

Development of reaching to the body in early infancy: From experiments to robotic models

Matej Hoffmann^{*†}, Lisa K. Chinn[‡], Eszter Somogyi[§], Tobias Heed[¶],
Jacqueline Fagard[§], Jeffrey J. Lockman[‡] and J. Kevin O'Regan[§]

^{*}Department of Cybernetics, Faculty of Electrical Engineering, Czech Technical University in Prague
Email: matej.hoffmann@fel.cvut.cz

[†]iCub Facility, Istituto Italiano di Tecnologia, Via Morego 30, 16163 Genoa, Italy

[‡]Department of Psychology, Tulane University, New Orleans, LA, USA

[§]Laboratoire Psychologie de la Perception – CNRS UMR 8242, Université Paris Descartes, Paris, France

[¶]Biopsychology and Cognitive Neuroscience, Department of Psychology and Sports Science, and
Center of Excellence in Cognitive Interaction Technology (CITEC), Bielefeld University, Bielefeld, Germany

Abstract—We have been observing how infants between 3 and 21 months react when a vibrotactile stimulation (a buzzer) is applied to different parts of their bodies. Responses included in particular movement of the stimulated body part and successful reaching for and removal of the buzzer. Overall, there is a pronounced developmental progression from general to specific movement patterns, especially in the first year. In this article we review the series of studies we conducted and then focus on possible mechanisms that might explain what we observed. One possible mechanism might rely on the brain extracting “sensorimotor contingencies” linking motor actions and resulting sensory consequences. This account posits that infants are driven by intrinsic motivation that guides exploratory motor activity, at first generating random motor babbling with self-touch occurring spontaneously. Later goal-oriented motor behavior occurs, with self-touch as a possible effective tool to induce informative contingencies. We connect this sensorimotor view with a second possible account that appeals to the neuroscientific concepts of cortical maps and coordinate transformations. In this second account, the improvement of reaching precision is mediated by refinement of neuronal maps in primary sensory and motor cortices—the homunculi—as well as in frontal and parietal cortical regions dedicated to sensorimotor processing. We complement this theoretical account with modeling on a humanoid robot with artificial skin where we implemented reaching for tactile stimuli as well as learning the “somatosensory homunculi”. We suggest that this account can be extended to reflect the driving role of sensorimotor contingencies in human development. In our conclusion we consider possible extensions of our current experiments which take account of predictions derived from both these kinds of models.

I. INTRODUCTION

The presence of various “body maps” in the brain has fascinated scientists and the general public alike, spurred by the account of Head and Holmes [1] and the discovery of somatotopic representations (the “homunculi”) in the primary motor and somatosensory cortices [2]. The attention devoted to the representations of the body in the brain has also led to numerous attempts to describe or define them, and has given rise to proposals of a variety of concepts including superficial and postural schema [1], body schema, body image, corporeal schema, etc. Yet, these concepts are umbrella notions for a range of observed phenomena rather than the result of

identification of specific mechanisms, and it has been criticized that this area of research is in a somewhat “chaotic state of affairs” [3], with limited convergence to a common view [4]. Here, we will focus on body representations that mediate implicit knowledge related to the body, its parts, and their posture relevant in the context of sensorimotor coordination.

It seems clear that body representations in the adult brain are a result of a complex interplay between genetic predispositions and both pre- and postnatal development. Work in recent years has focused on establishing the developmental trajectory of their underlying multisensory processes. This development starts in the fetus before birth (e.g., [5]; [6] for an embodied computational model), and then continues for many years (e.g., [7]–[9]). In this process, spontaneous movement and self-touch (which may also involve “grasping” the body) may play a key part. Infants frequently touch their bodies, with a rostral-caudal progression as they grow older—with head and trunk contacts more frequent in the beginning. As infants age, contacts become more caudal including hips, then legs, and eventually the feet [10]. The redundant information induced by these configurations in the motor-proprioceptive-tactile-visual manifold may facilitate learning about the body in space. Furthermore, as self-touch configurations are unique—with tactile stimulation on two different body parts and only in specific joint configurations—they might constitute a “contingent stimulus” associated with a reward or neuromodulation that bootstraps learning (e.g., [11]). As this knowledge develops, infants gain the ability to reach directly to targets on the body.

In the present article, we first report results from a series of completed as well as ongoing studies in which we observe infants’ behavioral responses, including reaching and grasping, to stimulation with buzzers on different body parts (Section II). The results from these studies then provide constraints for a sensorimotor account of our observations (Section III), followed by a (brief) integration with evidence from the neurosciences (Section IV). Then we present our modeling endeavor on a humanoid robot with artificial sensitive skin (V) and close with a discussion (Section VI).

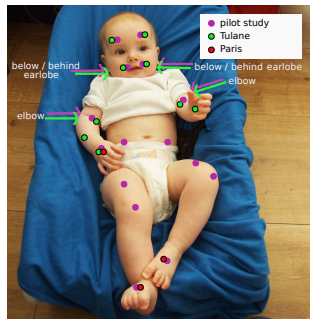


Fig. 1. An illustration of buzzer locations in each study reported here. Red dots indicate the cross sectional foot and hand locations study (Paris). Violet dots indicate the longitudinal pilot study. Green dots indicate the cross-sectional face and arms study (Tulane, New Orleans).

II. BUZZERS ON INFANTS’ BODY AND FACE

In two cross-sectional and one longitudinal study, we analyzed how 3 to 21 month old infants respond when a vibrating buzzer is attached to different parts of their bodies. We expected that differentiated movement patterns as a function of stimulus location would emerge only after about 4 months of age (c.f. [12]) and that well before infants are able to retrieve the buzzer [13], they would produce other behavioral responses that indicate knowledge of where their body was being stimulated.

A. Participants and Method

In total we observed 122 infants of ages ranging from 3 to 21 months. The infants were supine, seated in an infant seat, or on the caregiver’s lap. We attached a vibrating target to locations on the face and body using double-sided tape [13], a single location at a time and we left it there until either the infant had removed it or approximately 35 seconds had elapsed. The set of locations we used is shown in Fig. 1. From the video recordings we coded the infants’ motor responses, in particular their overall limb activity and any (attempted or successful) reaches towards the buzzer. More details are available elsewhere [13], [14].

B. Which limb is it? Increased movement of specific body parts

Our first cross-sectional study (Paris) involved 43 infants aged 3-6 months, where the buzzer locations were confined to the four limbs while the infants were in a fixed supine position in an infant seat. Very few infants were able to actually reach and grasp the buzzer, and their reactions mainly consisted of moving the limbs – see Fig. 2. We found that at 3 months, infants did not seem to differentiate stimulation on their different limbs, since independently of which limb was stimulated they responded to the buzzer stimulation in the same way, namely by increasing movements of the whole body. Interestingly, at 4 months, there was a global decrease in limb activity, and we did not find significant differences in limb activity across stimulation conditions. This may perhaps be explained by the fact that at this age, with the onset of reaching, the motor system is being reorganized and refined

Activity of stimulated and non stimulated limbs as well as baseline activity across age groups

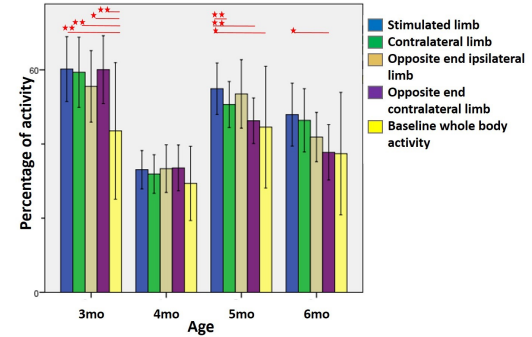


Fig. 2. Mean percentage of activity of the limb stimulated with a buzzer as compared to the three non-stimulated limbs and whole body activity at baseline (averaged activity of the four limbs) across age groups. In case of hand stimulations, ‘Opposite end limb’ refers to the feet and in case of foot stimulations it refers to the hands. Within each age group, significant differences between means are marked with an asterisk ($*p < 0.05$; $**p < 0.01$), as calculated with pairwise comparisons following the Generalized Estimating Equations (GEE) procedure.

(e.g., [15]). From 5 months, infants demonstrated specific movement patterns associated with the stimulated hand or foot (moving the stimulated limb significantly more than the non-stimulated ones or touching the stimulated limb).

C. Reaching for buzzers

To study reaching towards and grasping the buzzer, we first conducted a pilot study with one child that was followed longitudinally at home from age 4 to 18 months and with a rich set of buzzer locations including the trunk and legs. In this study, posture was not fixed but alternated between sessions (mostly supine or infant car seat – collapsed in the Figure). Fig. 3 summarizes the results for our infant (up to 12 months). Each data point is the result for a single trial: ‘Contact’ or ‘No Contact’. We found that first successful manual buzzer contact was at the upper lip location – at 4.5 months. For the body locations, the abdomen, knee, and foot, success appeared between 5 and 6 months, with an apparent proximal-to-distal trend (the thigh location not following this pattern). Success for other locations on the face (forehead and below ears) appeared at around 7 months. Success for locations on the upper limb started with the hand after 6 months, and elbow locations only after 8 months.

We also conducted a cross-sectional study on 78 children aged 7 to 21 months to investigate reaching for the buzzer (Tulane, New Orleans). This time we only used buzzer locations on the face and arms. The results are summarized in Fig. 4. Similarly to the longitudinal pilot study, infants at 7 months could already reach to the mouth locations, but the ears and forehead developed more gradually. For the buzzer locations on the body (elbow, crook of elbow, forearm, palm, top of hand), infants at 7 months could already contact the hand buzzers, but the other buzzers emerged later. For the palm buzzer, 50 percent of buzzer contacts were made with the ipsilateral fingers, and 50 percent were made with the

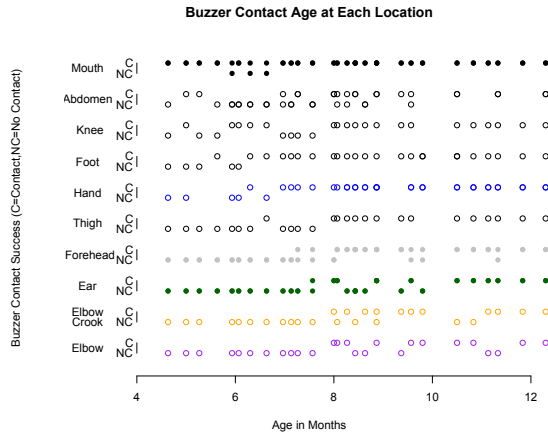


Fig. 3. Buzzer contact success (C=Contact, NC=No Contact) is shown for the pilot infant across age. The color code is chosen to match with the locations in Fig. 4 below, including filled markers for face locations. Each buzzer location is collapsed across left and right buzzer placement (hence the possibility of both C and NC for the same location and age).

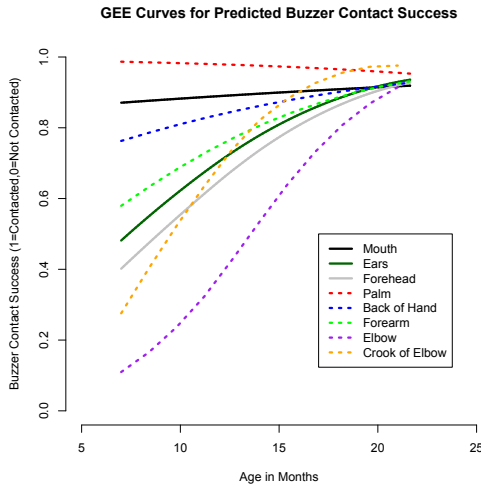


Fig. 4. The GEE predicted value of the average response is plotted over age for each buzzer location. Predicted responses were obtained using generalized estimation equations (GEE) testing the effects of Age, Buzzer Location, and the Age x Buzzer Location interaction on buzzer contact success. A value of 0 on the y-axis indicates an average prediction of no buzzer contact, while 1 indicates an average prediction of buzzer contact. Color codes match Fig. 3 for common locations.

contralateral hand. Contralateral reaches for the palm buzzer (and other locations that could be reached with either hand) increased with age. For the back of hand, all buzzer contacts were made with the contralateral hand, since ipsilateral contacts were impossible.

D. Conclusion of experiments with infants

Overall, our infant experiment results suggest that: (i) at 3 and 4 months the infant does not respond to a buzzer on a limb by moving that particular limb, but rather responds in an undifferentiated way by moving its whole body; (ii) the limb-specific movement and buzzer-oriented reaching responses

develop dramatically between 4 and 12 months. Certain locations are reached earlier than others, presumably because they correspond to innate reflexes (around the mouth), because they are easier to attain from the infant’s natural postures, or because they do not move very much relative to the body.

III. A SENSORIMOTOR FRAMEWORK

In order to understand the empirical data, we set out some theoretical suggestions. We divide our considerations into two parts: first, how does the infant’s brain determine which body part is stimulated (to then possibly be able to move that body part)? Second, how does the infant’s brain implement reaching to the buzzer with a hand or other effector?

A. Determining which body part is stimulated

Evidence from the neurosciences suggests that somatosensory and motor “homunculi”—orderly neural maps that receive peripheral somatosensory input and, in turn, project from the cortex to the periphery—are present in the brain very early. However the mere presence of such map-like neuronal organization does not mean that the infant’s brain “knows” where a stimulation is on its body, or how to move its arm rather than, say, its foot: the brain must establish mechanisms that link sensory and motor maps and allow the infant to make movements appropriate for the somatosensory input.

The basis of such mechanisms would presumably rely on the analysis of the statistical relationships of sensory and motor information, a mechanism that has been called “sensorimotor contingencies” [16]. The idea is that infant exploratory behavior may be guided by intrinsically defined rewards related to sensorimotor information (perhaps specifically related to tactile receptors [11] or “the joy of grasping” [17]), as articulated by the “intrinsic motivation” or “adaptive curiosity” frameworks [18]. During exploration, the infant’s brain continually elicits actions and attempts to catalogue and organize the resulting sensory effects so as to become familiar with, and be able to predict, the resulting interactions it has with the world.

The existence of anatomically pre-wired maps in the brain, which approximately preserve the topology of the body, may be a starting point that facilitates the creation of coordinated movement and the organization of the related sensorimotor contingencies. Overall however, the task of extracting sensorimotor contingencies will be a difficult task because of the vast number of sensory inputs, motor outputs, and their statistical dependencies. We therefore expect this process of lining up sensory and motor information through their statistical properties to be long and gradual. In particular, we imagine that the correlations that will emerge most easily will be those that are most systematic. Thus, perhaps the simplest relationships to extract are those that link motor actions to immediately resulting proprioceptive changes: Whenever a muscle is innervated, accompanying muscle spindles will systematically tend to fire. Relations between motor output and tactile input will be almost as systematic. If the infant happens to move its hand, then not only proprioceptive sensors, but

also the skin on the hand will deform, possibly brush against clothes or an object, and skin receptors on the hand will systematically signal a change; if the infant happens to move its foot, there will be systematic changes in the somatosensory foot region (we use somatosensory to denote proprioceptive and tactile afferents together).

Our sketch is simplistic in many ways. For instance, we currently ignore the question about the origin and nature of the initial movements. It is often assumed that infants initially move randomly (“motor babbling”), but more detailed accounts have been put forward of how behavior may emerge from basic neural properties [6] and changes in the role of transmitters and neuronal communication [19]. On the sensory side, we must consider that body surface areas that cannot be moved directly, like the back and abdomen, will also receive tactile stimulation through movements of the limbs: if the baby is lying on its back and pushes on a leg, stimulation on its back will change as the leg push causes the body to roll over.

Finally, our current sketch, as well as the tactile-motor experiments we have reported, ignore all social aspects of child development. Social interactions not only lead to numerous other-induced sensory experiences, but also embed these experiences in complex, reciprocal interaction cascades that are critical for the development of action concepts and language. Such factors, in addition to the basic sensorimotor processes we address in the current project, are most likely also important determinants of body representations.

Knowledge of sensorimotor contingencies does, furthermore, not per se explain which motor commands must be issued to attain a specific motor goal. Contingencies are developed as the sensory effects of ongoing movements, whereas a motor plan requires establishing the reverse contingencies, namely the motor commands necessary to obtain the related sensory signals. In psychology, ideomotor theory formalizes this approach and posits that motor actions are derived from the intended resulting sensory consequences [20]. In the current context, motor commands could be learned if the infant’s intrinsic motivation mechanism includes the goal of increasing and refining its knowledge of particular sensorimotor correlations: this would cause the infant, given a sensory stimulation, to use motor babbling and later, systematic exploration, to discover the particular motor actions that give rise to that particular sensation. In this way it would learn, over time, which actions to undertake in order to obtain any particular sensation.

What would be the behavioural manifestation of the progressive learning of sensorimotor contingencies? If we assume that somatosensory and motor maps are, at first, only crudely organized, and that the learnt contingencies are initially unspecific, stimulation of a body location would not be expected to elicit movements of the baby specific to that location. On the contrary, we would expect fairly global—random or exploratory—motor responses of the whole body. But as knowledge of the contingencies improves in precision, the infant would progressively explore actions that more specifically modulate the sensation at a particular stimulated

location. This is clearest in the case of stimulation of a limb: prior spontaneous movement of the limb might often produce tactile stimulation on that limb through rubbing of clothes or contact with an object. At a later time, when stimulated in a similar way on the limb, the infant’s brain might try to explore how it could replicate or modulate that stimulation by moving the limb that was previously stimulated. To find the appropriate action, the infant would move the whole body, and then progressively narrow down its exploration until it finds the limb movement that most effectively modulates that stimulation.

We hypothesize that sensorimotor experience and extraction of contingencies are driving factors that guide the formation and refinement of unisensory and multisensory maps that relate body and environment. Presumably, these “body models” are strongly related to space in parietal regions, whereas the primary sensory and motor regions reflect statistics that are predominantly related to the physical body. Accordingly, we interpret the higher-level functions currently assigned to these areas, such as multisensory integration, memory, and executive control, as subfunctions related to the handling of the statistical properties of the organism’s environment.

B. Reaching for a tactile stimulus

Our proposal may provide an account for how a baby responds to touch on a limb, first by moving its whole body, and later by moving the appropriate limb. In this section, we apply this idea to our infant tactile stimulation experiments to attempt an explanation of the infant’s hand reaches.

In the first stages of development, correlations between somatosensory and motor maps will allow the infant to move a limb that has been stimulated with a buzzer. More rarely however, and therefore learned presumably somewhat later in development, the infant will detect correlations deriving from (unintended) self-touch, that is, one of its hands touches some other body part, such as the trunk, the knee, the face, or the other hand. Neurons that are specifically related to self-touch have been reported in area 5 of the monkey parietal cortex [21].

Equipped with the intrinsic motivation to further explore such correlations, the infant will learn that, when stimulated say on the abdomen, it can recreate such stimulation by a certain motor command, namely moving one hand to that location. This then provides a mechanism by which the infant will eventually be able to reach towards a buzzer that is attached to that location.

However, such a mechanism will presumably provide movement trajectories only for previously used initial arm postures. We would expect that, at least at first, accurate reaching would only occur starting from these previously occurring arm postures. Furthermore, this simple explanation cannot explain how the infant might additionally account for the posture of the target limb. Body parts such as the leg, foot, or other hand can move in space relative to the trunk. Thus, information about the posture of the target limb must be factored into the movement.

It may be, as suggested by Graziano et al. [22] for monkeys, that such “factoring in” of a third, postural variable has been innately pre-wired for some behaviors in the form of “complex sensorimotor primitives”. This would account for an infant’s ability to reach to its mouth from any arm posture, and perhaps even independently of the head and mouth position. However, it is also conceivable that such movement patterns are learned in the womb, a place in which movement is strongly restricted, thus favoring certain particular contingency experiences. During development, these behaviors will be tuned as motor abilities unfold and the body changes shape. The tuning will be gradual and it will be based on learning of third-order correlations involving proprioception and/or vision, in addition to tactile and motor information.

The proposed mechanisms differ from the “classical” perspective based on vector geometry and transformation of spatial information between different reference frames [23]. Robotic simulations to be presented in Section V-C will help flesh them out.

IV. INTEGRATING SENSORIMOTOR AND NEUROSCIENTIFIC ACCOUNTS

Over the last 30 years, neuroscientific research has established that many neurons in parietal and premotor cortex produce firing patterns that reflect spatial information in many different reference frames, integrating information from all sensory modalities. The prevalent view of sensorimotor processing in these regions is that this integration requires transformation between the reference frames inherent to the different senses, such as a 3D-like reference frame in vision and a skin-based reference frame in touch [23]. Infant development, then, would involve establishing and refining unisensory spatial maps and the transformations between them to allow sensory integration and their use for motor output. For instance, the infant must learn how tactile information on the foot must be combined with postural information of the leg to learn a transformation, or “mapping”, from skin to 3D space. Having derived the 3D location of a touch by appropriate spatial transformation, an eye or hand movement can then be planned towards the spatial location of the tactile stimulus on the foot.

It is becoming increasingly obvious that these presumed transformation and integration processes optimise the use of information so as to be statistically optimal with respect to the reliability of each integrated signal (e.g. [24], [25]). In this view, development involves deriving the statistical properties of the body’s sensory systems. For instance, the infant must learn that proprioceptive information of the leg is comparatively unreliable and learn to use vision to refine the estimate of limb position.

Several computational mechanisms that achieve transformation and optimal integration for some specific sensorimotor functions, such as integration of two senses, have been put forward. Current proposals involve different levels of abstraction, such as explaining behavior with Bayesian statistical principles and explaining neuronal firing in neural networks. Although

they do not yet give a coherent view of the general mechanisms the brain may be using (see [23], [25]), such accounts are promising.

The sensorimotor contingency framework we have laid out above relies even more strongly on the idea that the brain derives statistical properties—those that link body and environment. Here, integrating sensory information, transforming between reference frames, and taking account of signal reliability, are by-products of the brain’s main purpose of relating body and world for the purpose of action. In this view, the infant must learn that a concurrent touch on the left hand and the nose, combined with specific postural information of the arm, entails that the hand has touched the nose, and that this sensory information must be reproduced to relieve an itch on the nose at a later time.

These considerations represent interesting ideas for robot development: they suggest that both the modular structure of cortical regions and the characteristics of neuronal firing may be emergent properties of an overarching processing principle.

V. REMAPPING AND SELF-TOUCH IN ROBOTS

The body, with its geometry and sensorimotor capacities, is of course constitutive in the construction of body representations. Thus, simulated agents or, better, robots, constitute the best tools for such a modeling endeavor. For human body representations, humanoid robots are the platform of choice. Robot “body schemas” often have quite different characteristics (fixed, centralized, explicit, amodal) than what we expect from their biological counterpart, but there has been work on robot body models learning (self-calibration) as well as modeling the biological body representations and their development using robots (see [26], [27] for surveys). The majority of this work is more in line with the “classical” account of body representations (with explicit frame of reference transformations and perception separated from action), which lends itself more easily to robotic implementations. However, there are notable exceptions: in particular the work of Kuniyoshi and colleagues (e.g., [6]) dealing with fetal development.

A. *The iCub humanoid robot with whole-body artificial skin*

The morphology of the iCub humanoid robot (Fig. 5B, [28]) is modeled after a 4-year old child: it has a similar kinematic configuration and sensory repertoire to humans (on some level of abstraction). Importantly, it has been recently equipped with a whole-body artificial skin comprising around 3000 pressure-sensitive tactile elements (taxels) (Fig. 7 A). Thus, it is now possible to model body representation acquisition through tactile-proprioceptive-visual-motor correlations on this platform. The parallel of a baby removing a buzzer and the robot performing self-touch on the torso is in Fig. 5.

B. *Reaching for a tactile stimulus using inverse kinematics*

In Roncone et al. (2014) [29], we implemented reaching for a tactile stimulus by modifying classical robotic solutions and developing a new inverse kinematics formulation to deal with

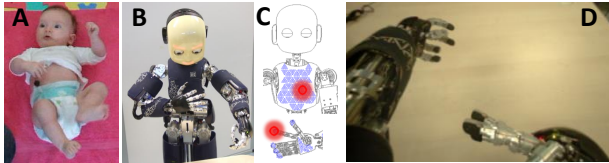


Fig. 5. Self-touch on torso. (A) Removal of buzzer from abdominal area in 5-month old infant. (B) iCub touching its trunk with index finger. (C) Tactile stimulation corresponding to “double touch” event—torso and right index finger. (D) View from iCub’s left camera—contact location out of sight.

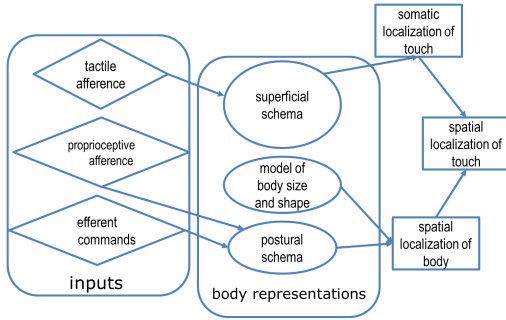


Fig. 6. Model of tactile spatial localization. Adapted from [30].

the fact that the target is on the body rather than fixed in space (cf. video: <https://www.youtube.com/watch?v=pfse424t5mQ>). This work serves as a baseline here: the behavior is instantiated in the robot, thus the whole loop from tactile stimulation to motor action is in place. Our next steps consist of replacing the engineered modules with those that are inspired by infant development (behaviorally and neurally).

C. Remapping decomposed into modules

Longo et al. [30] propose that spatial localization of touch may be obtained by combining (1) tactile localization on skin and (2) spatial localization of body / position sense (i.e. where in space the particular body part is). These components (high-level percepts) draw on tactile and proprioceptive (and possibly motor) inputs and three modules or representations: superficial schema, postural schema, and a model of body size and shape – as illustrated in Fig. 6. This approach provides an easier starting point for robotic modeling than the sensorimotor approach. We have set out to implement this modular framework in the robot, which will be detailed in the next sections.

1) *Tactile homunculus (superficial schema)*: One component or “representation” that seems necessary is the “tactile homunculus” or superficial schema. In Hoffmann et al. [31], we have obtained this homuncular representation for one half of the upper body of the iCub humanoid: Local stimulations of the skin surface were fed into a self-organizing map algorithm (SOM) that was additionally constrained such that the sequence of body parts on the output sheet mimicked that from the cortex (area 3b) – see Fig. 7B. This representation now provides a building block that we can deploy in further modeling.

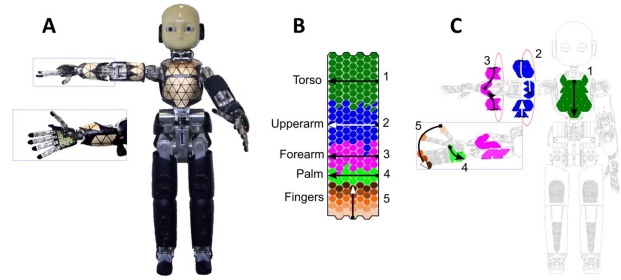


Fig. 7. iCub skin and tactile homunculus. (A) Photograph of the iCub robot with artificial skin exposed on the right half of the upper body (1154 taxels in total). (B) Representation of tactile inputs learned using a Self-Organizing Map – a 24×7 neuronal sheet. (C) Schematics with skin patches unfolded and colored to mark the correspondence with (B). Arrows illustrate the relationship in orientation between the skin parts and the learned map. From [31].

2) *Proprioceptive homunculus (postural schema)*: In Hoffmann and Bednarova [32], we strived to provide a computational model of the representation of proprioception in the brain and its development. We used a simulator of the iCub humanoid robot and had it randomly move its arm in front of the face and follow the arm with gaze, thus “babbling” in Cartesian space, inspired by analogous behavior in infants (“hand regard”). Unlike for the “superficial schema”, attempting to obtain a robot “postural schema” revealed a number of gaps in our knowledge.

As elaborated in [32] in more detail and with additional references, first, the principal proprioceptors are constituted by muscle spindles, which deliver information about muscle length and speed. In primates, this information is relayed to the primary somatosensory cortex and eventually the posterior parietal cortex, where integrated information about body posture (postural schema) is presumably available. However, it is not clear what variable neurons in the ascending pathway and in the cortex are actually encoding. To an engineer, joint angles would seem the most useful variables. However, the lengths of individual muscles have nonlinear relationships with the angles at joints and it is not clear where this transformation would occur. Second, Kim et al. (2015) [33] identified different types of proprioceptive neurons in SI, namely neurons that fire proportionally to joint angle (single or multi-digit) and those that directly register posture. The SOM algorithm seems to naturally support the latter type only though, learning to pick up the most frequent postures (or “postural synergies”). In summary, the nature of encoding of posture as well as the development of the postural schema remains unclear.

3) *Spatial localization of touch – a neural model proposal*: Finally, we present our work in progress—a proposal for a neurobotic implementation of the scheme proposed in [30] (Section V-C and Fig. 6) – see Fig. 8. Tactile afferents are simply the pressure values read off the individual taxels stimulated on the robot skin. Proprioceptive afferents consist of joint angles of all the degrees of freedom (joints) relevant for the task. The primary representations draw on the output of previous sections. The activations in the superficial schema—

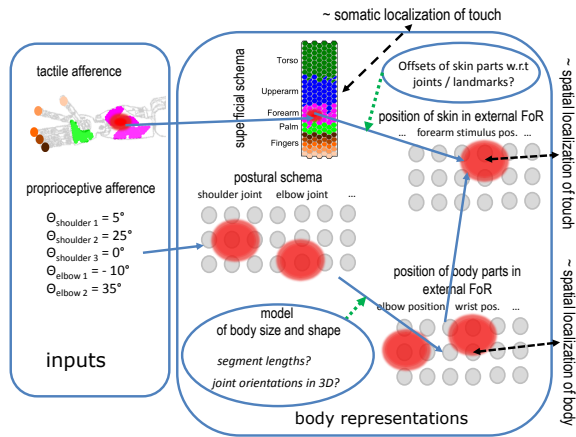


Fig. 8. Spatial localization of touch – neural network model proposal (cf. Fig. 6). FoR = Frame of Reference. See text for details.

which is a distorted map of the skin surface—provide tactile localization on the skin. The key challenge is to determine the form that the “model of body size and shape” will take. As an initial hypothesis, we can consider this model as knowledge embedded in (synaptic) weights in the connections from the postural schema to the “position of body parts in external FoR” (FoR = Frame of Reference) neural population. First guesses as to what the information encoded may be are guided by the forward kinematics mapping in the robot (segment lengths and joint orientations in 3D). The “position of body parts in external FoR” hypothetical neural population thus corresponds to the spatial localization of body. Combining the inputs from the “superficial schema” and the “position of body parts in external FoR” populations finally gives rise to remapping of the tactile stimulus into external coordinates (it seems that knowledge about the position/offset of skin parts with respect to some joints/landmarks will also be needed).

To wrap up the section on robotic modeling, our work so far has a bias toward “classical”, modular, divide-and-conquer solutions, as is often symptomatic of robotic and artificial intelligence approaches to cognition. In the future, we will strive to obtain the “modules” and the use of specific frames of reference in an emergent fashion—as proposed at the end of section IV. The primary homuncular-like representations obtained for the robot may then still constitute useful building blocks, but their connections and interactions should emerge in a more holistic sensorimotor setting. The (intrinsic) motivational component that may drive the exploration and facilitate learning constitutes one of our next foci.

VI. DISCUSSION, CONCLUSION, FUTURE WORK

The empirical data, conceptual framework, and robotic modeling described above are at present too disparate to allow a proper connection between them. The sensorimotor approach is not sufficiently developed to make precise predictions about the course of infants’ responses to buzzers. Models using the humanoid robot are currently mostly couched in the classical framework in which “spatial remapping” to reach for the body

occurs through an explicit chain of frame of reference transformations, rather than implicitly as presumably happens in the infant’s brain. We are however planning work more in line with the sensorimotor account. Meanwhile our collaboration has generated new hypotheses, insights, and predictions that will be investigated further in existing data or tested in future experiments. Some of the points that have come to light are as follows.

There undoubtedly exist some (more or less complex) pre-wired primitive movement “reflexes” [22], that may help bootstrap the baby’s acquisition of body knowledge. It will be interesting to check whether such reflexes already incorporate the equivalent of coordinate transformations, allowing, for example, a reach to the mouth to occur independently of the arm’s starting position, and independently of the rest of the baby’s posture. Primitive reflexes, and more generally the first reaching movements, may also be limited by the fact that connections between brain hemispheres develop later than connections within hemispheres. We are planning in future to confront this idea with the empirical data.

Another factor that may prioritize development of certain particular reaching capacities might be the baby’s habitual resting posture, favouring natural frequent contact of the hands with certain body parts, and thereby learning of reaching to those parts. In particular, in our longitudinal pilot study with a single baby we observed that between 5 and 7 months of age, the infant’s arms initially rested around the waist, but later, as the legs started bending, the hands would more often spontaneously contact the knees and then the feet—these habitual resting locations were then correlated with the progression of buzzer removal success. This is to be documented more accurately on a larger sample.

Presumably, but this remains to be confirmed in further analysis of the empirical data, reaching that necessitates remapping of spatial coordinates (for example to the other hand or to the legs) appears later than reaching to body parts that are more or less fixed with respect to the body (the abdomen, the face region – although this moves to some extent). Also, we expect that a reach learned starting from an initial arm posture will not be possible from a different arm posture. Evaluating these claims will be a way of distinguishing sensorimotor type models from the more classical models in which reaching is realized in a sequential fashion composed of stimulus localization, remapping into an external reference frame, and computation of a reaching trajectory to that location—whereby these transformations would have to automatically incorporate current body posture. Another point is the implication of vision. We have not yet included vision in our analyses—since it seems that at first infants are not using visual feedback. However clearly at the later stages of development visual tracking must be included, and we will modify the models that we postulate to accommodate the results.

Finally, we have been focusing on reaching with the upper limbs in order to understand how body maps develop. It should be noted, however, that the lower limbs are effectors as well and can be used to localize targets on the body, especially those

that are situated on the opposite leg. Our informal observations suggest that young infants spend a considerable amount of time rubbing their feet together as well as rubbing one foot along the opposite leg. Infants also spend time bringing their feet to their hands (or vice versa) and in some instances bringing the foot to the face. Understanding how a fully integrated map of the body develops will also require viewing the feet and legs as effectors that are incorporated into an overall sensorimotor representation of the body.

In conclusion, our converging program of infant and robotic approaches has provided a starting point for further work on modelling how the infant reaches its body.

ACKNOWLEDGMENT

M.H. was supported by a Marie Curie Intra European Fellowship (iCub Body Schema 625727) within the 7th European Community Framework Programme and the Czech Science Foundation under Project GA17-15697Y. E.S., J.F. and K. O’R. are grateful for financing from ERC Advanced Project #323674, FEEL and FET-OPEN grant GoalRobots. L.C. and J.L. were supported in part by the National Institutes of Health Award 5R01HD067581. T.H. is supported by Emmy Noether grant He 6368/1-1 by the German Research Foundation (DFG).

REFERENCES

- [1] H. Head and H. G. Holmes, “Sensory disturbances from cerebral lesions,” *Brain*, vol. 34, pp. 102–254, 1911.
- [2] W. Penfield and E. Boldrey, “Somatic motor and sensory representation in the cerebral cortex of man as studied by electrical stimulation,” *Brain*, vol. 37, pp. 389–443, 1937.
- [3] G. Berlucchi and S. M. Aglioti, “The body in the brain revisited,” *Exp. Brain Res.*, vol. 200, pp. 25–35, 2009.
- [4] F. de Vignemont, “Body schema and body image - pros and cons,” *Neuropsychologia*, vol. 48(3), pp. 669–680, 2010.
- [5] M. Milh, A. Kaminska, C. Huon, A. Lapillonne, Y. Ben-Ari, and R. Khazipov, “Rapid cortical oscillations and early motor activity in premature human neonate,” *Cerebral Cortex*, vol. 17, no. 7, pp. 1582–1594, 2006.
- [6] Y. Yamada, H. Kanazawa, S. Iwasaki, Y. Tsukahara, O. Iwata, S. Yamada, and Y. Kuniyoshi, “An embodied brain model of the human foetus,” *Scientific Reports*, vol. 6, 2016.
- [7] A. J. Bremner and C. Spence, “Chapter seven - the development of tactile perception,” in *Advances in Child Development and Behavior*, ser. JAI, 2017, vol. 52, pp. 227–268.
- [8] M. Gori, M. Del Viva, G. Sandini, and D. C. Burr, “Young children do not integrate visual and haptic form information,” *Current Biology*, vol. 18, no. 9, pp. 694–698, 2008.
- [9] B. Pagel, T. Heed, and B. Röder, “Change of reference frame for tactile localization during child development,” *Developmental science*, vol. 12, no. 6, pp. 929–937, 2009.
- [10] B. L. Thomas, J. M. Karl, and I. Q. Wishaw, “Independent development of the reach and the grasp in spontaneous self-touching by human infants in the first 6 months,” *Frontiers in psychology*, vol. 5, p. 1526, 2015.
- [11] O. Sporns and G. M. Edelman, “Solving Bernstein’s problem: A proposal for the development of coordinated movement by selection,” *Child development*, vol. 64, no. 4, pp. 960–981, 1993.
- [12] H. Watanabe and G. Taga, “General to specific development of movement patterns and memory for contingency between actions and events in young infants,” *Infant Behavior and Development*, vol. 29, no. 3, pp. 402–422, 2006.
- [13] J. E. Leed, “Canonical body knowledge, perceptuo-motor coordination, and tactile localization,” Ph.D. dissertation, Tulane University, New Orleans, Louisiana, USA, 2014.
- [14] E. Somogyi, L. Jacquey, T. Heed, M. Hoffmann, J. J. Lockman, L. Granjon, J. Fagard, and J. K. O’Regan, “Which limb is it? Responses to vibrotactile stimulation in early infancy,” *British Journal of Developmental Psychology*, [in revision].
- [15] D. Corbetta, S. L. Thurman, R. F. Wiener, Y. Guan, and J. L. Williams, “Mapping the feel of the arm with the sight of the object: on the embodied origins of infant reaching,” *Frontiers in psychology*, vol. 5, p. 576, 2014.
- [16] J. K. O’Regan and A. Noe, “A sensorimotor account of vision and visual consciousness,” *Behavioral and Brain Sciences*, vol. 24, pp. 939–1031, 2001.
- [17] E. Oztop, N. S. Bradley, and M. A. Arbib, “Infant grasp learning: a computational model,” *Experimental brain research*, vol. 158, no. 4, pp. 480–503, 2004.
- [18] J. Gottlieb, M. Lopes, and P.-Y. Oudeyer, “Motivated cognition: Neural and computational mechanisms of curiosity, attention, and intrinsic motivation,” in *Recent Developments in Neuroscience Research on Human Motivation*. Emerald Group Publishing Limited, 2016, pp. 149–172.
- [19] N. Dehorter, L. Vinay, C. Hammond, and Y. Ben-Ari, “Timing of developmental sequences in different brain structures: physiological and pathological implications,” *European Journal of Neuroscience*, vol. 35, no. 12, pp. 1846–1856, 2012.
- [20] O. Herbort and M. V. Butz, “Too good to be true? ideomotor theory from a computational perspective,” *Frontiers in psychology*, vol. 3, p. 494, 2012.
- [21] H. Sakata, Y. Takaoka, A. Kawarasaki, and H. Shibusani, “Somatosensory properties of neurons in the superior parietal cortex (area 5) of the rhesus monkey,” *Brain research*, vol. 64, pp. 85–102, 1973.
- [22] M. S. Graziano, C. S. Taylor, T. Moore, and D. F. Cooke, “The cortical control of movement revisited,” *Neuron*, vol. 36, no. 3, pp. 349–362, 2002.
- [23] T. Heed, V. N. Buchholz, A. K. Engel, and B. Röder, “Tactile remapping: from coordinate transformation to integration in sensorimotor processing,” *Trends in cognitive sciences*, vol. 19, no. 5, pp. 251–258, 2015.
- [24] S. Badde and T. Heed, “Towards explaining spatial touch perception: weighted integration of multiple location codes,” *Cognitive neuropsychology*, vol. 33, no. 1-2, pp. 26–47, 2016.
- [25] X. Pitkow and D. E. Angelaki, “Inference in the brain: Statistics flowing in redundant population codes,” *Neuron*, vol. 94, no. 5, pp. 943–953, 2017.
- [26] M. Hoffmann, H. Marques, A. Hernandez Arieta, H. Sumioka, M. Lungarella, and R. Pfeifer, “Body schema in robotics: A review,” *Autonomous Mental Development, IEEE Transactions on*, vol. 2, no. 4, pp. 304–324, Dec 2010.
- [27] G. Schillaci, V. V. Hafner, and B. Lara, “Exploration behaviors, body representations, and simulation processes for the development of cognition in artificial agents,” *Frontiers in Robotics and AI*, vol. 3, p. 39, 2016.
- [28] G. Metta, L. Natale, F. Nori, G. Sandini, D. Vernon, L. Fadiga, C. von Hofsten, K. Rosander, M. Lopes, J. Santos-Victor, A. Bernardino, and L. Montesano, “The iCub humanoid robot: An open-systems platform for research in cognitive development,” *Neural Networks*, vol. 23, no. 8-9, pp. 1125–1134, 2010.
- [29] A. Roncone, M. Hoffmann, U. Pattacini, and G. Metta, “Automatic kinematic chain calibration using artificial skin: self-touch in the iCub humanoid robot,” in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, 2014, pp. 2305–2312.
- [30] M. Longo, E. Azanon, and P. Haggard, “More than skin deep: Body representation beyond primary somatosensory cortex,” *Neuropsychologia*, vol. 48, pp. 655–668, 2010.
- [31] M. Hoffmann, Z. Straka, I. Farkas, M. Vavrecka, and G. Metta, “Robotic homunculus: Learning of artificial skin representation in a humanoid robot motivated by primary somatosensory cortex,” *IEEE Transactions on Cognitive and Developmental Systems*, 2017.
- [32] M. Hoffmann and N. Bednarova, “The encoding of proprioceptive inputs in the brain: knowns and unknowns from a robotic perspective,” in *Kognice a unely život XVI [Cognition and Artificial Life XVI]*, M. Vavrecka, O. Becev, M. Hoffmann, and K. Stepanova, Eds., 2016, pp. 55–66.
- [33] S. S. Kim, M. Gomez-Ramirez, P. H. Thakur, and S. S. Hsiao, “Multimodal interactions between proprioceptive and cutaneous signals in primary somatosensory cortex,” *Neuron*, vol. 86, no. 2, pp. 555–566, 2015.