Neurocognitive modulation of pain perception

State-trace analysis
Infants lost in peripersonal space
Decision making and movement planning
A significant challenge in developing spatial representations for the control of action is one of multisensory integration. Specifically, we require an ability to efficiently integrate sensory information arriving from multiple modalities pertaining to the relationships between the acting limbs and the nearby external world (i.e. peripersonal space), across changes in body posture and limb position. Evidence concerning the early development of such spatial representations points towards the independent emergence of two distinct mechanisms of multisensory integration. The earlier-developing mechanism achieves spatial correspondence by representing body parts in their typical or default locations, and the later-developing mechanism does so by dynamically remapping the representation of the position of the limbs with respect to external space in response to changes in postural information arriving from proprioception and vision.

Embodied spatial representations

When we explore extrapersonal space (Glossary), not only do we register its objective properties but we also perceive its affordances for action and interaction [1]. To act on our environment, we require ‘embodied representations’ of the locations of objects that are coded with respect to our body and limbs. Numerous advances in our understanding of embodied processes in mature adults and non-human animals have emerged in recent years. Notably, neuroscientific research has uncovered evidence for the existence of neural circuits that selectively represent the multisensory space within immediate reach, known as ‘peripersonal space’ [2–8]. The distinction between peripersonal space and extrapersonal space has, however, remained largely unexplored by developmental researchers (e.g. Refs [9,10]). In this article we show how seemingly conflicting findings from research on early spatial abilities in infancy can be resolved by considering spatial representations in an embodied context. We go on to outline some of the specific computational challenges associated with peripersonal representations and, based on recent behavioural and neuroscientific research, propose a two-mechanism framework for explaining the development of spatial representations underlying action in peripersonal space.

Conflicting findings in research on spatial development in infants

Before infants begin to manipulate objects and navigate through their environments, they have little obvious need for detailed spatial representations. Yet, research using measures of looking-duration has shown that, within a few months of birth, human infants are able to form sophisticated spatial representations of their environment [11,12].

Glossary

**Efferent copies:** copies of motor commands sent from motor regions to other regions that are not involved in the immediate control of movement. They can be used, for example, to update representations of current limb position, thus providing a rapid estimate of current limb position, independently (or in advance of) sensory input.

**Embodied representations:** representations of the external environment in relation to the perceiver’s body (including their individual limbs). Embodied representations are required if one is to act upon the environment.

**Extrapersonal space:** the space beyond the body (cf. personal space). Extrapersonal space can be subdivided into that which is out of reach of the body and that which is in reach of the body (peripersonal space).

**Mirror illusion:** participants sit with both arms held out straight in front of their body, with a mirror placed between them – one arm is hidden, the other is visible both directly and via reflection. The reflected arm provides a visual substitute for the hidden arm. Changing the distance of either arm from the mirror results in the ‘virtual’ and the real arm occupying different locations. This conflict between vision and proprioception leads to a recalibration of proprioception towards vision, and the illusion that the virtual arm is, in fact, the real arm.

**Multisensory space:** a neural representation of space that encodes stimulus location across multiple sensory modalities in a similar way – for example, in a single map of space in which individual neurons respond to visual, auditory and somatosensory stimuli arising from approximately the same location. Such maps are found in the superior colliculus, posterior parietal cortex and the premotor cortex.

**Peripersonal space:** the reachable space immediately surrounding the body and limbs or individual body parts.

**Premotor cortex:** a large cortical territory immediately anterior to primary motor cortex that receives input from multiple sensory modalities and cortical areas. This region has been studied extensively in macaque monkeys and is associated, among other things, with the dynamic updating of limb and body position, the representation of stimuli in the space immediately surrounding the limbs (peripersonal space) and the selection, generation and control of bodily movements.

**Principle of optimal integration:** information arising from different sensory modalities, or different sources, differs in variability from situation to situation (or task to task). A signal arising from a source with high variability is less reliable than a signal arising from a source with low variability. Optimal integration combines the information provided by different sources in proportion to their reliability, thus maximizing the reliability of the combined estimate.

**Rubber hand illusion:** a phenomenologically striking illusion in which participants feel their own hand being stroked with a brush while watching a dummy hand being stroked in synchrony. Soon participants come to feel that the visible strokes are identical to the strokes they feel, that their perception of touch has been ‘captured’ by (or referred onto) the dummy hand, and that the dummy hand is, in fact, their own hand.

**Spatial orienting:** moving or preparing to move an effector (e.g. a finger or hand) or a sensory organ (e.g. the fovea) towards a specific target in space.

**Spatial recognition:** the recognition of a spatial relationship between a feature and a frame of reference that can be either intrinsically defined (e.g. in relation to the body or the retina) or extrinsically defined (e.g. in relation to the layout of a room or in relation to an axis of an object).

**Superior colliculus (SC):** a subcortical mid-brain area that receives input from multiple sensory modalities (e.g. vision, audition and touch). The SC has been studied extensively in cats and ferrets, and is strongly implicated in the initiation of saccadic eye and head orienting responses.
Box 1. Paradigms for investigating spatial representation in infants

Methods for examining spatial representations in infants can be classified into spatial ‘recognition’ and ‘orienting’ tasks. Spatial-recognition tasks [14–17] (Figure 1a) take advantage of the tendency to look preferentially towards novel or familiar spatial arrays. The infant is first habituated to a particular spatial array. To examine in which reference frame habituation occurred, the infant or the array is moved and the infant’s preferential looking behaviour is observed. By contrast, spatial-orienting tasks [18,19] (Figure 1b) make use of directional (visual or manual) responses of infants to a given location. In these tasks, infants are led to expect a stimulus at a particular location. Again, to determine which frame of reference they use, either the array or the infant is moved before the directional response is made (in anticipation of an event, or in the context of goal-directed reaching).

The precocious spatial abilities demonstrated in spatial-recognition studies (which measure looking-duration) contrast with the limited abilities demonstrated in spatial-orienting tasks [18,19,25,65,67,68], which have tended to support Piaget’s [25] account of spatial development in infants. Piaget argued that infants are initially reliant on an egocentric (body-centred) spatial code and only later construct objective representations of external space through patterns of activity in their environment. Although the representation of objects within external frames of reference by young infants (as revealed by spatial-recognition tasks) is inconsistent with Piaget’s [25] framework, the necessity of explaining the delayed development of spatial-orienting abilities indicates another possible, constructionist account: development might proceed via the construction of spatial representations of the relationships between the location of targets and the sensorimotor coordinate transformations required to perform actions upon those targets – peripersonal spatial representations.

For instance, by three to four months of age, infants form the perceptual categories of ‘above’ and ‘below’ [13], and encode the spatial distance between objects [14]. Strikingly, young infants can also recognize the locations of objects and features in relation to external frames of reference across changes in their orientation [15–17]. However, whereas looking-duration measures of ‘spatial recognition’ [14–17] (Box 1) have tended to indicate precocious abilities to represent stimulus locations relative to external frames of reference, ‘spatial orienting’ tasks have provided a mixed picture of early spatial abilities. When orienting to targets, young infants seem to code their responses with respect to their own body and ignore changes in the position of the target or of themselves. When either is moved before the orienting response occurs, young infants make ‘egocentric’ errors, and it is only in their second year that they correctly update their responses [18,19] (Box 1 compares spatial recognition and orienting tasks).

One way of resolving these conflicting findings is to consider the kinds of spatial reference required in these two different types of task. In recognition tasks it is possible to identify changes in the location of objects by reference to environmental features. By contrast, orienting tasks require infants both to represent the location of objects with respect to their own body (to direct their orienting responses) and to update this body-centred location in response to any changes in their orientation with respect to the environment. Thus, infants’ poorer performance in spatial-orienting tasks might reflect their difficulties with registering correspondences between the location of targets in the environment, and the intrinsic body-centred coordinates required to orient to them. Such difficulties could help explain a well-known paradox of cognitive development in the first year of life: that infants’ early competence at representing spatiotemporal information about objects, as demonstrated in looking-duration measures (e.g. Ref. [11]), is not matched by their ability to act manually on that information until much later in their first year [20–24].

Regardless of discussions concerning early knowledge about objects and space, the relatively protracted development of spatial-orienting abilities in infancy brings into focus the need for further research into the early development of spatial representations for action. We know little about the developmental emergence of representations of the relationship between the environment and the spatial coordinates for action within that environment – that is, the development of peripersonal spatial representations.

Figure 1. Paradigms for investigating spatial reference in early infancy. (a) Shows a simplified illustration of a spatial-recognition paradigm [17]. In this study, 6.5-month-old infants dishabituated (demonstrated increases in looking after familiarization; indicated by alert eyes) to displays in which the object had moved, irrespective of whether they themselves had moved relative to the spatial array. That is, they used an environmental spatial reference. (b) Shows a simplified illustration of a spatial-orienting paradigm [19]. In this study, nine-month-old infants observed an object being hidden at one of two locations, and were then moved to the other side of the spatial array and allowed to search manually. The typical responses at nine months were incorrect, indicating their use of an egocentric spatial reference.

Forming representations of peripersonal space: the postural challenge

Despite the limited consideration given to the development of peripersonal spatial abilities (e.g. by Piaget [25]), locating objects in peripersonal space is a non-trivial problem. This is because, to retrieve an object, our brain must represent the location of the object via the distal spatial senses (i.e. vision and audition), and must also take into account the location of the retrieving limb relative to the object. The necessary multisensory information that specifies the layout of our body with respect to the world is typically provided by touch, proprioception, vision and, occasionally, audition. A major difficulty arises at this
point because the limbs and body move relative to each other and to visual and auditory space whenever posture changes. The challenge posed by this postural variation is even more complex when considered across development because not only do the relative sizes and shapes of the limbs, body and head change rapidly from month to month [26], but the number and variety of postural changes that an infant can readily make also increase with age [27–31]. These problems caused by posture highlight two key aspects of peripersonal spatial representations. First, that they depend on multisensory inputs and, second, that their boundaries and the ways in which sensory information is integrated shift dynamically as the posture of the limbs and sense organs change in the service of action [4,5]. Box 2 summarizes some of the key findings that have led researchers to these conclusions. Next, we consider how multisensory integration contributes to such peripersonal spatial representations and propose a theoretical framework for considering the development of peripersonal space.

Two mechanisms of multisensory integration underlying peripersonal spatial representations and their development

As we have just seen, when we orient towards locations in peripersonal space, our brains must integrate and align the spatial frames of reference used by our distal senses and the sensory information arising from our bodies. The evidence now points to the existence of two mechanisms of multisensory integration that (typically) achieve unified, consistent representations of peripersonal space:

(i) Visual spatial reliance. Our reliance on information from a given sensory modality depends on the variability of information in that modality in the context of a particular task [32–35]. By relying on the fact that the limbs usually occupy particular locations in the visual field and that vision typically provides reliable spatial information about limb position, limb position can be approximated with respect to particular visual locations. This greater weighting of the visually-derived location of the limb, rather than the proprioceptive location, will normally lead to accurate localization because of the greater reliability of visual spatial information. But it can also lead to errors (as highlighted by striking bodily illusions such as the ‘rubber hand illusion’ and the ‘mirror illusion’ [36–38]). The greater weighting of a visual frame of reference can also be observed in the absence of direct visual spatial cues. When adults make temporal order judgments (TOJs) concerning tactile stimuli, presented on one hand and then the other in quick succession, performance is much less accurate in the unusual crossed-hands posture than in the more

![Image](https://example.com/image1)

Figure 1. Saccades made by one adult human to tactile stimuli on their right hand in a crossed-hands posture (with the right hand in the left visual field). (a) Saccades are made to the tactile stimulus without any intervening delay, and (b) saccades are made to the tactile stimulus with a delay of 600–1000 ms between stimulus and response. Gradients indicate ten degrees of visual angle. Note that in (a) the majority of saccades begin by heading in the direction in which the tactile stimulus would normally lie, and then a later corrective process takes the current hand posture into account and shifts the saccade direction. Redrawn, with permission, from Ref. [43].

Box 2. Neural and behavioural correlates of peripersonal spatial representations

Peripersonal representations require multisensory integration between the body senses (somatosensation, proprioception and kinaesthesia) and the distal senses (vision and audition). The superior colliculus (SC) has long been identified as a brain region in which neurons respond to multisensory stimuli in approximate spatial register [69,70]. Multisensory neurons in the SC code stimuli in terms of the motor responses required to orient the eyes and head to the location of those stimuli (i.e. in a multisensory-motor map of space). More recently, research with macaques [2,3] has revealed neurons in a region of premotor cortex (and other brain areas) that have similar multisensory properties, but which code stimulus location with respect to individual body parts, such as the arm or the mouth. Such cells probably have an important role in generating and controlling rapid multisensory-guided target-directed or avoidance movements. A frequently used manipulation when studying peripersonal space is to cross the hands over the midline (Figure 2a in main text). This manipulation changes the spatial correspondence of body sense information to distal locations, such that hemispheric correspondence between inputs from these senses is reversed [45,46]. Thus, the appropriate integration of sensory information coming from the body and the distal area requires some form of spatial remapping.

Research with adult humans has shown that multisensory interactions in attentional processes take account of postural changes across the midline [47]. Additionally, the same brain areas that have been identified as sites of multisensory integration have been implicated in processes of postural remapping. Neurons that remap sensory correspondence across changes in posture have been reported in the monkey SC [71,72] and premotor cortex [53,54].
typical uncrossed-hands posture. Thus, representations of stimuli in peripersonal space can rely on a spatial frame of reference which is defined by the usual layout of the body with respect to vision [39–42].

(ii) Postural remapping. By taking postural changes into account (either passively, through visual and proprioceptive cues, or actively through ‘efferent copies’ of the movement plans used to change posture), the spatial correspondence between distal targets and the limbs can be ‘remapped’. The research described in Box 2 indicates the existence of such an integrative mechanism in human and non-human primates. The action of this mechanism can also be observed in adults’ saccades to tactile stimuli. If saccadic orienting

![Figure 2](image-url)

Figure 2. Integrate this! (a) In the uncrossed-hands posture both the visual information about the hand (circle) and a tactile stimulus on that hand (zigzag pattern) arrive at the contralateral hemisphere. With crossed-hands, these signals initially arrive in opposite hemispheres. (b) The sources of information available to be integrated into a representation of stimulus location. Our framework stipulates that all sources of information are available to ten-month-olds, and all but current postural information is available to 6.5-month-olds. (c) and (d) Manual responses of 6.5- and 10-month-old infants to tactile stimuli. The infants’ first responses on each trial were coded (from video recordings) in terms of their direction in visual space with respect to the hemisphere receiving the tactile signal. Thus, contralateral responses are appropriate in the uncrossed-hands posture, and ipsilateral responses in the crossed-hands posture. The manual responses of the 6.5-month-olds (c) showed an overall contralateral bias, as predicted by a hypothesized reliance on the typical layout of their body relative to vision. The ten-month-olds (d) were able to respond manually in the appropriate direction in either posture, indicating, in agreement with the proposed framework, that this age group are able to use information about current posture to remap their orienting responses. Asterisks represent significant comparisons. Solid arrows represent a strong contribution of a particular source of information to behaviour. Dotted arrows represent a weak contribution of the same. Figure adapted, with permission, from Ref. [44].
response to tactile stimuli are delayed by 600–1000 ms, then they are directed appropriately in visual space, even when the touch is delivered in an unfamiliar or atypical location (such as in the opposite visual hemifield when the hands are crossed [43]; see Figure 1). Thus, it seems that an integrative mechanism that is sensitive to posture is required to make correct gaze-orienting responses to atypical hand-locations.

**Development of peripersonal space**
Recently, the developments of these mechanisms of multisensory integration were examined in 6.5- and 10-month-old infants. This was achieved by measuring their spontaneous manual orienting response to vibrotactile sensations, which were presented to the infants’ hands in uncrossed- and crossed-hand postures [44] (Figure 2a). The 6.5-month-olds demonstrated a bias to respond in the direction appropriate to the uncrossed-hands posture across both arm postures, thus indicating a reliance on the typical location of the tactile stimulus in visual space (Figure 2c). The manual responses of the ten-month-olds were made appropriately in both postures, indicating the development of an ability to take posture into account in remapping correspondences between visual and tactile stimulation (Figure 2d).

These developmental findings converge with neuroscientific and behavioural research in indicating that representations of peripersonal space arise from two distinct mechanisms of sensory integration that follow separate developmental trajectories. The first mechanism, ‘visual spatial reliance’, integrates bodily and visual sensory information but relies substantially on the probable location of the hand, derived primarily from visual information and prior experience. This mechanism is present early in the first six months of life. The second mechanism, ‘postural remapping’, updates these multisensory spatial correspondences by dynamically incorporating information about the current hand and body posture. This second mechanism develops after 6.5-months of age. We are not suggesting that the early mechanism of visual spatial reliance is wholly replaced by that of postural remapping, but that they continue to work together as is observed in adults [39–43,45–47] (Figure 2b).

Of the measurable behaviours in early infancy, perhaps the most relevant ways to observe the development of such mechanisms of peripersonal space are reaches and grasps made towards nearby objects.

**Spatial representations guiding early reaching**

Box 3 summarizes some of the major developments in reaching that have been observed in the first year of life. A key question raised by the framework outlined here concerns whether infants’ reaches at any given stage of development are based on neural systems that take current limb posture into account (postural remapping) or, instead, whether successful reaches are based on prototypical representations of the limbs in their familiar locations derived from visual experience (visual spatial reliance) [48]. Given that infants’ first successful reaches towards visual targets can occur without any visual input concerning the position of their limbs, it seems that these actions are generated within multisensory peripersonal spatial representations. Nonetheless, it remains possible that their reaches in the dark are not guided by current proprioceptive information but, rather, by multisensory representations of limb position that are strongly weighted towards the location that the limb would normally occupy in the visual field. Because studies of infants’ reaching in the dark [49–51] have not systematically varied limb posture before reaching, it is difficult to disentangle these interpretations (cf. Ref. [37]). However, within the novel framework put forward here, the predictions are that, if posture were to be varied, young infants’ early reaches would be error-prone but that, in the second six months of life they will become better able to take the current position of the limbs into account to reach accurately from a variety of starting postures.

Improvements in the ability to use postural information to maintain spatial alignment between different sensory inputs arising from peripersonal space can also explain the later development of infants’ ability to produce more fine-grained (‘goal-directed’) postural adjustments (especially towards visual targets can occur without any visual input concerning the position of their limbs, it seems that these actions are generated within multisensory peripersonal spatial representations. Nonetheless, it remains possible that their reaches in the dark are not guided by current proprioceptive information but, rather, by multisensory representations of limb position that are strongly weighted towards the location that the limb would normally occupy in the visual field. Because studies of infants’ reaching in the dark [49–51] have not systematically varied limb posture before reaching, it is difficult to disentangle these interpretations (cf. Ref. [37]). However, within the novel framework put forward here, the predictions are that, if posture were to be varied, young infants’ early reaches would be error-prone but that, in the second six months of life they will become better able to take the current position of the limbs into account to reach accurately from a variety of starting postures.

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**Box 3. The development of reaching behaviour in the first year of life**

Although newborn infants do not often manually contact objects, their reaches are more often directed towards an object if they are looking at it [73,74]. Newborns have also been shown to change the position of their hand to bring it into sight under the illumination of a spotlight that alternated between two locations near their body [75]. Thus, at birth there is at least some spatial integration between the information coming from nearby visible objects, and that coming from the body parts with which responses are made.

A key question is whether or not early reaching is guided by visual feedback concerning the relative locations of hand and object. That newborns demonstrate a deceleration in the movement of their arm in anticipation of the appearance of their hand in the spotlight [75] is indicative of a coordination of visual, proprioceptive and kinaesthetic information (purely visual guidance cannot explain the anticipatory adjustments because the hand was invisible when outside the spotlight). However, it is difficult to determine whether this indicates early crossmodal spatial correspondence between proprioceptive and visual space or, rather, operant conditioning of particular arm movements, contingent upon the reward of seeing one’s hand.

The coordination of proprioceptive and visual space in the guidance of reaching has been investigated more fully by comparing infants’ early successful reaches for distal targets in the light against those in the dark (i.e. towards sounding or glowing targets without visual cues to the location of their hand) [49–51]. These studies have shown that successful reaching in the dark develops at the same age as in the light, indicating that the first reaches (at approximately three to four months of age) can be based on proprioceptive guidance of hand position towards a sighted visual target. However, a (as yet unaddressed) question concerns whether this proprioceptive guidance constitutes a representation of the current posture of the body, or one that defines the location of the limbs with respect to their typical location in visual space (see main text).

From four months of age, reaches gradually become more ‘goal-directed’ in nature. Grasps that anticipate the orientation of an object begin to emerge at around five months [76,77]. By eight months, re-orienting of the hand in anticipation of the orientation of a visual target also occurs independently of vision of the hand [52], indicating that postural guidance is achieved proprioceptively at this age. Grasps that anticipate the size of an object are first observed from nine months of age [78].
those made without sight of the hand [52]; see Box 3). These behaviours clearly require postural calibration and feed-forward prediction in actions made towards objects.

**Neural construction of peripersonal space**

We have argued that two mechanisms of multisensory integration underlying peripersonal space (visual spatial-reliance and postural remapping) develop independent-ly in the first year of life. The sensory interactions subserving the early visual spatial reliance mechanism could be governed both by subcortical [e.g. the superior colliculus (SC) or putamen] and cortical loci for multisensory integration (Box 2). The strongest evidence for neural systems underlying the dynamic updating of peripersonal space across changes in posture (postural remapping) has been obtained from single unit recordings made in macaque premotor cortex [53,54]. Thus, the more protracted development of mechanisms subserving postural remapping could be explained by a developmental shift from subcortical to cortical processing of multisensory stimuli in early infancy [55]. However, several factors speak against cortical maturation as the sole explanation for these developments.

First, there have been several demonstrations of the influence of experience on multisensory integration. In one study [56], a newborn chimpanzee’s multisensory and motor experience with his own hands and feet was severely restricted during the first 30 months of life by fixing restricting cylinders over these limbs. This chimpanzee later demonstrated almost no ability to learn a conditioned crossmodal orienting response between two tactile cued locations on the index finger of either hand. Consistent with this finding, neurophysiological evidence has demonstrated that multisensory neurons in the SC of cats that were reared in the dark fail to demonstrate the normal distinct responses to multisensory and unimodal stimuli [57].

More recently, Röder et al. [58] have shown that early visual experience could have a key role in establishing how tactile stimuli are related to visual spatial coordinates, and the typical (visual) posture of the limbs. By using the tactile TOJ task described earlier [39–42], they found that, unlike normally sighted or blindfolded adults, congenitally blind participants exhibited no impairment in the crossed-hands posture. Late blind participants showed similar crossed-hands impairment to those of the sighted participants, indicating that early visual experience is necessary for the normal development of tactile spatiotemporal perception [59]. Indeed, there are several indications that changes in patterns of sensory weighting in spatial tasks continue well beyond infancy and into late childhood [60–64].

Second, the more protracted development of postural remapping in infancy might depend largely on changes in the kinds of active experience that infants have of their environment. Indeed, the developments in postural remapping observed between 6.5 and 10 months coincide with the emergence (at ~six months) of spontaneous reaching towards and across the midline for visually presented objects [29–31]. The multisensory experience associated with this behaviour is well-suited for driving the development of the postural remapping mechanism.

**Box 4. Questions for future research**

- How is the emergence of peripersonal spatial abilities related to developing brain function?
- Neurons have been found in parietal and premotor areas that, when stimulated, trigger defensive reactions to stimuli approaching the body [2,3]. Can the ability to make accurate defensive reactions to such stimuli be traced in infancy?
- Which experiences drive the development of postural remapping in infants? What role do exploratory manual behaviours have in this development? Longitudinal training studies could be used to investigate these questions.
- In adults, patterns of visual–proprioceptive sensory weighting in manual control vary depending on the spatial dimension in which stimuli are localized (e.g. depth versus azimuth [35]), as predicted by the principle of optimal integration [34]. Recent research has indicated that optimal integration in navigational and form discrimination tasks develops through childhood and into adolescence [63,64]. But do patterns of sensory weighting in early reaching behaviours follow a similar trajectory of suboptimal to optimal integration? Are early processes of sensory weighting in infants’ reaching characterized by the dominance of one modality, as is the case with young children’s form discrimination abilities [64]?
- What are the relationships between the development of representations of one’s own peripersonal space, and that of others [79]? Early representations of peripersonal space are dependent upon the prototypical layout of the limbs [44]. Is this also the case concerning early abilities to recognize one’s own body [80]?

Roles for experience in the development of representations of peripersonal space are consistent with ‘interactive specialization’ frameworks for understanding the developments of neural systems [65,66] in that some degree of specialization in earlier developed brain regions (such as the SC) for multisensory orienting responses could lay the behavioural foundations required for experientially driven development of more specialized networks underlying peripersonal representations. The provision of a default prototypical representation of peripersonal space, underpinned by patterns of relative weighting of the senses, could provide a basis upon which (later developing) experience-dependent dynamic networks can be efficiently deployed when changes in the posture of the body make this necessary for successful orienting. This is not to say that brain networks underlying a default prototypical representation would be unaffected by experience. Changes in the body across development would require such networks to be flexible and, indeed, evidence indicates that sensory experience is necessary for their normal development (cf. Ref. [58]). Rather, it seems more reasonable to suggest that the general function of such networks in establishing a unitary (if vague) default representation of peripersonal space could be specified before birth.

**Concluding remarks**

An important challenge to infants in the first year of life is forming detailed and accurate representations of multisensory peripersonal space. Indeed the challenges posed by this problem might help explain some of the puzzling dissociations between perception and action that have been uncovered in studies of early cognitive development [20–24]. The framework presented here argues for the
independent development (at least over the first year of life) of two integrative mechanisms that give rise to multisensory representations of peripersonal space: visual spatial reliance and postural remapping. We have argued that a mechanism of visual spatial reliance provides an approximate default multisensory integration, upon which more dynamic systems of integration can later be efficiently deployed. The later development of more dynamic integrative systems might arise in response to changes in the demands of multisensory and sensorimotor interactions in peripersonal space, commensurate with the emergence of certain kinds of postural changes related to exploratory behaviours. Future data notwithstanding, we present this as a framework for considering the early development of representations of the space in which we act. Several future research questions (Box 4) will help enlighten this vital area of study.

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