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In Enfance **Volume 2, Issue 2, April 2020**, pages 175 to 192

ISSN 0013-7545
ISBN 9782130823162

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ABSTRACT

This literature review examines how babies' body know-how develops during the first year of life. It surveys studies describing this development through the exploration of the body and of the physical environment. This early development may help babies acquire a sense of agency and a sense of body ownership. The development of body know-how, as a precursor to more in-depth knowledge of the body and of the self, may play an essential role in chi ldren's socio-cognitive and psychomotor development.

Keywords: body know-how, body knowledge, early development.

RÉSUMÉ

Développement du savoir-faire corporel durant la première année de vie du bébé

Cette revue de la littérature propose d'examiner de quelle manière le savoir-faire corporel du bébé s'affine au cours de la première année de vie, en décrivant ce développement à travers l'exploration du corps et l'exploration de l'environnement physique. Ce développement précoce pourrait participer à l'acquisition par le bébé d'un sens de l'agentivité (*sense of agency*) et d'un sens du corps propre (*body ownership*). Le développement du savoir-faire corporel, par son statut de précurseur d'une connaissance plus approfondie du corps et de soi, jouerait un rôle essentiel dans le développement sociocognitif et psychomoteur de l'enfant.

Mots-clés : savoir-faire corporel, connaissance du corps, développement précoce.

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Introduction

Let us imagine a baby who is just a few months old lying on a play mat, and take a look at their behaviors: they bring their hands together above their chest, intertwine them, and observe them. They then tip over to one side and grab a toy, which they bring back to their mouth, and then shake vigorously several times. With this attentive gaze, we can discover the wealth of actions a young baby performs while immersed in the exploration of their own body and their environment. These behaviors, which are a part of the daily experience of those who care for babies, reveal babies' ability to use their bodies appropriately to interact with the world around them. This ability is what we define as babies' "body know-how".

Body know-how is at the heart of multiple theories in psychology. Notable examples include O'Regan's sensorimotor contingency theory (O'Regan, 2011) and Varela's enactivist framework (Varela, Thompson, & Rosch, 1991). Examples in developmental psychology include Piaget's constructivism (Piaget, 1936), Neisser's "ecological self" theory (Neisser, 1991), and Gibson's ecological approach (Gibson & Pick, 2000). A rich body of experimental work has explored body know-how in babies. To our knowledge, however, there has only been one literature review on the early development of body know-how (in French), by Rochat and Goubet (2000). In their review, they argue that early knowledge of the body may be a precursor to the later development of self-knowledge.

In the present article, we seek to extend Rochat and Goubet's literature review, exploring how studies published in the intervening 20 years have shed new light on these issues. We survey a range of studies on body know-how in babies, with two aims: (1) to recall that babies show body know-how in the first year of life, and even in utero, and (2) to describe how babies develop body know-how by exploring their bodies and the physical world around them. We do not seek to exhaustively review all research related to the development of body know-how: there are various examples that are not cited here which may indirectly speak to babies' body know-how, such as studies on peripersonal space (see e.g., Bremner, Mareschal, Lloyd-Fox, & Spence, 2008; Begum Ali, Spence, & Bremner, 2015), visuo-tactile/motor correspondence (see e.g., Filippetti, Johnson, Lloyd-Fix, Dragovic, & Farroni, 2013; Filippetti, Orioli, Johnson, & Farroni, 2015; Rochat & Morgan, 1998), and their understanding of means-end relationships (Elsner & Aschersleben, 2003; Munakata, McClelland, Johnson, & Siegler, 1997). The studies reviewed in each section are based on a variety of experimental methods. This choice has the advantage of highlighting the richness of the literature on body know-how, but the drawback that divergent results can sometimes be difficult to compare.

The present article looks at studies examining babies' development of body know-how through two modes of exploration: exploration of the body and of the physical environment. However, the development of babies' body know-how can also be seen in their interactions with social partners. Studies of babies' engagement in social interactions and imitation abilities shed light on the ways in which the social environment guides the development of body know-how during the first year of life. Here, however, we have decided to focus on the exploration of the body and the physical environment. Studies on social interactions deserve separate analysis in a full literature review of their own.

Exploration: the mechanisms

Before examining the development of body know-how, we must seek to understand the mechanisms underlying this type of development. Here we hypothesize that two mechanisms are involved: the exploitation of sensitivity to sensorimotor contingencies, and curiosity.

Babies' sensitivity to sensorimotor contingencies[1] (or redundancies) is their ability to detect the link between their own actions and their consequences, such as the link between moving their hand in front of their eyes and the resulting visual feedback. This sensitivity to sensorimotor contingencies seems to be present in babies from birth, and even in utero. The exploitation of this sensitivity, which is richly documented by Bullinger (2007) as "instrumentation",[2] allows babies to master (first implicitly, and then consciously) the means by which they can interact with their own body and their physical environment. However, this mechanism alone would not allow babies to learn effectively. The set of sensorimotor contingencies that could possibly explored would be far too large. Their exploration must thus be organized.

Here, a second learning mechanism, curiosity, may play a role. Curiosity is babies' intrinsic motivation to explore situations that offer them the opportunity to progress in either their knowledge of the world (knowledge-based motivation) or their means of acting on the world (skills-based motivation). This is illustrated, for example, by babies' preference for exploring situations that fit with their "sensory expectations" over those that do not (Schaal *et al.*, 2004; Schaal *et al.*, 2008), as well as for new situations (see Colombo & Mitchell, 2009 for a review), impossible situations (e.g., Stahl & Feigenson, 2015) and improbable situations (e.g., Sim & Xu, 2017) relative to common ones. Babies' exploration of particular sensorimotor contingencies rather than others thus seems to be not arbitrary, but motivated by a search for situations that they can learn from. Babies also show signs of contentment (smiling and/or babbling) when their search for opportunities to learn is satisfied, such as when their movements trigger the appearance of audiovisual stimuli (Lewis, Sullivan & Brooks-Gunn,

[1] The term contingency is not to be understood here according to its philosophical definition.

[2] Bullinger uses the term 'instrumentation' to describe "the way in which babies manage to make their sensorimotor systems into tools that allow them to understand and act on their environment" (Bullinger, 2007).

1985); and signs of frustration (shouting and/or crying) in situations where these expectations are not met (e.g., Watson, 1972; Fagen & Ohr, 1985).

Exploration of the body

One way to describe the development of babies' body know-how is through their tactile exploration of their own body: that is, when they touch their own body with their hands and feet. We can distinguish two types of studies on the movements that babies direct toward their own bodies: studies of spontaneous tactile exploration of the body (self-touch), and studies on babies' reactions to external tactile stimuli applied to their bodies.

Spontaneous tactile exploration of the body

Movements in utero can be observed in detail using 4D ultrasound, an imaging technology that provides very precise images of the fetus's actions (for a review, see Kurjak *et al.*, 2008) (see Fig. 1.a). It has shown that fetuses engage in spontaneous tactile exploration of the body, and that this exploration, which probably begins as random, quickly becomes organized (Piontelli, 2010, Kurjak *et al.*, 2004). For example, fetuses seem to preferentially explore highly innervated areas of the body (e.g., mouth and eyes), as well as areas falling at the boundary between innervated and non-innervated parts (e.g., between the face and the skull at the trigeminal nerve), over less innervated areas, which they explore only very rarely (e.g., the skull) (Piontelli, 2010). This organized exploration of the body allows fetuses to experience sensations of double touch—simultaneous tactile sensations in the hands or feet and in the explored area—which presumably plays a role in the establishment of early sensorimotor maps (Fagard *et al.*, 2018).

The fetus's sensitivity to sensorimotor contingencies probably underpins the organization of this tactile exploration of the body (see above). This sensitivity seems already to be present in utero, although in a rudimentary form which does not imply that the fetus has explicit knowledge of the consequences of its actions. This early sensitivity to sensorimotor contingencies may, then, involve simple reinforcement learning: when an action produces stimulation that is pleasant and/or interesting for the fetus, this action is reinforced and repeated. For example, fetuses from the second trimester of pregnancy have been observed to make coordinated movements of the hand and mouth: that is, to open the mouth before the arrival of the hand (see Fig. 1.a) (Myowa-Yamakoshi & Takeshita, 2006; Reissland, Francis, Aydin, Mason, & Schaal, 2014). Moreover, it has been found that fetal hand movements can have different spatial and temporal characteristics depending on their consequences, with movements decelerating more when the hand approaches the eyes than the mouth (Zoia *et al.*, 2007). The fetus thus seems to be sensitive to the link between the movements of its hands and the subsequent tactile sensations, at least for certain movements of the hands directed toward the mouth and the eyes, which surely explains why the spontaneous tactile exploration observed in the fetus can be organized.

At birth, despite a massive, abrupt change of environment, babies show body know-how that is in continuity with the know-how that can be observed in utero. Newborns also engage in spontaneous tactile exploration of the body (Thomas, Karl, & Whishaw, 2015; DiMercurio, Connell, Clark, & Corbetta, 2018). They are able to differentiate the tactile sensations caused by the exploration of their own body from those caused by external stimuli. For example, Rochat and Hespos (1997) observed that newborns did not show the "rooting reflex" (a reflexive movement of the head in response to a caress on the cheek) when the tactile stimulation applied to their cheek was caused by contact with their own hand, whereas they did when tactile stimulation was applied by an experimenter. Over the first six months of life, spontaneous tactile exploration of the body evolves, from movements directed toward the top half of the body (face and trunk) with the outside of the hand, to movements directed toward the bottom half of the body (legs and feet), with the palm of the hand and then with grasping (Thomas *et al.*, 2015; DiMercurio *et al.*, 2018).

Reactions to external tactile stimulation of the body

This change over time in infants' self-directed movements is paralleled by change in their reactions to external tactile stimulation applied to the body. Recent neuroimaging studies suggest that the brain's responses to tactile stimuli are organized somatotopically from the first year of life, and even from the age of 60 days for stimuli on the hands and feet (Marshall & Meltzoff, 2015; Saby, Meltzoff, & Marshall, 2015; Meltzoff, Saby, & Marshall, 2018). Babies' responses to tactile stimulation have also been studied using behavioral methods. Studies have been carried out in babies aged 2-8 months by placing buzzers on different parts of the baby's body and measuring their ability to move the stimulated limb or to touch/grasp the buzzers (Hoffmann *et al.*, 2017; Somogyi *et al.*, 2018; Chinn, Noonan, Hoffman, & Lockman, 2019). The results of studies using this methodology suggest that when a buzzer is applied to one of their limbs, 3-month-olds move their whole body, whereas 5- to 6-month-olds mainly move the stimulated limb (Somogyi *et al.*, 2018). Moreover, it seems that babies are initially (around the age of 2 months) only able to locate buzzers placed on the face and not on the rest of the body (Hoffmann *et al.*, 2017; Chinn *et al.*, 2019), and that over the following months, they gradually become able to locate buzzers placed in other positions: on the abdomen at 5 months, on the arms at 6 months, and on the shoulders at 8 months (Hoffmann *et al.*, 2017). Babies' ability to respond to the buzzers also seems to improve between the ages of 2 and 8 months, going from touching them with the outside of the hand, to touching them with the open palm, and on to real grasping (Somogyi *et al.*, 2018; Chinn *et al.*, 2019).

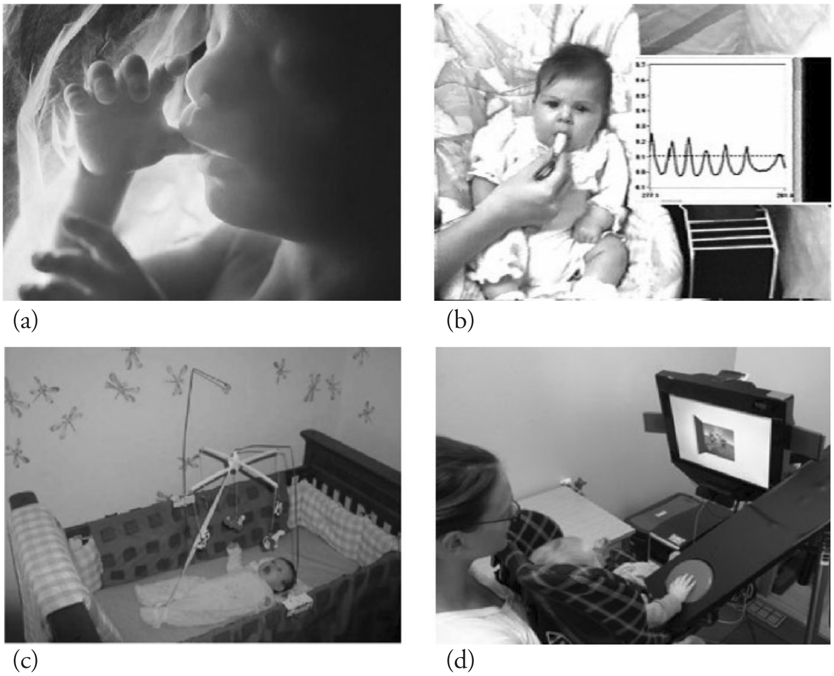

Figure 1.
Examples of paradigms for the study of body know-how in babies.
(a) 4D ultrasound: an imaging technology that can be used to observe the movements of the fetus in utero, such as coordinated movements of the hands and mouth (Myowa-Yamakoshi & Takeshita, 2006).
(b) nonnutritive sucking: the baby varies its sucking rate when this causes the pitch of an auditory stimulus to vary (Rochat & Striano, 1999).
(c) mobile paradigm: the baby is placed on its back, and one of its limbs is attached with a string to a mobile placed above it, so that the baby's movements trigger movements of the mobile (Rovee & Rovee, 1969).
(d) appearance of an image on a screen triggered by pressing a button with the hand: 10-month-olds anticipate the appearance of the image (Kenward, 2010).

Interaction with the physical environment

A second way of characterizing the development of body know-how is through interactions between babies and their physical environment. Here we detail three types of studies: studies demonstrating babies' early ability to respond to environmental stimuli, those looking at their interactions with their physical environment, and those on the development of manual skills during the first year of life.

Early ability to respond to environmental stimuli

From the first trimester of pregnancy, fetuses interact with their environment: they move (Kurjak *et al.*, 2008) and as a result receive sensory information concerning the intra- and extra-uterine world that surrounds them (see Lecanuet & Schaal, 1996 for a review of the literature). Fetuses perform not only general movements caused by an overall excitation of the motor system, but also isolated movements of the arms and legs (see e.g. Kurjak *et al.*, 2008). They seem to be capable of performing movements in response to stimulation. For example, fetuses increase their movements in response to their mother's voice (Marx & Nagy, 2015; Reissland *et al.*, 2016; Ferrari *et al.*, 2016) or movements (Marx & Nagy, 2015). At birth, babies' movements are not only reflexes. Some of newborns' movements are performed in an apparently controlled and structured way. Newborns have good control of a small repertoire of movements, such as movements of the arms along the vertical axis (van der Meer, van der Weel, and Lee, 1995, 1996; van der Meer, 1997; Delafield-Butt *et al.*, 2018), nonnutritive sucking movements (e.g., Rochat & Striano, 1999; DeCasper & Fifer, 1980) and gaze movements (e.g., Farroni, Massaccesi, Pividori, & Johnson, 2004). Observing actions from this limited motor repertoire has allowed researchers to discover newborns' ability to modify their movements in response to perceptual information. For example, under appropriate conditions, newborns who are exposed to optical flows change their walking movements (stepping) in reaction to the characteristics of the flow (Barbu-Roth *et al.*, 2009).

It is worth noting that certain actions (e.g., sucking, eye movements) are often forgotten when looking at babies' early motor skills, even though these actions, which newborns are able to perform from birth, demonstrate their body know-how. It is also important to remember that this body know-how can only be fully expressed under conditions that allow its expression (e.g., in water to mitigate the effects of gravity, with the head supported, etc.), which is not always the case either in laboratory studies or in daily life.

Abilities to act on the physical environment

Babies' ability to act on their physical environment can be measured in the laboratory using operant conditioning methods, in which the baby's performance of a certain action triggers a pleasant stimulus. Researchers then measure the baby's propensity to perform the "contingent" action before, during, and after this conditioning. Studies of this type in newborns have shown that they are sensitive to sensorimotor contingencies involving certain specific stereotypical actions which are part of their motor repertoire, such as arm movements along the vertical axis (van der Meer *et al.*, 1995, 1996; van der Meer, 1997 where the contingent visual feedback is the vision of the hand) and nonnutritive sucking (e.g., Rochat & Striano, 1999; DeCasper & Fifer, 1980) (see Fig. 1.b).

Over the course of their development, babies' abilities to act on the physical world around them grow richer. This has been highlighted by a research literature using the mobile paradigm developed by Rovee-Collier and collaborators (Rovee & Rovee, 1969) (see Fig. 1.c). In this method, the baby is placed on its back and one of its limbs (arm or leg) is attached by a string to a mobile placed above, causing the movements of this limb to trigger movements of the mobile. From the age of 2-3 months, babies explore their motor repertoire and perform the specific action that causes the mobile to move, even when this movement is not one that they perform on a daily basis, such as knee bends and extensions (e.g., Thelen, 1994; Angulo-Kinzler, 2001; Angulo-Kinzler, Ulrich, & Thelen, 2002; Chen, Fetters, Holt, & Saltzman, 2002; Sargent, Schweighofer, Kubo, Fetters, & Ivanenko, 2014; Sargent, Reimann, Kubo, & Fetters, 2015). This refinement of babies' body know-how is also illustrated by their ability to use their limbs in a differentiated way to act on the world. To study this ability, researchers have put babies of different ages in a situation where only one of their arms or legs produces movements of the mobile (e.g., Rovee-Collier, Morrongiello, Aron, & Kupersmidt, 1978; Watanabe & Taga, 2006) or a character on a screen (Jacquey *et al.*, 2020). They have observed that when only the movements one of the baby's limbs trigger pleasant stimuli, young babies (aged 2-3 months) engage in undifferentiated movements of their whole body or both arms (Watanabe & Taga, 2006), while older babies (aged 4-8 months) move the arm that is connected to the device more than they do the other arm (Watanabe & Taga, 2006; Jacquey *et al.*, 2020). The results of these studies suggest that during the first months of life, babies gradually become able to differentially use specific limbs when particular movements result in pleasant and/or interesting consequences. It is important to note that throughout the first year of life, babies continue to present "overflow" movements of the limbs that are not involved in a given action—which does not mean that they are not capable of differentiated movements in certain situations, as explained above. For example, when a baby grasps an object or shakes a rattle with one hand, the other hand performs movements that are less marked but that have the same characteristics (Soska, Galeon, & Adolph, 2012; D'Souza, Cowie, Karmiloff-Smith, & Bremner, 2017), particularly when the movements are rapid (D'Souza *et al.*, 2017).

The studies presented above suggest that very early on, babies are able to act on their physical environment. But are they able to anticipate the effects of their actions on the physical environment? Studies using eye trackers have provided some initial responses to this question. These devices allow us to determine more or less precisely where a baby is looking on a screen, and therefore to measure whether or not they are able to anticipate the appearance of a contingent stimulus on a screen. It has been found that babies aged 6 and 8 months are able to trigger the appearance of an image on a screen by fixating a point on the screen, and to move their eyes toward the location where it will appear in anticipation of its appearance (Wang *et al.*, 2012). This capacity for anticipation has also been observed in 10-month-old babies in a task where they can trigger the display of a video by pressing a button with their hand (Kenward, 2010) (see fig. 1.d). In addition, a study by Zaadnoordijk *et al.* (2020) using neurophysiological measures highlighted the expectations that babies aged 3-4.5 months form during their exposure to the mobile paradigm (see above). When the contingency between their movements and those of the mobile ended (extinction phase), half of the 65 babies they observed showed a mismatch negativity, reflecting the violation of their expectations. Interestingly, the babies who presented a mismatch negativity were the same ones who showed a behavioral reaction to the disruption of the contingency: an increase and then a sudden decrease in their movements, which was more pronounced for the arm that had been connected to the mobile than for the other arm.

Babies' ability to act on their physical environment is intrinsically linked to their sensory experiences during exploration. By exploring their environment, babies not only discover the possible ways they can act on the world, they also refine their perception. A study by DeCasper and Spence (1986), for example, showed that newborns are able to adapt their sucking so that it triggers the auditory presentation of a text that their mother had read during pregnancy rather than a new text. There are various examples in the literature of babies' adaptation of their actions to the sensory consequences: babies aged 3-4 months seem to be able to maintain a preferred level of visual stimulation by adapting their leg movements (Fagen & Rovee, 1976; Mast, Fagen, Rovee-Collier, & Sullivan, 1980); at 12 months, babies are more interested in contingencies that involve varied rather than repeated images as perceptual feedback (Siqueland & DeLucia, 1969). Babies' learning and memorization of a contingency that they have explored also seems to be modulated by the sensory feedback that is involved. Multimodal stimuli seem to be more effective than unimodal stimuli in increasing babies' propensity to perform an action that triggers them as perceptual feedback, both during and after exposure (McKirdy & Rovee, 1978; Kraebel, Fable, & Gerhardstein, 2004; Tiernan & Angulo-Barroso, 2008). This beneficial effect of multimodal stimuli on learning could be partly explained by Bahrick's intersensory redundancy hypothesis (Bahrick, Lickliter, & Flom, 2004). According to this theory, multimodal stimuli allow the baby to focus on the amodal aspects of the contingency (e.g., rhythm or intensity), thus increasing the baby's attention and interest in the contingency (Kraebel, 2012).

The development of manual skills

The development of manual skills during the first year of life is easily observable, and seems to clearly illustrate babies' development of body knowledge. As an example, let us look at babies' ability to reach toward an object that is placed in front of them. During pregnancy, fetuses already exhibit the beginnings of this ability: for example, they make hand movements directed toward the mouth, the eyes (Zoia *et al.*, 2007; Kurjak *et al.*, 2004), or the umbilical cord (Piontelli, 2010). The beginnings of reaching movements are also found at birth: newborns are able to reach their hands out toward an object, but only under very specific conditions of «liberated motor activity»[3] (Grenier, 1981; von Hofsten, 1982). The development of reaching movements during the first months of life has been richly documented since the original work of White, Castle, and Held (1964). The findings of the work carried out on the subject over the last fifty years suggest that babies perform their first "real" reaching movements around the age of 3-5 months (see e.g., Fagard, 2001 for a review of the literature). Various hypotheses, not all of which we will explore here, have been put forward in order to explain the development of reaching movements during the first months of life (see chapter XI of Fagard, 2001). One of these hypotheses (see e.g., Corbetta, DiMercurio, Wiener, Connell, & Clark, 2018) argues that three mechanisms underpin the development of reaching movements: (1) intermodal perception, which offers babies unified perceptual feedback from their arm movements, (2) sensitivity to sensorimotor contingencies, which allows them to detect the link between their arm movements and the haptic sensations resulting from contact between the hand and the object, and (3) motivation to interact with the world around them, which drives babies to repeat the movements that had previously allowed them to touch the object. According to this hypothesis, the first instance of reaching out and touching an object—which may take place by chance—is caused by an increase in babies' spontaneous motor activity in the presence of an object that occurs toward the age of 3 months (Bhat & Galloway, 2006). The multisensory (proprioceptive, haptic, and visual) sensations resulting from this first reaching/touching experience provide the baby with an observable consequence of its own action, resulting in positive reinforcement of the action. This could explain why babies repeatedly make first attempts at reaching movements accompanied by looking at the object, although these first attempts do not always result in the baby actually touching the object. In parallel to their acquisition of reaching movements, babies acquire a second manual skill during the first year of life: grasping, whose acquisition we will not present here.

Babies' manual skills become progressively more refined over the first year of life. Initially, babies' reaching and grasping movements are stereotypical and similar for any object (palmar grip with both hands). Babies then progressively take into account the affordances of the objects around them: they begin to adapt their reaching and grasping movements to the characteristics of each object. For example, they perform reaching movements only toward objects that are within reach (Rochat, Goubet, & Senders, 1999), adapt their grip to the object's size, shape, and texture (Fagard & Jacquet, 1996; Corbetta, Thelen & Johnson, 2000; Bourgeois, Kawar, Neal, & Lockman, 2005), orient the hand in anticipation of the object's position (von Hofsten & Fazel-Zandy, 1984; Lockman, Ashmead, & Bushnell, 1984), and use their two hands in complementary ways to perform

[3] "Liberated motor activity" is a method developed by Albert Grenier (1981) that consists of supporting the nape of the neck as well as the trunk during interactions, thus promoting the attention of the baby by allowing motor relaxation and prolonged visual contact.

complex actions (Fagard, 1998). Repeated practice, and thus babies' interaction with their physical environment, play a role in the enrichment of manual skills during the first year of life, as does social learning (not detailed here).

Conclusion

The studies presented in this literature review suggest that from birth, and even in utero, babies are able to use their bodies appropriately to interact with the world around them. The development of babies' body know-how—to be differentiated from the self-awareness that young children demonstrate at the age of two years—can be described through the exploration of both the body and the physical environment. Babies' development of body know-how can also be seen in their interactions with their social environment, which provides them with multiple opportunities to interact with other people and to observe them in action (evidence not reviewed here). Body know-how may allow babies to acquire a sense of agency and a sense of body ownership, and thus be the precursor of explicit knowledge of the body. The body know-how that babies possess from the earliest days of life may thus play an essential role in socio-cognitive and psychomotor development during childhood.

Nonetheless, little is currently known about the mechanisms underlying the development of this body know-how. As illustrated in the first section of this article, and as suggested by the studies presented above, two mechanisms seem to be at the core of this development: the exploitation of sensitivity to sensorimotor contingencies, and curiosity. Future research must work to more precisely characterize these two mechanisms and their role in the establishment of body know-how. Moreover, the progression from practical use of the body to explicit knowledge of the body, and on to real self-awareness, deserves to be explored in more detail in future work in neuroscience and developmental psychology.

Acknowledgments

This publication was produced with the support of the FET Open Grant 713010 "GOAL-Robots" and the ERC Grant 323674, "FEEL". The authors thank Arlette Streri for her careful reading of the manuscript.

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