self have mostly focused on Western approaches to the self, which define an individual in *separation* from others. However, in other cultures, the self is conceptualized in *relation* to others. For example, in some African cultures, it is assumed that whatever happens to an individual, affects all of their close relatives (Kitcher, 2021). Therefore, the self may impact individuals' lives in very different ways. Indeed, it has been shown that there are cultural differences in tests of self-recognition (Broesch et al., 2011; Kärtner et al., 2012; Sui et al., 2009) which appear to be related to differences in social interactions (Kärtner et al., 2012).

It is still uncertain whether the process of categorizing perceptual information based on its contingency or predictability, which may underlie measures of the

"implicit self", differs across cultures. Previous research has produced mixed results. While the RHI has been observed in Asian cultures and has shown similar effects as in Western cultures (Nitta et al., 2018; Shimada et al., 2009), another study tested cultural differences in an intentional binding paradigm and found that Asian participants relied less on temporal cues than Western participants (Bart et al., 2024). Cross-cultural research can help us understand the extent to which the "implicit self" is related to the explicit self. As the conceptualization of the explicit self varies across cultures, the absence of cultural differences in the "implicit self" would suggest that the two aspects are independent of each other. This finding would pose a challenge to essentialist views of the self.

In conclusion, future research should focus on two main tasks. Firstly, it should explore whether the categorization process of contingent information is related to the explicit self. This would provide insight into whether this categorization process is related to self-development at all. Second, future research should further investigate the influence of social interactions on self-development in early years. The theoretical approach outlined in **Chapter 5**, as well as various recent theories (Carpendale & Lewis, 2021; Feldman Barrett, 2017; Fotopoulou & Tsakiris, 2017a; Montirosso & McGlone, 2020; Tamis-LeMonda & Masek, 2023) emphasize the importance of social interactions for development. Empirical evidence is needed to substantiate these theories.

5.5 Conclusions

The current thesis joins recent publications (Bednarski et al., 2022; Zaadnoordijk et al., 2019) in arguing that conceptual and methodological confusions in the field of self-research are hindering scientific progress. The thesis suggests that

these confusions may stem from the misconception that the self can be measured as an entity, and proposes that viewing the self as a linguistic concept that develops within social interactions could help resolve these issues. The categorization process of information based on contingency on an individual's perception, has been suggested to be an implicit self. However, there is limited empirical evidence that this categorization is related to the self. Our study demonstrates that social interactions in infancy influence the categorization process, which might indicate the start of a bi-directional process of linguistic self-development. Infants may learn to categorize information within social interactions, which in turn may trigger caregivers to attribute a self to infants thereby teaching them the use of a self-concept.

Once established, the self-concept can impact perceptual processing, leading to the commonly found "implicit self"-effects in adult research. Infants, who do not yet have a self-concept, process perceptual information differently. An example of this is shown in this thesis. Infants do not differentiate between self-produced and predictable externally-produced information. This ability may only emerge once a self-concept is established, which influences perceptual processing.

In conclusion, research on the self in infancy encounters several challenges that must be addressed to advance scientific progress. This thesis proposes avenues for future research, particularly in clarifying the relation between "implicit self"-measures in infancy and measures of an explicit self.

6 References

Adam, M., Reitenbach, I., Papenmeier, F., Gredebäck, G., Elsner, C., & Elsner, B. (2016). Goal saliency boosts infants' action prediction for human manual actions, but not for mechanical claws. *Infant Behavior and Development*, *44*, 29–37. https://doi.org/10.1016/j.infbeh.2016.05.001

Adolph, K. E., & Hoch, J. E. (2019). Motor development: Embodied, embedded, enculturated, and enabling. *Annual Review of Psychology*, *70*, 141–164. https://doi.org/10.1146/annurev-psych-010418-102836

Ainsworth, M. D. S. (1978). *Patterns of attachment: A psychological study of the strange situation*. Erlbaum.

Alvarenga, P., Kuchirko, Y., Cerezo, M. Á., de Mendonça Filho, E. J., Bakeman, R., & Tamis-LeMonda, C. S. (2021). An intervention focused on maternal sensitivity enhanced mothers' verbal responsiveness to infants. *Journal of Applied Developmental Psychology*, *76*, 101313. https://doi.org/10.1016/j.appdev.2021.101313

Ambrosini, E., Reddy, V., de Looper, A., Costantini, M., López, B., & Sinigaglia, C. (2013). Looking ahead: Anticipatory gaze and motor ability in infancy. *PLOS ONE*, *8*(7), e67916. https://doi.org/10.1371/journal.pone.0067916

American Psychological Association. (n.d.). *Reflex*. APA dictionary of psychology. Retrieved March 9, 2022, from https://dictionary.apa.org/reflex

Aminrazavi, M. (2003). Avicenna's (Ibn Sina) phenomenological analysis of how the soul (nafs) knows itself ('Ilm Al-Huduri). In A.-T. Tymieniecka (Ed.), *The passions of the soul in the metamorphosis of becoming* (pp. 91–98). Springer. https://doi.org/10.1007/978-94-017-0229-4_7

Amsterdam, B. (1972). Mirror self-image reactions before age two. *Developmental Psychobiology*, *5*, 297–305. https://doi.org/10.1002/dev.420050403

Anisfeld, E., Casper, V., Nozyce, M., & Cunningham, N. (1990). Does infant carrying promote attachment? An experimental study of the effects of increased physical contact on the development of attachment. *Child Development*, *61*(5), 1617–1627. https://doi.org/10.1111/j.1467-8624.1990.tb02888.x

Apps, M. A. J., & Tsakiris, M. (2014). The free-energy self: A predictive coding account of self-recognition. *Neuroscience and Biobehavioral Reviews*, *41*, 85–97. https://doi.org/10.1016/j.neubiorev.2013.01.029

Asendorpf, J. B., & Baudonnière, P.-M. (1993). Self-awareness and other-awareness: Mirror self-recognition and synchronic imitation among unfamiliar peers. *Developmental Psychology*, *29*, 88–95. https://doi.org/10.1037/0012-1649.29.1.88

Aytemur, A., Lee, K.-H., & Levita, L. (2021). Neural correlates of implicit agency during the transition from adolescence to adulthood: An ERP study. *Neuropsychologia*, *158*, 107908. https://doi.org/10.1016/j.neuropsychologia.2021.107908

Bahrick, L. E., & Moss, L. (1996). Development of visual self-recognition in infancy. *Ecological Psychology*, *8*(3), 189–208. https://doi.org/10.1207/s15326969eco0803_1

Bahrick, L. E., & Watson, J. S. (1985). Detection of intermodal proprioceptive-visual contingency as a potential basis of self-perception in infancy. *Developmental Psychology*, *21*, 963–973. https://doi.org/10.1037/0012-1649.21.6.963

Bakeman, R., Quera, V., & Gnisci, A. (2009). Observer agreement for timed-event sequential data: A comparison of time-based and event-based algorithms. *Behavior Research Methods*, *41*(1), 137–147. https://doi.org/10.3758/BRM.41.1.137

Baloh, R. W. (2011). *Clinical neurophysiology of the vestibular system*. Oxford University Press. https://doi.org/10.1093/med/9780195387834.001.0001

Balslev, D., Cole, J., & Miall, R. C. (2007). Proprioception contributes to the sense of agency during visual observation of hand movements: Evidence from temporal judgments of action. *Journal of Cognitive Neuroscience*, *19*(9), 1535–1541. https://doi.org/10.1162/jocn.2007.19.9.1535

Bart, V. K. E., Sharavdorj, E., Boldbaatar, E., Bazarvaani, K., & Rieger, M. (2024). When time does not matter: Cultures differ in their use of temporal cues to infer agency over action effects. *Psychological Research*, 1–11. https://doi.org/10.1007/s00426-023-01911-y

Bäss, P., Jacobsen, T., & Schröger, E. (2008). Suppression of the auditory N1 event-related potential component with unpredictable self-initiated tones: Evidence for internal forward models with dynamic stimulation. *International Journal of Psychophysiology*, *70*(2), 137–143. https://doi.org/10.1016/j.ijpsycho.2008.06.005

Bates, E. (Ed.). (1976). *Language, Thought, and Culture*. *Language and context: The acquisition of pragmatics*. Academic Press.

Bates, E. (1994). Language about me and you: Pronominal reference and the emerging concept of self. In D. Cicchetti & M. Beeghly (Eds.), *The self in transition: Infancy to childhood* (pp. 165–182). University of Chicago Press.

Becker Razuri, E., Hiles Howard, A. R., Purvis, K. B., & Cross, D. R. (2017). Mental state language development: The longitudinal roles of attachment and maternal language. *Infant Mental Health Journal*, *38*(3), 329–342. https://doi.org/10.1002/imhj.21638

Bednarski, F. M., Musholt, K., & Grosse Wiesmann, C. (2022). Do infants have agency? The importance of control for the study of early agency. *Developmental Review*, *64*, 101022. https://doi.org/10.1016/j.dr.2022.101022

Bennett, M. R., & Hacker, P. M. S. (2003). *Philosophical foundations of neuroscience*. Blackwell Publishing.

Berger, A., & Posner, M. I. (2023). Beyond infant's looking: The neural basis for infant prediction errors. *Perspectives on Psychological Science*, *18*(3), 664–674. https://doi.org/10.1177/17456916221112918

Berlucchi, G., & Aglioti, S. (1997). The body in the brain: Neural bases of corporeal awareness. *Trends in Neurosciences*, *20*(12), 560–564. https://doi.org/10.1016/s0166-2236(97)01136-3

Bigelow, A. E. (1981). The correspondence between self- and image movement as a cue to self-recognition for young children. *The Journal of Genetic Psychology*, *139*(11-26). https://doi.org/10.1080/00221325.1981.10533432

Bigelow, A. E. (2001). Discovering self through other: Infants' preference for social contingency. *Bulletin of the Menninger Clinic*, *65*(3), 335–346. https://doi.org/10.1521/bumc.65.3.335.19852

Biringen, Z. (2008). *The emotional availability (EA) scales: Infancy/early childhood version (child age: 0–5 years)* (4th ed.). emotionalavailability.com.

Biringen, Z., Derscheid, D., Vliegen, N., Closson, L., & Easterbrooks, M. A. (2014). Emotional availability (EA): Theoretical background, empirical research using the EA Scales, and clinical applications. *Developmental Review*, *34*, 114–167. https://doi.org/10.1016/j.dr.2014.01.002

Bischof-Köhler, D. (2011). *Soziale Entwicklung in Kindheit und Jugend: Bindung, Empathie, Theory of Mind*. Kohlhammer Verlag.

Bischof-Köhler, D., & Bischof, N. (2017). Self-recognition, empathy, and concern for others in toddlers. In N. Roughley & T. Schramme (Eds.), *Forms of fellow feeling: Empathy, sympathy, concern and moral agency* (pp. 78–106). Cambridge University Press. https://doi.org/10.1017/9781316271698.003

Björnsdotter, M., Gordon, I., Pelphrey, K. A., Olausson, H., & Kaiser, M. D. (2014). Development of brain mechanisms for processing affective touch. *Frontiers in Behavioral Neuroscience*, *8*, 24. https://doi.org/10.3389/fnbeh.2014.00024

Blakemore, S. J., Frith, C. D., & Wolpert, D. M. (1999). Spatio-temporal prediction modulates the perception of self-produced stimuli. *Journal of Cognitive Neuroscience*, *11*(5), 551–559. https://doi.org/10.1162/089892999563607

Blakey, E., Tecwyn, E. C., McCormack, T., Lagnado, D. A., Hoerl, C., Lorimer, S., & Buehner, M. J. (2019). When causality shapes the experience of time: Evidence for temporal binding in young children. *Developmental Science*, *22*(3), e12769. https://doi.org/10.1111/desc.12769

Blanke, O. (2012). Multisensory brain mechanisms of bodily self-consciousness. *Nature Reviews. Neuroscience*, *13*(8), 556–571. https://doi.org/10.1038/nrn3292

Borhani, K., Beck, B., & Haggard, P. (2017). Choosing, doing, and controlling: Implicit sense of agency over somatosensory events. *Psychological Science*, *28*(7), 882–893. https://doi.org/10.1177/0956797617697693

Botvinick, M., & Cohen, J. (1998). Rubber hands 'feel' touch that eyes see. *Nature*, *391*(6669), 756. https://doi.org/10.1038/35784

Bowlby, J. (1969). *Attachment and loss*. Hogarth.

Brauer, J., Xiao, Y., Poulain, T., Friederici, A. D., & Schirmer, A. (2016). Frequency of maternal touch predicts resting activity and connectivity of the developing social brain. *Cerebral Cortex*, *26*(8), 3544–3552. https://doi.org/10.1093/cercor/bhw137

Bremner, A. J., & Spence, C. (2017). The development of tactile perception. In J. B. Benson (Ed.), *Advances in Child Development and Behavior* (Vol. 52, pp. 227–268). Elsevier Science. https://doi.org/10.1016/bs.acdb.2016.12.002

Bretherton, I. (1993). From dialogue to internal working models: The co-construction of self in relationships. In C. Nelson (Ed.), *Memory and affect in development: The Minnesota symposia on child psychology* (pp. 237–263). Lawrence Erlbaum Associates.

Broesch, T., Callaghan, T., Henrich, J., Murphy, C., & Rochat, P. R. (2011). Cultural variations in children's mirror self-recognition. *Journal of Cross-Cultural Psychology*, *42*(6), 1018–1029. https://doi.org/10.1177/0022022110381114

Brownell, C. A., Nichols, S. R., Svetlova, M., Zerwas, S., & Ramani, G. B. (2010). The head bone's connected to the neck bone: When do toddlers represent their own body topography? *Child Development*, *81*(3), 797–810. https://doi.org/10.1111/j.1467-8624.2010.01434.x

Bulgarelli, C., Blasi, A., de Klerk, C. C. J. M., Richards, J. E., Hamilton, A., & Southgate, V. (2019). Fronto-temporoparietal connectivity and self-awareness in 18-month-olds: A resting state fNIRS study. *Developmental Cognitive Neuroscience*, *38*, 100676. https://doi.org/10.1016/j.dcn.2019.100676

Burin, D., Pyasik, M., Ronga, I., Cavallo, M., Salatino, A., & Pia, L. (2018). "As long as that is my hand, that willed action is mine": Timing of agency triggered by body ownership. *Consciousness and Cognition*, *58*, 186–192. https://doi.org/10.1016/j.concog.2017.12.005

Butterworth, G. (1992). Origins of self-perception in infancy. *Psychological Inquiry*, *3*(2), 103–111. https://doi.org/10.1207/s15327965pli0302_1

Butterworth, G. (1994). Self-perception in infancy. In D. Cicchetti & M. Beeghly (Eds.), *The self in transition: Infancy to childhood* (pp. 119–138). University of Chicago Press.

Butterworth, G., & Cicchetti, D. (1978). Visual calibration of posture in normal and motor retarded Down's syndrome infants. *Perception*, *7*(5), 513–525. https://doi.org/10.1068/p070513

Carpendale, J. I. M. (2018). Communication as the coordination of activity: The implications of philosophical preconceptions for theories of the development of communication. In A. S. Dick & U. Müller (Eds.), *Advancing developmental science: Philosophy, theory, and method* (pp. 145–156). Routledge.

Carpendale, J. I. M., & Lewis, C. (2004). Constructing an understanding of mind: The development of children's social understanding within social interaction. *The Behavioral and Brain Sciences*, *27*(1), 79-96. https://doi.org/10.1017/s0140525x04000032

Carpendale, J. I. M., & Lewis, C. (2021). *What makes us human: How minds develop through social interactions*. Routledge.

Chambon, V., & Haggard, P. (2012). Sense of control depends on fluency of action selection, not motor performance. *Cognition*, *125*(3), 441–451. https://doi.org/10.1016/j.cognition.2012.07.011

Ciaunica, A., Constant, A., Preissl, H., & Fotopoulou, A. K. (2021). The first prior: From co-embodiment to co-homeostasis in early life. *Consciousness and Cognition*, *91*, 103117. https://doi.org/10.1016/j.concog.2021.103117

Ciaunica, A., & Crucianelli, L. (2019). Minimal self-awareness: From within a developmental perspective. *Journal of Consciousness Studies*, *26*(3-4), 207-226.

Ciaunica, A., & Fotopoulou, A. K. (2017). The touched self: Psychological and philosophical perspectives on proximal intersubjectivity and the self. In C. Durt, T. Fuchs, & C. Tewes (Eds.), *Embodiment, enaction, and culture: Investigating the constitution of the shared world* (pp. 173–192). MIT Press.

Cimpian, A., Hammond, M. D., Mazza, G., & Corry, G. (2017). Young children's self-concepts include representations of abstract traits and the global self. *Child Development*, *88*(6), 1786–1798. https://doi.org/10.1111/cdev.12925

Collie, R., & Hayne, H. (1999). Deferred imitation by 6- and 9-month-old infants: More evidence for declarative memory. *Developmental Psychobiology*, *35*(2), 83–90. https://doi.org/10.1002/(SICI)1098-2302(199909)35:2<83::AID-DEV1>3.0.CO;2-S

Colonnesi, C., Bögels, S. M., Vente, W. de, & Majdandžić, M. (2013). What coy smiles say about positive shyness in early infancy. *Infancy*, *18*(2), 202–220. https://doi.org/10.1111/j.1532-7078.2012.00117.x

Coltheart, M. (2013). How can functional neuroimaging inform cognitive theories? *Perspectives on Psychological Science*, *8*(1), 98–103. https://doi.org/10.1177/1745691612469208

Cowie, D., McKenna, A., Bremner, A. J., & Aspell, J. E. (2018). The development of bodily self-consciousness: Changing responses to the Full Body Illusion in childhood. *Developmental Science*, *21*(3), e12557. https://doi.org/10.1111/desc.12557

Crucianelli, L., Metcalf, N. K., Fotopoulou, A. K., & Jenkinson, P. M. (2013). Bodily pleasure matters: Velocity of touch modulates body ownership during the rubber hand illusion. *Frontiers in Psychology*, *4*, 703. https://doi.org/10.3389/fpsyg.2013.00703

Crucianelli, L., Wheatley, L., Filippetti, M. L., Jenkinson, P. M., Kirk, E., & Fotopoulou, A. K. (2019). The mindedness of maternal touch: An investigation of maternal mind-mindedness and mother-infant touch interactions. *Developmental Cognitive Neuroscience*, *35*, 47–56. https://doi.org/10.1016/j.dcn.2018.01.010

Csibra, G., & Johnson, M. H. (2007). Investigating event-related oscillations in infancy. In M. de Haan (Ed.), *Infant EEG and event-related potentials* (pp. 289–305). Psychology Press.

Damon, W., & Hart, D. (1982). The development of self-understanding from infancy through adolescence. *Child Development*, *53*(4), 841–864. https://doi.org/10.2307/1129122

de Klerk, C. C. J. M., Filippetti, M. L., & Rigato, S. (2021). The development of body representations: An associative learning account. *Proceedings of the Royal Society B: Biological Sciences*, *288*(1949), 20210070. https://doi.org/10.1098/rspb.2021.0070

de Klerk, C. C. J. M., Hamilton, A., & Southgate, V. (2018). Eye contact modulates facial mimicry in 4-month-old infants: An EMG and fNIRS study. *Cortex*, *106*, 93–103. https://doi.org/10.1016/j.cortex.2018.05.002

de León, L. (2023). Socialization of attention. In A. Duranti, R. George, & R. Conley Riner (Eds.), *A new companion to linguistic anthropology* (pp. 410–427). John Wiley & Sons.

Della Longa, L., Filippetti, M. L., Dragovic, D., & Farroni, T. (2019). Synchrony of caresses: Does affective touch help infants to detect body-related visual-tactile synchrony? *Frontiers in Psychology*, *10*, 2944. https://doi.org/10.3389/fpsyg.2019.02944

Deroy, O., & Battich, L. (2022). *The neuroscience & philosophy of personal identity.* Ludwig-Maximilians-Universität München, München.

Descartes, R. (1641). *Meditationes de prima philosophia, in qua Dei existentia et animae immortalitas demonstratur.*

Dewey, J. A., & Knoblich, G. (2014). Do implicit and explicit measures of the sense of agency measure the same thing? *PLOS ONE*, *9*(10), e110118. https://doi.org/10.1371/journal.pone.0110118

Di Lorenzo, R., Pirazzoli, L., Blasi, A., Bulgarelli, C., Hakuno, Y., Minagawa, Y., & Brigadoi, S. (2019). Recommendations for motion correction of infant fNIRS data applicable to multiple data sets and acquisition systems. *NeuroImage*, *200*, 511–527. https://doi.org/10.1016/j.neuroimage.2019.06.056

Dieguez, S. (2018). The illusion illusion. *Constructivist Foundations*, *14*(1), 108–110.

Duschinsky, R., & Solomon, J. (2017). Infant disorganized attachment: Clarifying levels of analysis. *Clinical Child Psychology and Psychiatry*, *22*(4), 524–538. https://doi.org/10.1177/1359104516685602

Egan, S., Ghio, M., & Bellebaum, C. (2023). Auditory N1 and P2 attenuation in action observation: An event-related potential study considering effects of temporal predictability and individualism. *Biological Psychology*, *180*, 108575. https://doi.org/10.1016/j.biopsycho.2023.108575

Elsner, B. (2007). Infants' imitation of goal-directed actions: The role of movements and action effects. *Acta Psychologica*, *124*(1), 44–59. https://doi.org/10.1016/j.actpsy.2006.09.006

Essler, S., Becher, T., Pletti, C., Gniewosz, B., & Paulus, M. (2023). Longitudinal evidence that infants develop their imitation abilities by being imitated. *Current Biology*, *33*(21), 4674–4678. https://doi.org/10.1016/j.cub.2023.08.084

Feldman Barrett, L. (2017). *How emotions are made: The secret life of the brain*. MacMillan.

Filippetti, M. L. (2021). Being in tune with your body: The emergence of interoceptive processing through caregiver-infant feeding interactions. *Child Development Perspectives*, *15*(3). https://doi.org/10.1111/cdep.12420

Filippetti, M. L., & Crucianelli, L. (2019). If I were a grown up: Children's response to the rubber hand illusion with different hand sizes. *Journal of Experimental Child Psychology*, *185*, 191–205. https://doi.org/10.1016/j.jecp.2019.04.016

Filippetti, M. L., Johnson, M. H., Lloyd-Fox, S., Dragovic, D., & Farroni, T. (2013). Body perception in newborns. *Current Biology*, *23*(23), 2413–2416. https://doi.org/10.1016/j.cub.2013.10.017

Filippetti, M. L., Lloyd-Fox, S., Longo, M. R., Farroni, T., & Johnson, M. H. (2015). Neural mechanisms of body awareness in infants. *Cerebral Cortex*, *25*(10), 3779–3787. https://doi.org/10.1093/cercor/bhu261

Fonagy, P., & Target, M. (2007). The rooting of the mind in the body: New links between attachment theory and psychoanalytic thought. *Journal of the American Psychoanalytic Association*, *55*(2), 411–456. https://doi.org/10.1177/00030651070550020501

Forch, V., & Hamker, F. H. (2021). Building and understanding the minimal self. *Frontiers in Psychology*, *12*, 716982. https://doi.org/10.3389/fpsyg.2021.716982

Fotopoulou, A. K., & Tsakiris, M. (2017a). Mentalizing homeostasis: The social origins of interoceptive inference. *Neuropsychoanalysis*, *19*(1), 3–28. https://doi.org/10.1080/15294145.2017.1294031

Fotopoulou, A. K., & Tsakiris, M. (2017b). Mentalizing homeostasis: The social origins of interoceptive inference - Replies to Commentaries. *Neuropsychoanalysis*, *19*(1), 71–76. https://doi.org/10.1080/15294145.2017.1307667

Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *360*(1456), 815–836. https://doi.org/10.1098/rstb.2005.1622

Frith, C. D. (2005). The self in action: Lessons from delusions of control. *Consciousness and Cognition*, *14*(4), 752–770. https://doi.org/10.1016/j.concog.2005.04.002

Frith, C. D., Blakemore, S. J., & Wolpert, D. M. (2000). Abnormalities in the awareness and control of action. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*, *355*(1404), 1771–1788. https://doi.org/10.1098/rstb.2000.0734

Gallagher, S. (2000). Philosophical conceptions of the self: Implications for cognitive science. *Trends in Cognitive Sciences*, *4*, 14–21. https://doi.org/10.1016/S1364-6613(99)01417-5

Gallagher, S., & Zahavi, D. (2010). *The phenomenological mind*. Taylor and Francis.

Gecas, V. (1982). The self-concept. *Annual Review of Sociology*, *8*(1), 1–33. https://doi.org/10.1146/annurev.so.08.080182.000245

Gergely, G. (2003). The development of understanding self and agency. In U. Goswami (Ed.), *Blackwell handbook of childhood cognitive development* (pp. 26–46). Blackwell Publishing.

Gergely, G., Koós, O., & Watson, J. S. (2010). Contingent parental reactivity in early socio-emotional development. In T. Fuchs, H. Sattel, & P. Henningsen (Eds.), *The embodied self: Dimensions, coherence and disorders* (pp. 141–168). Schattauer Verlag.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Houghton Mifflin. https://doi.org/10.4324/9781315740218

Gillihan, S. J., & Farah, M. J. (2005). Is self special? A critical review of evidence from experimental psychology and cognitive neuroscience. *Psychological Bulletin*, *131*(1), 76–97. https://doi.org/10.1037/0033-2909.131.1.76

Goldberg, M., Busch, N., & van der Meer, E. (2017). The amount of recent action-outcome coupling modulates the mechanisms of the intentional binding effect: A behavioral and ERP study. *Consciousness and Cognition*, *56*, 135–149. https://doi.org/10.1016/j.concog.2017.07.001

Gottwald, J. M., Bird, L.-A., Keenaghan, S., Diamond, C., Zampieri, E., Tosodduk, H., Bremner, A. J., & Cowie, D. (2021). The developing bodily self: How posture constrains body representation in childhood. *Child Development*, *92*(1), 351–366. https://doi.org/10.1111/cdev.13425

Haan, M. de. (2007). Visual attention and recognition memory in infancy. In M. de Haan (Ed.), *Infant EEG and event-related potentials* (pp. 101–144). Psychology Press.

Haggard, P., Clark, S., & Kalogeras, J. (2002). Voluntary action and conscious awareness. *Nature Neuroscience*, *5*(4), 382–385. https://doi.org/10.1038/nn827

Haith, M. M. (1998). Who put the cog in infant cognition? Is rich interpretation too costly? *Infant Behavior and Development*, *21*(2), 167–179. https://doi.org/10.1016/S0163-6383(98)90001-7

Hakuno, Y., Hata, M., Naoi, N., Hoshino, E., & Minagawa, Y. (2020). Interactive live fNIRS reveals engagement of the temporoparietal junction in response to

social contingency in infants. *NeuroImage*, *218*, 116901. https://doi.org/10.1016/j.neuroimage.2020.116901

Hakuno, Y., Pirazzoli, L., Blasi, A., Johnson, M. H., & Lloyd-Fox, S. (2018). Optical imaging during toddlerhood: Brain responses during naturalistic social interactions. *Neurophotonics*, *5*(01), 1. https://doi.org/10.1117/1.NPh.5.1.011020

Hammond, S. I., Bibok, M., & Carpendale, J. I. M. (2010). Theoretical perspectives on self and social regulation. In B. W. Sokol, U. Müller, J. I. M. Carpendale, A. Young, & G. Iarocci (Eds.), *Self- and social-regulation: The development of social interaction, social understanding, and executive functions* (pp. 1–7). Oxford University Press.

Han, N., Jack, B. N., Hughes, G., & Whitford, T. J. (2022). The role of action-effect contingency on sensory attenuation in the absence of movement. *Journal of Cognitive Neuroscience*, *34*(8), 1488–1499. https://doi.org/10.1162/jocn_a_01867

Harel, J., Eshel, Y., Ganor, O., & Scher, A. (2002). Antecedents of mirror self-recognition of toddlers: Emotional availability, birth order, and gender. *Infant Mental Health Journal*, *23*(3), 293–309. https://doi.org/10.1002/imhj.10016

Harel, J., Oppenheim, D., Tirosh, E., & Gini, M. (1999). Associations between mother-child interaction and children's later self and mother feature knowledge. *Infant Mental Health Journal*, *20*(2), 123–137. https://doi.org/10.1002/(SICI)1097-0355(199922)20:2<123::AID-IMHJ1>3.0.CO;2-I

Harrison, A. W., Mannion, D. J., Jack, B. N., Griffiths, O., Hughes, G., & Whitford, T. J. (2021). Sensory attenuation is modulated by the contrasting effects of predictability and control. *NeuroImage*, *237*, 118103. https://doi.org/10.1016/j.neuroimage.2021.118103

Harter, S. (2012). *The construction of the self: Developmental and sociocultural foundations*. Guilford Press.

Hauf, P. (2007). Infants' perception and production of intentional actions. *Progress in Brain Research*, *164*, 285–301. https://doi.org/10.1016/S0079-6123(07)64016-3

Hauf, P., & Aschersleben, G. (2008). Action-effect anticipation in infant action control. *Psychological Research*, *72*(2), 203–210. https://doi.org/10.1007/s00426-006-0101-3

Heilbron, M., & Chait, M. (2018). Great expectations: Is there evidence for predictive coding in auditory cortex? *Neuropsychoanalysis*, *389*, 54–73. https://doi.org/10.1016/j.neuroscience.2017.07.061

Hertenstein, M. J. (2002). Touch: Its communicative functions in infancy. *Human Development*, *45*(2), 70–94. https://doi.org/10.1159/000048154

Hesse, E. (2008). The adult attachment interview: Protocol, method of analysis, and empirical studies. In J. Cassidy & P. R. Shaver (Eds.), *Handbook of attachment: Theory, research, and clinical applications* (pp. 552–598). The Guilford Press.

Hoffman, M. L. (2007). *Empathy and moral development: Implications for caring and justice*. Cambridge University Press.

Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, *8*(11), 494–500. https://doi.org/10.1016/j.tics.2004.08.007

Hommel, B. (2009). Action control according to TEC (theory of event coding). *Psychological Research*, *73*(4), 512–526. https://doi.org/10.1007/s00426-009-0234-2

Hommel, B. (2015). Action control and the sense of agency. In P. Haggard & B. Eitam (Eds.), *The sense of agency* (pp. 307–326). Oxford University Press.

Hommel, B. (2018). Representing oneself and others: An event-coding approach. *Experimental Psychology*, *65*(6), 323–331. https://doi.org/10.1027/1618-3169/a000433

Hommel, B. (2021). The me-file: An event-coding approach to self-representation. *Frontiers in Psychology*, *12*, 698778. https://doi.org/10.3389/fpsyg.2021.698778

Hommel, B., Müsseler, J., Aschersleben, G., & Prinz, W. (2001). The theory of event coding (TEC): A framework for perception and action planning. *The Behavioral and Brain Sciences*, *24*(5), 849-78. https://doi.org/10.1017/s0140525x01000103

Horváth, J. (2015). Action-related auditory ERP attenuation: Paradigms and hypotheses. *Brain Research*, *1626*, 54–65. https://doi.org/10.1016/j.brainres.2015.03.038

Hughes, G., Desantis, A., & Waszak, F. (2013a). Attenuation of auditory N1 results from identity-specific action-effect prediction. *The European Journal of Neuroscience*, *37*(7), 1152–1158. https://doi.org/10.1111/ejn.12120

Hughes, G., Desantis, A., & Waszak, F. (2013b). Mechanisms of intentional binding and sensory attenuation: The role of temporal prediction, temporal control, identity prediction, and motor prediction. *Psychological Bulletin*, *139*(1), 133–151. https://doi.org/10.1037/a0028566

Huppert, T. J., Diamond, S. G., Franceschini, M. A., & Boas, D. A. (2009). Homer: A review of time-series analysis methods for near-infrared spectroscopy of the brain. *Applied Optics*, *48*(10), D280-98. https://doi.org/10.1364/ao.48.00d280

Hyde, D. C., Jones, B. L., Porter, C. L., & Flom, R. (2010). Visual stimulation enhances auditory processing in 3-month-old infants and adults. *Developmental Psychobiology*, *52*(2), 181–189. https://doi.org/10.1002/dev.20417

Ionta, S., Heydrich, L., Lenggenhager, B., Mouthon, M., Fornari, E., Chapuis, D., Gassert, R., & Blanke, O. (2011). Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron*, *70*(2), 363–374. https://doi.org/10.1016/j.neuron.2011.03.009

James, W. (1890). *The principles of psychology*. Henry Holt and Company.

Jönsson, E. H., Kotilahti, K., Heiskala, J., Wasling, H. B., Olausson, H., Croy, I., Mustaniemi, H., Hiltunen, P., Tuulari, J. J., Scheinin, N. M., Karlsson, L., Karlsson, H., & Nissilä, I. (2018). Affective and non-affective touch evoke differential brain responses in 2-month-old infants. *NeuroImage*, *169*, 162–171. https://doi.org/10.1016/j.neuroimage.2017.12.024

Jopling, D. (1994). Cognitive science, other minds, and the philosophy of dialogue. In U. Neisser (Ed.), *The perceived self: Ecological and interpersonal sources of self-knowledge* (pp. 290–309). Cambridge University Press.

Kagan, J. (1998). Is there a self in infancy? In R. J. Sternberg & M. Ferrari (Eds.), *Self-awareness: Its nature and development* (pp. 137–147). Guilford Press.

Kagan, J., Mount, R., Hiatt, S., Linn, S., Reznick, J. S., Richman, C. L., & Katz, M. M. (1981). *The second year: The emergence of self-awareness*. Harvard University Press. https://doi.org/10.4159/harvard.9780674181410

Kaiser, J., & Schütz-Bosbach, S. (2018). Sensory attenuation of self-produced signals does not rely on self-specific motor predictions. *The European Journal of Neuroscience*, *47*(11), 1303–1310. https://doi.org/10.1111/ejn.13931

Kärtner, J., Keller, H., Chaudhary, N., & Yovsi, R. D. (2012). The development of mirror self-recognition in different sociocultural contexts. *Monographs of the Society for Research in Child Development*, *77*(4), i-101. http://www.jstor.org/stable/23361846

Kayhan, E., Meyer, M., O'Reilly, J. X., Hunnius, S., & Bekkering, H. (2019). Nine-month-old infants update their predictive models of a changing environment. *Developmental Cognitive Neuroscience*, *38*, 100680. https://doi.org/10.1016/j.dcn.2019.100680

Keller, H., Bard, K., Morelli, G., Chaudhary, N., Vicedo, M., Rosabal-Coto, M., Scheidecker, G., Murray, M., & Gottlieb, A. (2018). The myth of universal sensitive responsiveness: Comment on Mesman et al. (2017). *Child Development*, *89*(5), 1921–1928. https://doi.org/10.1111/cdev.13031

Keller, H., Kärtner, J., Borke, J., Yovsi, R., & Kleis, A. (2005). Parenting styles and the development of the categorical self: A longitudinal study on mirror self-recognition in Cameroonian Nso and German families. *International Journal*

of Behavioral Development, *29*, 496–504. https://doi.org/10.1080/01650250500147485

Keller, H., Lohaus, A., Volker, S., Cappenberg, M., & Chasiotis, A. (1999). Temporal contingency as an independent component of parenting behavior. *Child Development*, *70*(2), 474–485. https://doi.org/10.1111/1467-8624.00034

Kim Koh, J. B., & Wang, Q. (2012). Self-development. *Wiley Interdisciplinary Reviews: Cognitive Science*, *3*(5), 513–524. https://doi.org/10.1002/wcs.1187

Kitcher, P. (2021). Introduction. In P. Kitcher (Ed.), *The self: A history* (pp. 1–27). Oxford University Press. https://doi.org/10.1093/oso/9780190087265.003.0001

Klaffehn, A. L., Baess, P., Kunde, W., & Pfister, R. (2019). Sensory attenuation prevails when controlling for temporal predictability of self- and externally generated tones. *Neuropsychologia*, *132*, 107145. https://doi.org/10.1016/j.neuropsychologia.2019.107145

Klein-Radukic, S., & Zmyj, N. (2020). No evidence for infants' contingency detection as a precursor of toddlers' self-recognition. *Infant Behavior and Development*, *60*, 101459. https://doi.org/10.1016/j.infbeh.2020.101459

Kogo, N., & Trengove, C. (2015). Is predictive coding theory articulated enough to be testable? *Frontiers in Computational Neuroscience*, *9*, 111. https://doi.org/10.3389/fncom.2015.00111

Kohda, M., Sogawa, S., Jordan, A. L., Kubo, N., Awata, S., Satoh, S., Kobayashi, T., Fujita, A., & Bshary, R. (2022). Further evidence for the capacity of mirror self-recognition in cleaner fish and the significance of ecologically relevant marks. *PLOS Biology*, *20*(2), e3001529. https://doi.org/10.1371/journal.pbio.3001529

Kollakowski, N.-A., Mammen, M., & Paulus, M. (2023). What is the implicit self in infancy? A classification and evaluation of current theories on the early self. *Cognitive Development*, *68*, 101394. https://doi.org/10.1016/j.cogdev.2023.101394

Kontaris, I., Wiggett, A. J., & Downing, P. E. (2009). Dissociation of extrastriate body and biological-motion selective areas by manipulation of visual-motor congruency. *Neuropsychologia*, *47*(14), 3118–3124. https://doi.org/10.1016/j.neuropsychologia.2009.07.012

Korka, B., Widmann, A., Waszak, F., Darriba, Á., & Schröger, E. (2022). The auditory brain in action: Intention determines predictive processing in the auditory system - A review of current paradigms and findings. *Psychonomic Bulletin & Review*, *29*(2), 321–342. https://doi.org/10.3758/s13423-021-01992-z

Kristen-Antonow, S., Sodian, B., Perst, H., & Licata, M. (2015). A longitudinal study of the emerging self from 9 months to the age of 4 years. *Frontiers in Psychology*, *6*, 789. https://doi.org/10.3389/fpsyg.2015.00789

Kühn, S., Nenchev, I., Haggard, P., Brass, M., Gallinat, J., & Voss, M. (2011). Whodunnit? Electrophysiological correlates of agency judgements. *PLOS ONE*, *6*(12), e28657. https://doi.org/10.1371/journal.pone.0028657

Kushnerenko, E., Ceponiene, R., Balan, P., Fellman, V., Huotilainen, M., & Näätänen, R. (2002). Maturation of the auditory event-related potentials during the first year of life. *NeuroReport*, *13*(1), 47.

Lähteenmäki, V. (2021). Descartes on subjects and selves. In P. Kitcher (Ed.), *The self: A history* (pp. 99–117). Oxford University Press. https://doi.org/10.1093/oso/9780190087265.003.0005

Lee, L., Ma, W., & Kammers, M. (2021). The rubber hand illusion in children: What are we measuring? *Behavior Research Methods*, *53*(6), 2615–2630. https://doi.org/10.3758/s13428-021-01600-x

Leube, D. T., Knoblich, G., Erb, M., Grodd, W., Bartels, M., & Kircher, T. T. J. (2003). The neural correlates of perceiving one's own movements. *NeuroImage*, *20*(4), 2084–2090. https://doi.org/10.1016/j.neuroimage.2003.07.033

Lewis, E., & Ramsay, D. (2004). Development of self-recognition, personal pronoun use, and pretend play during the 2nd year. *Child Development*, *75*(6), 1821–1831. https://doi.org/10.1111/j.1467-8624.2004.00819.x

Lewis, M. (1979). *Social cognition and the acquisition of self*. Plenum Press.

Lewis, M., Brooks-Gunn, J., & Jaskir, J. (1985). Individual differences in visual self-recognition as a function of mother-infant attachment relationship. *Developmental Psychology*, *21*(6), 1181–1187. https://doi.org/10.1037/0012-1649.21.6.1181

Lewis, M., Sullivan, M. W., Stanger, C., & Weiss, M. (1989). Self development and self-conscious emotions. *Child Development*, *60*(1), 146. https://doi.org/10.2307/1131080

Lewkowicz, D. J. (1996). Perception of auditory-visual temporal synchrony in human infants. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(5), 1094–1106. https://doi.org/10.1037/0096-1523.22.5.1094

Licata, M., Paulus, M., Thoermer, C., Kristen, S., Woodward, A. L., & Sodian, B. (2014). Mother-infant interaction quality and infants' ability to encode actions as

goal-directed. *Social Development*, *23*(2), 340–356. https://doi.org/10.1111/sode.12057

Liesner, M., Hinz, N.-A., & Kunde, W. (2021). How action shapes body ownership momentarily and throughout the lifespan. *Frontiers in Human Neuroscience*, *15*, 697810. https://doi.org/10.3389/fnhum.2021.697810

Limanowski, J., & Blankenburg, F. (2013). Minimal self-models and the free energy principle. *Frontiers in Human Neuroscience*, *7*, 547. https://doi.org/10.3389/fnhum.2013.00547

Lipschits, O., & Geva, R. (2024). An integrative model of parent-infant communication development. *Child Development Perspectives.* Advance online publication. https://doi.org/10.1111/cdep.12507

Lloyd, D. M., Gillis, V., Lewis, E., Farrell, M. J., & Morrison, I. (2013). Pleasant touch moderates the subjective but not objective aspects of body perception. *Frontiers in Behavioral Neuroscience*, *7*, 207. https://doi.org/10.3389/fnbeh.2013.00207

Lloyd-Fox, S., Széplaki-Köllőd, B., Yin, J., & Csibra, G. (2015). Are you talking to me? Neural activations in 6-month-old infants in response to being addressed during natural interactions. *Cortex*, *70*, 35–48. https://doi.org/10.1016/j.cortex.2015.02.005

Lobo, L., Heras-Escribano, M., & Travieso, D. (2018). The history and philosophy of ecological psychology. *Frontiers in Psychology*, *9*, 2228. https://doi.org/10.3389/fpsyg.2018.02228

Lockman, J. J., & Kahrs, B. A. (2017). New insights into the development of human tool use. *Current Directions in Psychological Science*, *26*(4), 330–334. https://doi.org/10.1177/0963721417692035

Long, M., Verbeke, W., Ein-Dor, T., & Vrtička, P. (2020). A functional neuro-anatomical model of human attachment (NAMA): Insights from first- and second-person social neuroscience. *Cortex*, *126*, 281–321. https://doi.org/10.1016/j.cortex.2020.01.010

Ma, K., Qu, J., Yang, L., Zhao, W., & Hommel, B. (2021). Explicit and implicit measures of body ownership and agency: Affected by the same manipulations and yet independent. *Experimental Brain Research*, *239*(7), 2159–2170. https://doi.org/10.1007/s00221-021-06125-5

Mahler, M. S., Pine, F., & Bergman, A. (1985). *The psychological birth of the human infant: Symbiosis and individuation*. Routledge. https://doi.org/10.4324/9780429482915

Maister, L., Hodossy, L., Tsakiris, M., & Shinskey, J. L. (2020). Self or (m)other? Infants' sensitivity to bodily overlap with their mother reflects their dyadic coordination. *Child Development*, *91*(5), 1631–1649. https://doi.org/10.1111/cdev.13361

Maister, L., Tang, T., & Tsakiris, M. (2017). Neurobehavioral evidence of interoceptive sensitivity in early infancy. *ELife*, *6.* https://doi.org/10.7554/eLife.25318

Mandler, J. M. (1988). How to build a baby: On the development of an accessible representational system. *Cognitive Development*, *3*(2), 113–136. https://doi.org/10.1016/0885-2014(88)90015-9

Marinović, V., Hoehl, S., & Pauen, S. (2014). Neural correlates of human-animal distinction: An ERP-study on early categorical differentiation with 4- and 7-month-old infants and adults. *Neuropsychologia*, *60*, 60–76. https://doi.org/10.1016/j.neuropsychologia.2014.05.013

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). Opensesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

McGillion, M. L., Herbert, J. S., Pine, J. M., Keren-Portnoy, T., Vihman, M. M., & Matthews, D. E. (2013). Supporting early vocabulary development: What sort of responsiveness matters? *IEEE Transactions on Autonomous Mental Development*, *5*(3), 240–248. https://doi.org/10.1109/TAMD.2013.2275949

Mcquaid, N., Bigelow, A. E., McLaughlin, J., & MacLean, K. (2008). Maternal mental state language and preschool children's attachment security: Relation to children's mental state language and expressions of emotional understanding. *Social Development*, *17*(1), 61–83. https://doi.org/10.1111/j.1467-9507.2007.00415.x

Mead, G. H. (1934). *Mind, self and society*. University of Chicago Press.

Medin, D., & Ortony, A. (1989). Comments on part I: Psychological essentialism. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 179–196). Cambridge University Press. https://doi.org/10.1017/CBO9780511529863.009

Meltzoff, A. N. (2007a). 'like me': A foundation for social cognition. *Developmental Science*, *10*(1), 126–134. https://doi.org/10.1111/j.1467-7687.2007.00574.x

Meltzoff, A. N. (2007b). The 'like me' framework for recognizing and becoming an intentional agent. *Acta Psychologica*, *124*(1), 26–43. https://doi.org/10.1016/j.actpsy.2006.09.005

Meltzoff, A. N., & Moore, M. K. (1977). Imitation of facial and manual gestures by human neonates. *Science*, *198*(4312), 75–78. https://doi.org/10.1126/science.198.4312.75

Mermelshtine, R. (2017). Parent-child learning interactions: A review of the literature on scaffolding. *The British Journal of Educational Psychology*, *87*(2), 241–254. https://doi.org/10.1111/bjep.12147

Mesman, J. (2018). Sense and sensitivity: A response to the commentary by Keller et al. (2018). *Child Development*, *89*(5), 1929–1931. https://doi.org/10.1111/cdev.13030

Mesman, J., Minter, T., Angnged, A., Cissé, I. A. H., Salali, G. D., & Migliano, A. B. (2018). Universality without uniformity: A culturally inclusive approach to sensitive responsiveness in infant caregiving. *Child Development*, *89*(3), 837–850. https://doi.org/10.1111/cdev.12795

Metzinger, T. (2011). The no-self alternative. In S. Gallagher (Ed.), *The oxford handbook of the self* (pp. 279–296). Oxford University Press.

Meyer, M., & Hunnius, S. (2021). Neural processing of self-produced and externally-generated events in 3-month-old-infants. *Journal of Experimental Child Psychology*, *204*, 105039. https://doi.org/10.1016/j.jecp.2020.105039

Meyer, M., Lamers, D., Kayhan, E., Hunnius, S., & Oostenveld, R. (2021). Enhancing reproducibility in developmental EEG research: Bids, cluster-based

permutation tests, and effect sizes. *Developmental Cognitive Neuroscience*, *52*, 101036. https://doi.org/10.1016/j.dcn.2021.101036

Mitchell, R. W. (1997). Kinesthetic-visual matching and the self-concept as explanations of mirror-self recognition. *Journal for the Theory of Social Behaviour*, *27*(1), 17–39. https://doi.org/10.1111/1468-5914.00024

Monachino, A. D., Lopez, K. L., Pierce, L. J., & Gabard-Durnam, L. J. (2022). The HAPPE plus Event-Related (HAPPE+ER) software: A standardized preprocessing pipeline for event-related potential analyses. *Developmental Cognitive Neuroscience*, *57*, 101140. https://doi.org/10.1016/j.dcn.2022.101140

Montirosso, R., & McGlone, F. (2020). The body comes first: Embodied reparation and the co-creation of infant bodily-self. *Neuroscience and Biobehavioral Reviews*, *113*, 77–87. https://doi.org/10.1016/j.neubiorev.2020.03.003

Moore, C. (1996). Theories of mind in infancy. *British Journal of Developmental Psychology*, *14*, 19–40.

Moore, C. (2006). *The development of commonsense psychology*. Psychology Press. https://doi.org/10.4324/9780203843246

Moore, C. (2007). Understanding self and others in the second year. In C. A. Brownell & C. B. Kopp (Eds.), *Socioemotional development in the toddler years: Transitions and transformations* (pp. 43–65). Guilford Press.

Moore, C., & Lemmon, K. (2001). *The self in time: Developmental perspectives*. Lawrence Erlbaum Associates.

Moore, C., & Paulus, M. (2013). A second-person approach cannot explain intentionality in social understanding. *The Behavioral and Brain Sciences*, *36*(4), 430–431. https://doi.org/10.1017/s0140525x12001987

Moore, J. W., & Fletcher, P. C. (2012). Sense of agency in health and disease: A review of cue integration approaches. *Consciousness and Cognition*, *21*(1), 59–68. https://doi.org/10.1016/j.concog.2011.08.010

Moore, J. W., & Obhi, S. S. (2012). Intentional binding and the sense of agency: A review. *Consciousness and Cognition*, *21*(1), 546–561. https://doi.org/10.1016/j.concog.2011.12.002

Morrison, I., Löken, L. S., & Olausson, H. (2010). The skin as a social organ. *Experimental Brain Research*, *204*(3), 305–314. https://doi.org/10.1007/s00221-009-2007-y

Nava, E., Bolognini, N., & Turati, C. (2017). The development of a cross-modal sense of body ownership. *Psychological Science*, *28*(3), 330–337. https://doi.org/10.1177/0956797616682464

Nava, E., & Tajadura-Jiménez, A. (2020). Auditory-induced body distortions in children and adults. *Scientific Reports*, *10*(1), 3024. https://doi.org/10.1038/s41598-020-59979-0

Neisser, U. (1988). Five kinds of self-knowledge. *Philosophical Psychology*, *1*(1), 35–59. https://doi.org/10.1080/09515088808572924

Neisser, U. (1991). Two perceptually given aspects of the self and their development. *Developmental Review*, *11*, 197–209. https://doi.org/10.1016/0273-2297(91)90009-D

Nguyen, T., Hoehl, S., & Vrtička, P. (2021). A guide to parent-child fNIRS hyperscanning data processing and analysis. *Sensors*, *21*, 4075. https://doi.org/10.3390/s21124075

Nicholls, A., & Kirkland, J. (1996). Maternal sensitivity: A review of attachment literature definitions. *Early Child Development and Care*, *120*(1), 55–65. https://doi.org/10.1080/0300443961200106

Nielsen, M., & Dissanayake, C. (2004). Pretend play, mirror self-recognition and imitation: A longitudinal investigation through the second year. *Infant Behavior and Development*, *27*(3), 342–365. https://doi.org/10.1016/j.infbeh.2003.12.006

Nielsen, M., Suddendorf, T., & Slaughter, V. (2006). Mirror self-recognition beyond the face. *Child Development*, *77*, 176–185. https://doi.org/10.1111/j.1467-8624.2006.00863.x

Nitta, H., Tomita, H., Zhang, Y., Zhou, X., & Yamada, Y. (2018). Disgust and the rubber hand illusion: A registered replication report of Jalal, Krishnakumar, and Ramachandran (2015). *Cognitive Research: Principles and Implications*, *3*(1), 15. https://doi.org/10.1186/s41235-018-0101-z

Oldroyd, K., Pasupathi, M., & Wainryb, C. (2019). Social antecedents to the development of interoception: Attachment related processes are associated with interoception. *Frontiers in Psychology*, *10*, 712. https://doi.org/10.3389/fpsyg.2019.00712

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J.-M. (2011). Fieldtrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, *2011*, 156869. https://doi.org/10.1155/2011/156869

Oostenveld, R., & Praamstra, P. (2001). The five percent electrode system for high-resolution EEG and ERP measurements. *Clinical Neurophysiology*, *112*(4), 713–719. https://doi.org/10.1016/S1388-2457(00)00527-7

O'Regan, J. K., & Noë, A. (2001). A sensorimotor account of vision and visual consciousness. *The Behavioral and Brain Sciences*, *24*(5), 939-73; discussion 973-1031. https://doi.org/10.1017/s0140525x01000115

Overton, W. F. (2015). Processes, relations, and relational-developmental-systems. In R. M. Lerner (Ed.), *Handbook of child psychology and developmental science* (pp. 1–54). John Wiley & Sons. https://doi.org/10.1002/9781118963418.childpsy102

Paulus, M. (2014). How and why do infants imitate? An ideomotor approach to social and imitative learning in infancy (and beyond). *Psychonomic Bulletin & Review*, *21*(5), 1139–1156. https://doi.org/10.3758/s13423-014-0598-1

Paulus, M. (2022a). Should infant psychology rely on the violation-of-expectation method? Not anymore. *Infant and Child Development*, *31*(1). https://doi.org/10.1002/icd.2306

Paulus, M. (2022b). *Theoretische Grundlagen und Geschichte der Psychologie und Psychotherapie.* Ludwig-Maximilians-Universität München, München.

Paulus, M., Hunnius, S., & Bekkering, H. (2013). Neurocognitive mechanisms underlying social learning in infancy: Infants' neural processing of the effects of others' actions. *Social Cognitive and Affective Neuroscience*, *8*(7), 774–779. https://doi.org/10.1093/scan/nss065

Paulus, M., Hunnius, S., van Elk, M., & Bekkering, H. (2012). How learning to shake a rattle affects 8-month-old infants' perception of the rattle's sound:

Electrophysiological evidence for action-effect binding in infancy. *Developmental Cognitive Neuroscience*, *2*, 90–96. https://doi.org/10.1016/j.dcn.2011.05.006

Paulus, M., Licata, M., Gniewosz, B., & Sodian, B. (2018). The impact of mother-child interaction quality and cognitive abilities on children's self-concept and self-esteem. *Cognitive Development*, *48*, 42–51. https://doi.org/10.1016/j.cogdev.2018.07.001

Perez-Osorio, J., & Wykowska, A. (2020). Adopting the intentional stance toward natural and artificial agents. *Philosophical Psychology*, *33*(3), 369–395. https://doi.org/10.1080/09515089.2019.1688778

Piaget, J. (1970). *Meine Theorie der geistigen Entwicklung*. Beltz.

Piazza, C., Cantiani, C., Akalin-Acar, Z., Miyakoshi, M., Benasich, A. A., Reni, G., Bianchi, A. M., & Makeig, S. (2016). Ica-derived cortical responses indexing rapid multi-feature auditory processing in six-month-old infants. *NeuroImage*, *133*, 75–87. https://doi.org/10.1016/j.neuroimage.2016.02.060

Piazza, E. A., Hasenfratz, L., Hasson, U., & Lew-Williams, C. (2020). Infant and adult brains are coupled to the dynamics of natural communication. *Psychological Science*, *31*(1), 6–17. https://doi.org/10.1177/0956797619878698

Pipp, S., Easterbrooks, M. A., & Brown, S. R. (1993). Attachment status and complexity of infants' self- and other-knowledge when tested with mother and father. *Social Development*, *2*(1), 1–14. https://doi.org/10.1111/j.1467-9507.1993.tb00001.x

Pipp, S., Easterbrooks, M. A., & Harmon, R. J. (1992). The relation between attachment and knowledge of self and mother in one to three-year-old

infants. *Child Development*, *63*(3), 738–750. https://doi.org/10.1111/j.1467-8624.1992.tb01658.x

Pipp-Siegel, S., Brown, S. R., Easterbrooks, M. A., & Harmon, R. J. (1995). The relation between infants' self/mother knowledge and three attachment categories. *Infant Mental Health Journal*, *16*(3), 221–232. https://doi.org/10.1002/1097-0355(199523)16:3<221::AID-IMHJ2280160308>3.0.CO;2-B

Pirazzoli, L., Lloyd-Fox, S., Braukmann, R., Johnson, M. H., & Gliga, T. (2019). Hand or spoon? Exploring the neural basis of affective touch in 5-month-old infants. *Developmental Cognitive Neuroscience*, *35*, 28–35. https://doi.org/10.1016/j.dcn.2018.06.002

Pohl, J., Nikolovska, K., Küster, D., Maurelli, F., Kappas, A., & Hommel, B. (2024). Attribution of selfhood based on simple behavioral cues: Towards a pars pro toto account [Manuscript submitted for publication].

Pomiechowska, B., & Gliga, T. (2019). Lexical acquisition through category matching: 12-month-old infants associate words to visual categories. *Psychological Science*, *30*(2), 288–299. https://doi.org/10.1177/0956797618817506

Pope, M. J. (1984). *Visual proprioception in infant postural development* [Doctoral Thesis]. University of Southampton, United Kingdom.

Povinelli, D. J., Landau, K. R., & Perilloux, H. K. (1996). Self-recognition in young children using delayed versus live feedback: Evidence of a developmental asynchrony. *Child Development*, *67*(4), 1540–1554. https://doi.org/10.1111/j.1467-8624.1996.tb01813.x

Prebble, S. C., Addis, D. R., & Tippett, L. J. (2013). Autobiographical memory and sense of self. *Psychological Bulletin*, *139*(4), 815–840. https://doi.org/10.1037/a0030146

Prinz, W. (2012). *Open minds: The social making of agency and intentionality*. MIT Press.

Provenzi, L., Rosa, E., Visintin, E., Mascheroni, E., Guida, E., Cavallini, A., & Montirosso, R. (2020). Understanding the role and function of maternal touch in children with neurodevelopmental disabilities. *Infant Behavior and Development*, *58*, 101420. https://doi.org/10.1016/j.infbeh.2020.101420

Pyasik, M., Ciorli, T., & Pia, L. (2022). Full body illusion and cognition: A systematic review of the literature. *Neuroscience and Biobehavioral Reviews*, *143*, 104926. https://doi.org/10.1016/j.neubiorev.2022.104926

Quesque, F., & Brass, M. (2019). The role of the temporoparietal junction in self-other distinction. *Brain Topography*, *1233*(3), 106. https://doi.org/10.1007/s10548-019-00737-5

Reddy, V. (2000). Coyness in early infancy. *Developmental Science*, *3*(2), 186–192. https://doi.org/10.1111/1467-7687.00112

Reddy, V. (2003). On being the object of attention: Implications for self-other consciousness. *Trends in Cognitive Sciences*, *7*(9), 397–402. https://doi.org/10.1016/S1364-6613(03)00191-8

Reddy, V. (2004). Feeling shy and showing-off: Self-conscious emotions must regulate self-awareness. In J. Nadel & D. Muir (Eds.), *Emotional development* (pp. 183–204). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198528845.003.0007

Reddy, V. (2008). *How infants know minds*. Harvard University Press. https://doi.org/10.4159/9780674033887

Reddy, V., Markova, G., & Wallot, S. (2013). Anticipatory adjustments to being picked up in infancy. *PLOS ONE*, *8*(6), e65289. https://doi.org/10.1371/journal.pone.0065289

Ren, Q., Gentsch, A., Kaiser, J., & Schütz-Bosbach, S. (2023). Ready to go: Higher sense of agency enhances action readiness and reduces response inhibition. *Cognition*, *237*, 105456. https://doi.org/10.1016/j.cognition.2023.105456

Richardson, M. J., Shockley, K., Fajen, B. R., Riley, M. A., & Turvey, M. T. (2008). Ecological psychology: Six principles for an embodied-embedded approach to behavior. In P. Calvo (Ed.), *Handbook of cognitive science: An embodied approach* (pp. 161–188). Elsevier. https://doi.org/10.1016/B978-0-08-046616-3.00009-8

Rochat, P. R. (1998). Self-perception and action in infancy. *Experimental Brain Research*, *123*, 102–109. https://doi.org/10.1007/s002210050550

Rochat, P. R. (2003). Five levels of self-awareness as they unfold early in life. *Consciousness and Cognition*, *12*, 717–731. https://doi.org/10.1016/S1053-8100(03)00081-3

Rochat, P. R. (2004a). Emerging co-awareness. In J. G. Bremner & A. Slater (Eds.), *Theories of infant development* (pp. 258–283). Blackwell Publishing.

Rochat, P. R. (2004b). Origins of self-concept. In J. G. Bremner & T. D. Wachs (Eds.), *Blackwell handbook of infant development* (2nd ed.). Blackwell Publishing.

Rochat, P. R. (2009). *Others in mind: Social origins of self-consciousness*. Cambridge University Press. https://doi.org/10.1017/CBO9780511812484

Rochat, P. R. (2010). The innate sense of the body develops to become a public affair by 2-3 years. *Neuropsychologia*, *48*(3), 738–745. https://doi.org/10.1016/j.neuropsychologia.2009.11.021

Rochat, P. R. (2011). Emerging self-concept. In T. D. Wachs & J. G. Bremner (Eds.), *The Wiley-Blackwell handbook of infant development* (pp. 320–344). John Wiley & Sons.

Rochat, P. R., & Hespos, S. J. (1997). Differential rooting response by neonates: Evidence for an early sense of self. *Early Development and Parenting*, *6*(3-4), 105–112. https://doi.org/10.1002/(SICI)1099-0917(199709/12)6:3/4<105::AID-EDP150>3.0.CO;2-U

Rochat, P. R., & Morgan, R. (1995). Spatial determinants in the perception of self-produced leg movements by 3-5 month old infants. *Developmental Psychology*, *31*, 626–636. https://doi.org/10.1037/0012-1649.31.4.626

Rochat, P. R., & Striano, T. (2000). Perceived self in infancy. *Infant Behavior and Development*, *23*(3-4), 513–530. https://doi.org/10.1016/S0163-6383(01)00055-8

Roseberry, S., Hirsh-Pasek, K., & Golinkoff, R. M. (2014). Skype me! Socially contingent interactions help toddlers learn language. *Child Development*, *85*(3), 956–970. https://doi.org/10.1111/cdev.12166

Rovee, C. K., & Rovee, D. T. (1969). Conjugate reinforcement of infant exploratory behavior. *Journal of Experimental Child Psychology*, *8*, 33–39. https://doi.org/10.1016/0022-0965(69)90025-3

Saffran, J. R., & Kirkham, N. Z. (2018). Infant statistical learning. *Annual Review of Psychology*, *69*, 181–203. https://doi.org/10.1146/annurev-psych-122216-011805

Saito, N., Takahata, K., Murai, T., & Takahashi, H. (2015). Discrepancy between explicit judgement of agency and implicit feeling of agency: Implications for sense of agency and its disorders. *Consciousness and Cognition*, *37*, 1–7. https://doi.org/10.1016/j.concog.2015.07.011

Schmuckler, M. A., & Fairhall, J. L. (2001). Visual-proprioceptive intermodal perception using point light displays. *Child Development*, *72*(4), 949–962. https://doi.org/10.1111/1467-8624.00327

Shai, D., & Belsky, J. (2017). Parental embodied mentalizing: How the nonverbal dance between parents and infants predicts children's socio-emotional functioning. *Attachment & Human Development*, *19*(2), 191–219. https://doi.org/10.1080/14616734.2016.1255653

Shimada, S., Fukuda, K., & Hiraki, K. (2009). Rubber hand illusion under delayed visual feedback. *PLOS ONE*, *4*(7), e6185. https://doi.org/10.1371/journal.pone.0006185

Slater, A. (2004). Visual perception. In J. G. Bremner & T. D. Wachs (Eds.), *Blackwell handbook of infant development* (2nd ed., pp. 40–80). Blackwell Publishing.

Sokol, B. W., Hammond, S. I., Kuebli, J., & Sweetman, L. (2015). The development of agency. In R. M. Lerner (Ed.), *Handbook of child psychology and developmental science* (Vol. 35, pp. 284–322). John Wiley & Sons. https://doi.org/10.1002/9781118963418.childpsy108

Sroufe, L. A. (1994). An organizational perspective on the self. In D. Cicchetti & M. Beeghly (Eds.), *The self in transition: Infancy to childhood* (pp. 281–308). University of Chicago Press.

Sroufe, L. A. (1996). *Emotional development: The organization of emotional life in the early years*. Cambridge University Press. https://doi.org/10.1017/CBO9780511527661

Sroufe, L. A., Fox, N. E., & van Pancake, R. (1983). Attachment and dependency in developmental perspective. *Child Development*, *54*(6), 1615. https://doi.org/10.2307/1129825

Stapel, J. C., Hunnius, S., Meyer, M., & Bekkering, H. (2016). Motor system contribution to action prediction: Temporal accuracy depends on motor experience. *Cognition*, *148*, 71–78. https://doi.org/10.1016/j.cognition.2015.12.007

Steinmaßl, K., & Paulus, M. (2024). Malleability of the sense of bodily self in early childhood: Preschool children show the enfacement illusion [Manuscript submitted for publication].

Stets, M., Stahl, D., & Reid, V. M. (2012). A meta-analysis investigating factors underlying attrition rates in infant ERP studies. *Developmental Neuropsychology*, *37*(3), 226–252. https://doi.org/10.1080/87565641.2012.654867

Suddendorf, T., & Corballis, M. C. (1997). Mental time travel and the evolution of the human mind. *Genetic Social and General Psychology Monographs*, *123*(2), 133–167.

Sui, J., Liu, C. H., & Han, S. (2009). Cultural difference in neural mechanisms of self-recognition. *Social Neuroscience*, *4*(5), 402–411. https://doi.org/10.1080/17470910802674825

Synofzik, M., Vosgerau, G., & Newen, A. (2008). Beyond the comparator model: A multifactorial two-step account of agency. *Consciousness and Cognition*, *17*(1), 219–239. https://doi.org/10.1016/j.concog.2007.03.010

Tamis-LeMonda, C. S., & Masek, L. R. (2023). Embodied and embedded learning: Child, caregiver, and context. *Current Directions in Psychological Science*, *32*(5), 369–378. https://doi.org/10.1177/09637214231178731

Thompson, R. A. (2008). Early attachment and later development: Familiar questions, new answers. In J. Cassidy & P. R. Shaver (Eds.), *Handbook of attachment: Theory, research, and clinical applications* (pp. 348–365). Guilford Publications.

Thompson, R. A., Laible, D. J., & Ontai, L. L. (2004). Early understandings of emotion, morality, and self: Developing a working model. *Advances in Child Development and Behavior*, *31*, 137–171. https://doi.org/10.1016/S0065-2407(03)31004-3

Trainor, L. J. (2008). Event-related potential (ERP) measures in auditory development research. In L. A. Schmidt & S. J. Segalowitz (Eds.), *Developmental psychophysiology: Theory, systems, and methods* (pp. 69–102). Cambridge University Press.

Trainor, L. J., Samuel, S. S., Desjardins, R. N., & Sonnadara, R. R. (2001). Measuring temporal resolution in infants using mismatch negativity. *NeuroReport*, *12*(11), 2443.

Trevarthen, C., & Hubley, P. (1978). Secondary intersubjectivity: Confidence, confiding, and acts of meaning in the first year. In A. Lock (Ed.), *Action, gesture and symbol: The emergence of language* (pp. 183–229). Academic Press.

Tsakiris, M. (2008). Looking for myself: Current multisensory input alters self-face recognition. *PLOS ONE*, *3*(12), e4040. https://doi.org/10.1371/journal.pone.0004040

Tsakiris, M. (2010). My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia*, *48*(3), 703–712. https://doi.org/10.1016/j.neuropsychologia.2009.09.034

Tsakiris, M. (2017). The multisensory basis of the self: From body to identity to others. *Quarterly Journal of Experimental Psychology*, *70*(4), 597–609. https://doi.org/10.1080/17470218.2016.1181768

van Stralen, H. E., van Zandvoort, M. J. E., Hoppenbrouwers, S. S., Vissers, L. M. G., Kappelle, L. J., & Dijkerman, H. C. (2014). Affective touch modulates the rubber hand illusion. *Cognition*, *131*(1), 147–158. https://doi.org/10.1016/j.cognition.2013.11.020

Veer, M. W. de, & van den Bos, R. (1999). A critical review of methodology and interpretation of mirror self-recognition research in nonhuman primates. *Animal Behaviour*, *58*(3), 459–468. https://doi.org/10.1006/anbe.1999.1166

Verschoor, S. A., & Hommel, B. (2017). Self-by-doing: The role of action for self-acquisition. *Social Cognition*, *35*(2), 127–145. https://doi.org/10.1521/soco.2017.35.2.127

Verschoor, S. A., Weidema, M., Biro, S., & Hommel, B. (2010). Where do action goals come from? Evidence for spontaneous action-effect binding in infants. *Frontiers in Cognition*, *1*, 201. https://doi.org/10.3389/fpsyg.2010.00201

Vygotsky, L. S. (1934). *Thought and language*. MIT Press.

Walsh, K. S., McGovern, D. P., Clark, A., & O'Connell, R. G. (2020). Evaluating the neurophysiological evidence for predictive processing as a model of perception. *Annals of the New York Academy of Sciences*, *1464*(1), 242–268. https://doi.org/10.1111/nyas.14321

Wegner, D. M., & Wheatley, T. (1999). Apparent mental causation: Sources of the experience of will. *American Psychologist*, *54*(7), 480–492. https://doi.org/10.1037/0003-066x.54.7.480

Weijs, M. L., Macartney, E., Daum, M. M., & Lenggenhager, B. (2021). Development of the bodily self: Effects of visuomotor synchrony and visual appearance on virtual embodiment in children and adults. *Journal of Experimental Child Psychology*, *210*, 105200. https://doi.org/10.1016/j.jecp.2021.105200

Wittgenstein, L. (1953). *Philosophical investigations*. Blackwell Publishing.

Wolff, M. S. de, & van IJzendoorn, M. H. (1997). Sensitivity and attachment: A meta-analysis on parental antecedents of infant attachment. *Child Development*, *68*(4), 571–591. https://doi.org/10.1111/j.1467-8624.1997.tb04218.x

Woodhouse, S. S., Scott, J. R., Hepworth, A. D., & Cassidy, J [Jude] (2020). Secure base provision: A new approach to examining links between maternal caregiving and infant attachment. *Child Development*, *91*(1), e249-e265. https://doi.org/10.1111/cdev.13224

Wunderlich, J. L., Cone-Wesson, B. K., & Shepherd, R. (2006). Maturation of the cortical auditory evoked potential in infants and young children. *Hearing Research*, *212*(1), 185–202. https://doi.org/10.1016/j.heares.2005.11.010

Yin, J., & Csibra, G. (2015). Concept-based word learning in human infants. *Psychological Science*, *26*(8), 1316–1324. https://doi.org/10.1177/0956797615588753

Zaadnoordijk, L. (2020). *Discovering structure in the confusion: An interdisciplinary approach to studying the sense of agency and its development* [Doctoral Thesis]. Radboud University Nijmegen, Nijmegen.

Zaadnoordijk, L., Besold, T. R., & Hunnius, S. (2019). A match does not make a sense: On the sufficiency of the comparator model for explaining the sense of agency. *Neuroscience of Consciousness*, *2019*(1), niz006. https://doi.org/10.1093/nc/niz006

Zaadnoordijk, L., Meyer, M., Zaharieva, M., Kemalasari, F., van Pelt, S., & Hunnius, S. (2020). From movement to action: An EEG study into the emerging sense of agency in early infancy. *Developmental Cognitive Neuroscience*, 100760. https://doi.org/10.1016/j.dcn.2020.100760

Zaadnoordijk, L., Otworowska, M., Kwisthout, J., & Hunnius, S. (2018). Can infants' sense of agency be found in their behavior? Insights from babybot simulations of the mobile-paradigm. *Cognition*, *181*, 58–64. https://doi.org/10.1016/j.cognition.2018.07.006

Zehr, E., & Stein, R. B. (1999). What functions do reflexes serve during human locomotion? *Progress in Neurobiology*, *58*(2), 185–205. https://doi.org/10.1016/S0301-0082(98)00081-1

Zmyj, N., Jank, J., Schütz-Bosbach, S., & Daum, M. M. (2011). Detection of visual-tactile contingency in the first year after birth. *Cognition*, *120*, 82–89. https://doi.org/10.1016/j.cognition.2011.03.001

Zmyj, N., & Marcinkowski, N. (2017). The relationship between infants' interest in feedback of self-performed actions with different latency and their parents' temporally contingent behavior. *Cognitive Development*, *41*, 85–93. https://doi.org/10.1016/j.cogdev.2017.01.002

Zukow-Goldring, P. (2012). Assisted imitation: First steps in the seed model of language development. *Language Sciences*, *34*(5), 569–582. https://doi.org/10.1016/j.langsci.2012.03.012

7 Acknowledgements

Doctoral degrees are like miniature Nobel prizes. Although they are awarded to one person only, there is a whole team behind it that contributes piece after piece. This section is for the team. During the time I worked on this thesis, I grew tremendously, both scientifically and personally. Thank you to all the people I met in the last years – each of you enriched my life. I want to express a special gratitude...

To **Pia**: My scientific career began with you. You created a great atmosphere, trusting me to independently organize my work in conducting experiments. I think that I liked this job so much, and it inspired me to work in science later. I also learned so much about managing a team and all the practicalities of doing research, from which my later project management skills benefited tremendously.

To **Pablo**: Although already in a research-focused master's program, and therefore destined to continue with a scientific career anyway, you had a huge, if not the biggest, impact on the way my career took. I was new in the city, kind of new to research, and definitely new to the topic (trying to model a self in robots), but you made me forget all that. The trust you had in my (psychological) expertise, even though I had just graduated from my bachelor's program, made me believe in myself. The freedom you gave me in conducting my own experiment made me put so much effort into preparing that I felt like I knew everything about myself after this small research project. Also, you trusted me so much that you made me submit my first own paper to a conference, which I then even presented. I received so much praise from Gordon during the writing process and from people in the conference audience that I felt like this was the right thing for me. Thank you for bearing my crying in fear before the conference, and thank you the most for pointing out the SPP "Active Self"

to me in the end. Without all your support, I would never have conducted this research.

To **Simone**: Your class on "Current debates in neuro-cognitive psychology" really sparked my interest in theoretical discussions. Also, discussing predictive coding in this class largely helped me understand the theory that by now is so influential in cognitive research. The research project I conducted in your lab helped me so much to understand statistics and experimental design – abilities I greatly benefit from today. I am also pretty convinced that the great recommendation letter you wrote me for my GSN application got me into GSN. Not to speak of the enormous feedback you provided on my research within but also outside of the TAC meetings.

To **Verena, Jeremy, Ophelia, and Paul**: I deeply value your contributions to evaluating my thesis process. I know your schedules are full and the contributions to the thesis are time-consuming, so thank you.

To **Carolina**: I am very glad you were my supervisor. With you, I could further pursue neuro-cognitive research, and I learned a lot! You always guided me to learn more about the methods I was using, and I could take over a neatly organized EEG lab from you. I appreciate you spending so much time with me, even after leaving LMU, to make sure I was not lost in the process.

To **Markus**: Mentally, I wrote this section a hundred times, and depending on when I did, the gist of it was different. I felt like I had so much to say to you, but in the end, I always said it and never saved anything up. I am extremely grateful that I felt comfortable enough with you to say everything I wanted. I know we had ups and downs, but I never felt like this was actually an issue. Now, I am so proud of the

achievements I have made and of the researcher I have become. For much of this, you are to blame: you demanded much of me, scientifically and personally, but it made me grow. Your "What is the theory behind it?" will probably always be part of my inner voice. As you said, the time with you made me a developmental researcher, and although your emphasis was on the "developmental", mine is on "researcher". While writing this thesis, it also started to grow on me that despite our initial theoretical discrepancy, I ended up saying the same things about the self as you always did. I want to emphasize that this is not because of opportunistic reasons, but because I truly believe in it. I have no idea whether this was your strategic plan all the time and you have been nudging me in this direction, or whether it just happened by chance, but I am amazed by where our joint journey has brought me.

To **Regina and Marina**: Even though it was short, starting my PhD in your office incredibly helped me get accustomed to the new job. Not only was I comfortable with the nice team, but also the emotions you shared with me during this time - joy, anger, sadness - helped me validate my own emotions on this journey.

To **Carlotta, Sophia, Kim, Tim, Frank, Jesse, Marvin, Valentin, Annika, Jan, Katrin, Lisa, Markus, Maren, and Nils**: having you as peers, starting a PhD at around the same time (or later) on the same topic with such a fragile conceptual basis, was so helpful. We shared the same issues, not only as PhDs but also as researchers of the self. We did what the SPP wanted us to do: discuss our theoretical assumptions, thereby shaping our own. Without your input, a lot of this thesis would not have been the same.

To **Johannes, Konstantin, and Christina**: It was a great pleasure to have the opportunity to see you grow through your own research journeys. And as much as I

sometimes could help you in overcoming the first hurdles in PhD life, so much you helped me stay sane. Thank you for bearing my rants about journals, administration, and IT. I loved coming to work for you.

To **Natalie, Anja, and Maria**: Each of you supported me so much during my PhD journey. Your closeness to my situation paired with your strength built during your own journeys made conversations with you so reassuring and validating. I am also very grateful for all the times you shared your own insecurities about the science of your career with me. I hope this prepared me well for what's to come.

To **Mara**: I am very glad we got to share an office so that we could get to know each other. Your experience with longitudinal studies enormously helped me set up my own. But I am even more glad that we went to the workshop in Landau together so that we could become friends. All the times I could share my frustrations with you and you cheered me up, but also all the times I could share my successes with you. You always knew what to say and do - even if this would mean having dinner in the office together to finish up our tasks.

To **Lena**: I cannot describe how much my job satisfaction increased since I got to share an office with you. All the times you have been turning around and asked what's wrong when I release an enormous sigh in front of my computer screen. Understanding every single excitement and frustration that comes with publishing (or not publishing) the first paper as you just experienced the same things in the same moment. Sharing the stress of finishing up the thesis at the same time. And not to forget the uncounted number of times you made me show up at the Nordbad to enjoy a swim just before work. I am truly going to miss this companionship!

To **Britta, Esma, Marleen, and Lara**: For being my friends for like forever. Regardless of whether you were going through the same process like me or not, you always enjoyed my successes and cheered me up when I was questioning my decisions!

To **Mama, Papa, Timm, and Lars**: You are the major reasons I am what and where I am. You always encouraged me to be curious, to do the things I like and let life just adapt to my decisions. You knew what I would probably enjoy when I didn't. Even if you didn't understand most of the issues I was facing with journals and publications and the like, you rooted for me and cherished my successes. You were always my first or second option to call when I was devastated and overwhelmed, and you had my back. Without your support, this would have never happened.

To **Marius**: You are actually the reason I did this PhD here. Without you, I probably would never have come to Munich, to this lab, to this topic. You have been the tower of strength in this journey. Screwing and drilling endless props for my studies. Having my back in times when I was gone for work. Working to guarantee us a great life anyway. Keeping me sane when I lost it. Supporting me through all options in my career but still guiding me towards decisions that were best for me. I love you. Wuff.