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Review

Sensorimotor foundations of self-consciousness *in utero*

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We review recent work that examines the genesis of a prereflective self-consciousness *in utero* in humans. We focus on observable behaviours that suggest a state of anticipatory perceptual awareness evident in the foetal period and the foetus' first expression of agency through self-generative engagement with it. This predictive, anticipatory awareness is first evident in the prospective sensorimotor organisation of bodily movements of the second-trimester foetus, revealing an early adaptive awareness and agency that establishes the foundation for additional forms of abstract, reflective, and conceptually backed conscious experience in adults. Advanced understanding of these early sensorimotor foundations of psychological development and health may afford a better understanding of adult human consciousness, the nature of its early ontogeny, and its particular expression mediated by the integrative nervous system.

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Introduction: the sensorimotor roots of self-consciousness in humans

Self-consciousness underpins the rich, reflective and conceptually backed adult human consciousness we are all familiar with. It is a fundamental experience of being an integrated self, an 'I' that is distinct from, yet related to the world of objects and others. Its study has been typically addressed from an adult-centric perspective (see Ref. [1] for a review), yet its growth in development is critical to understanding the organisation of consciousness and the origins of a human mind [2,3].

Previous theoretical and empirical work has outlined the importance of bodily and sensorimotor roots in understanding human self-consciousness in human adults [4,5]. Yet, like all living biological systems, humans gestate, are born, grow, decay and eventually die. Recent work has suggested that to understand what self-consciousness is, one needs to first address how it dynamically develops from 'square one', in the womb [6-9].

Detecting and measuring awareness at its earliest origins in development is challenging conceptually and methodologically. First, there is an obvious lack of explicit verbal ability for self-reported sensations and experiences by foetuses, neonates, and infants, preventing a mainstay of psychological research. Consequently, investigation of the early development of self-consciousness can only capitalise on nonverbal behavioural and physiological measures and with limited access to those signals. Second, there are important limitations in *interpreting* behavioural and physiological variables as evidence of self-awareness or aspects of consciousness.

Despite these inherent challenges, the sensorimotor and agentive abilities of human foetuses have been investigated through complementary research strategies. The most prevalent methods aim to assess either the responses of foetuses tested directly *in utero*, the reactivity of newborns delivered preterm at different gestational ages, or the *a posteriori* response of neonates to stimuli experienced *in utero* (see [10-12] for recent reviews).

While the characterisation of minimal forms of bodily self-awareness *in utero* in humans remains an open research field, we summarise some key findings below while stressing that our discussion is by no means exhaustive. We draw special attention to accumulating empirical evidence that demonstrates human sensorimotor perception is already significantly elaborated *in utero* to give a necessary basis of awareness of the self-as-agent [3,13] on which experience grows and develops.

Evidence for self-awareness and intentional foetal action

Recent application of *in vivo* brain imaging techniques, such as functional magnetic resonance imaging or magnetoencephalography (MEG) of human foetal cortical activity, demonstrates its responses to external sensory stimuli within the uterine environment [14]. For example, unimodal testing of human foetuses (or infants born preterm, at the age of 25–28 gestational weeks) indicates that auditory stimuli activate cortical processing (e.g., [15,16]), despite its immature state. Similarly, visual stimuli applied *in utero* as light flashes elicit cortical responses in over 90% of assays ([17,18]; see also [10]). However, these approaches fail to take into account the richness of the bodily, dynamic, and sensorimotor perceptual activity observable in foetal behaviour well before this cortical activation stage [8].

An important angle of approach is the study of bodily movements *in utero*, which do not appear to support the notion that intentional actions develop from automatic reflexes. Rather, human bodies are from the outset intrinsically dynamic systems that must accommodate the responses of their actions prospectively, that is, with an eye to the future [19,20]. The first spontaneous movements of the human organism are discernible in the small embryo [21]. Using high-resolution transvaginal ultrasound methods, research revealed that these early movements consist of small, sideways bending of the head or rump and begin at precisely at 7 weeks 2 days gestational age [22]. By 8 weeks, so-called 'general movements' comprising rotations and displacements of the thorax, partial rotations of the head, and rotation and displacements of the limbs are observable [23,22,24]. From its early beginnings in writhing whole body movements, the foetus develops more sophisticated, controlled, and isolated actions of the limbs to direct purposive actions, such as self-touch.

Thumb sucking is observed as early as 10–15 weeks of gestation [18]. Foetal actions develop sensorimotor coordination for self-directed actions that generate an expected sensory response. For example, an ultrasound study of foetal movements recorded the velocity of the arm as a function of the target area of the body touched, *for example*, the eye or mouth [25]. The authors found that between 14 and 22 gestational weeks, the velocity of hand became lower when it touched an eye than when it touched the mouth, indicating differentiation of action as a function of the somatosensory feature of its active effect: touching the target object and generation of a specific sensory effect contingent on that action. The more sensitive area (the eye) was touched more 'delicately' than the mouth, and this expectant sensory response was organised ahead of time as evidenced in the target-specific velocity profiles. The actions were expectant – they anticipated a sensory response.

In the case of twin pregnancies, when the foetus touched itself, the placenta, or a co-twin, it produced different action kinematics and tactile patterns that differed in pressure, acceleration, and directedness dependent on the target. These findings demonstrate an anticipatory awareness shaped foetal actions; they were expectant of its sensory consequences [26,27,25]. By this point at 18 weeks' gestational age, the foetus had obtained the ability to move its hands with prospective awareness of their sensory effects, that is, they were 'acting with knowledge'.

Anticipatory perceptual awareness *in utero*

The development of foetal movements in the second trimester shows an increase in prospective control and sensorimotor anticipation. For example, from 19 weeks' gestational age, 4D ultrasound data demonstrate anticipatory mouth opening during hand movements directed there, suggesting intersensorimotor anticipatory coupling [28]. Similarly, human foetuses progressively shift from opening the mouth after an incidental hand contact to opening the mouth before the hand touches the perioral region [29]. As early as 24 weeks of gestational age, foetuses perform anticipatory mouth movements when they approach their face with their hands [30]. Feats such as 'bicycling' the legs, turning the body over and around in the womb, reaching to touch the placental lining, umbilical cord, twin foetus, or parts of one's own body [23,24,31] all indicate that foetal motor actions are enacted with a degree of precision that requires coordinated prospective control.

By 33 weeks' gestational age, foetuses detect acoustic frequency changes and anticipate their pattern, demonstrated by MEG of *in utero* perceptual responses to 'unexpected' auditory tones [32,33]. Similar paradigms of auditory expectations of a sequence of tones demonstrate foetal detection of auditory sequence violations, evident in the MEG signal from 35 weeks' gestational age (Moser et al., 2021; 2020). These acoustic expectant capacities require the integration and prediction of information over time to give anticipatory auditory awareness, a foundation of conscious perceptual awareness.

Intrauterine anticipatory perception is further demonstrated in studies where late-term foetuses discriminate their native language (mother tongue) from an unknown language [34]. More recent studies report intonation (melodic) features of native language prosody experienced *in utero* shapes postpartum vocal learning; newborns exhibit the same maternal pitch-based elements in their own cry melodies [35,36]. In a similar study testing foetal awareness of abdomen touch, foetal movement responses were found to be particular to maternal touch, reducing when their mother touched the abdomen, but

not when another adult did so, suggesting foetal awareness of maternal-specific behaviour [37]. Although not itself necessarily anticipatory at this stage, such awareness of maternal voice and movement contributes to active seeking of the mother's voice postpartum (see van der Meer and van der Weel [38]).

In sum, evidence indicates an anticipatory perceptual awareness present in foetuses first in their prospectively organised bodily actions, then in sensory responses to their environment. These early abilities, integrated with proprioceptive and tactile knowledge, developing visual and olfactory senses, allow the foetus to explore one's body and the uterine environment *via* bodily actions, detecting sensory changes and anticipating already the consequences of one's bodily movements. These observations indicate that, in the second-trimester human foetus, arm-hand movements are not mere reflexes, but actions that are modulated and attuned by a knowledge of the target's responses, including by the particular dimension of self *versus* non-self goals. Foetal sensorimotor functions develop to reach levels of complexities revealing integrative proficiency of the brain and body, which is indicative of of developing degrees of anticipatory planning and affective experience [8].

This active, bodily 'sensation-testing' nature of human action is illustrated nicely by the anticipatory and exploratory movements of the foetus evident from the start of the second trimester. Studies illustrate that by 24 weeks of gestation, foetuses increasingly touch sensitive parts of their bodies, especially faces ([30]; Piontelli 2011). They have been observed to spend a significant amount of time in tactile exploration of their bodies, and notably the boundary between innervated and non-innervated regions, to give self-generated learning [27,39,40]. For example, foetuses frequently touch the lips, cheeks, ears, and parietal bone, creating a self-stimulatory pattern. At the anterior fontanelle, as the nervous innervation of the forehead increases and the boundary migrates during development, the foetus' exploration of this region migrates with the boundary, demonstrating the foetus was not merely exploring a spatial region, but the special relationship between differences in auto stimulatory feedback either side of the boundary of innervation ([24], pp. 61–67), testing the boundaries of 'self' and 'other'.

Given that all skeletomuscular actions generated with perceptual and motor coherence allow the individual to successfully navigate a changing physical and social environment to achieve its own purposes, one may speculate that they form a basic, primary sensorimotor nature of early conscious awareness [41,42]. Sensorimotor activities may generate the first experiential knowledge mediated by the nervous system at a later stage. These basic actions are driven by brainstem-mediated 'intrinsic motive formations' [43] that compel the organism to move and engage.

Taken together, the above findings on human foetuses show that their sensorimotor abilities are functional and purposeful in their self-related anticipatory organisation at early stages. The foetal brain appears sufficiently developed to support associative learning and long-term memory, especially at the level of brainstem integrative function, notable as a critical substrate in ontogenetically primary human self-consciousness [8,44,45], before more specific sensory activations of cortical structures. Regardless of the nascent state of brain–body maturation, human foetuses display self-generated anticipatory action and differentiated responsiveness to stimulation, as well as a differential self- *versus* non-self-awareness. Finally, they show increasingly organised and discriminatory behaviours with advancing gestation, from undifferentiated whole body movement to increasingly specific, coordinated actions.

Conclusion and outlook

While the sensory worlds and scope of conscious awareness of foetal and infant differ in discriminatory, conceptual, and cognitive power to that of an adult, we suggest that it is not less informative nor constitutive of human self-consciousness *per se*. A growing body of work supports the hypothesis that the fundamental ingredients for developing bodily self-awareness are already in place. Further work needs to empirically establish the link between these early perceptions, bodily self-consciousness and subjective experiences at its origins. The human foetus is already exposed to, and hence acquires the sensorimotor elements that will be recruited in the postnatal niche [3]. Importantly, given that the foetus is also exposed to its own self-generated sensory bodily awareness within the uterine environment, an early sense of self appears present and developing *in utero*. Of special note is the intimate environment of the developing human body within another human body [46,6,7,47]. Hence, examination of bodily self-consciousness in isolation from its co-embodied developmental roots is an important dimension in the nature of this early emergence of self-consciousness for future consideration, and understanding the origins of conscious experience in adults.

Data Availability

No data were used for the research described in the article.

Declaration of Competing Interest

We declare we have no conflicts of interest.

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