Spatial tuning of electrophysiological responses to multisensory stimuli reveals a primitive coding of the body boundaries in newborns

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The ability to identify our own body and its boundaries is crucial for survival. Ideally, the sooner we learn to discriminate external stimuli occurring close to our body from those occurring far from it, the better (and safer) we may interact with the sensory environment. However, when this mechanism emerges within ontogeny is unknown. Is it something acquired throughout infancy, or is it already present soon after birth? The presence of a spatial modulation of multisensory integration (MSI) is considered a hallmark of a functioning representation of the body position in space. Here, we investigated whether MSI is present and spatially organized in 18- to 92-h-old newborns. We compared electrophysiological responses to tactile stimulation when concurrent auditory events were delivered close to, as opposed to far from, the body in healthy newborns and in a control group of adult participants. In accordance with previous studies, adult controls showed a clear spatial modulation of MSI, with greater superadditive responses for multisensory stimuli close to the body. In newborns, we demonstrated the presence of a genuine electrophysiological pattern of MSI, with older newborns showing a larger MSI effect. Importantly, as for adults, multisensory superadditive responses were modulated by the proximity to the body. This finding may represent the electrophysiological mechanism responsible for a primitive coding of bodily self boundaries, thus suggesting that even just a few hours after birth, human newborns identify their own body as a distinct entity from the environment.

peripersonal space | body representation | multisensory integration | newborns | ERP

The ability to identify one's own body as a distinct entity from the external word is a prerequisite for developing self-awareness and efficiently interact with the environment. There is extensive evidence demonstrating that in the primate brain this ability is rooted in the multisensory representation of the space surrounding the body (i.e., peripersonal space [PPS]) (1). This space has the adaptive function of discriminating external stimuli occurring close to our body from those occurring far from it, thus orienting goal-directed actions and supporting the body protection (2). However, when this mechanism emerges within ontogeny is still unknown.

PPS representation has been described as an "invisible bubble" surrounding the body, able to map body boundaries by exploiting multisensory integration (MSI) mechanisms (3). Accordingly, this portion of space is encoded by the integration of somatosensory signals originating on the body, with visual or auditory signals emanating from the environment, when the latter are presented within a limited distance from the body. In monkeys, responses of multimodal neurons to visual and auditory stimuli decrease as their distance from the body increases (2). Analogously, in humans, stimuli occurring close to the body speed up the behavioral responses to tactile stimuli and magnify the related neural activity (3–5) (MSI superadditivity). This spatial modulation of MSI is considered a proxy of a neural representation of the space surrounding the body (2), able to distinguish multisensory stimuli pertaining to the body from those occurring in the environment (3). Previous pioneering behavioral studies, measuring eye fixations, suggest the presence of cross-modal congruency effects at birth, in both the spatial and the temporal domains (6, 7). However, to date, there was no evidence of a neurophysiological hallmark of the spatial, body-proximity-dependent, modulation of MSI in human newborns. Here, we asked whether an electrophysiological marker of MSI is already present at birth and, if so, whether it is modulated by the proximity to the body.

Methods

In the present paradigm, we recorded electroencephalography (EEG) to compute event-related potentials (ERPs) to unimodal (audio and tactile) and bimodal (audiotactile) stimulation in newborns (mean age of 52.50 ± 19.51 h at the time of testing; $n = 25$; parents provided written informed consent; the Ethical Committee of Sant'Anna University Hospital, Turin, Italy approved study no. 0121061; 14/12/2017 to 14/12/2022) and adults ($n = 25$; all participants gave written informed consent; the Ethical Committee of the University of Turin approved study no. 125055, 12/07/16). Participants received tactile (electrical) stimuli on the hand dorsum, while auditory stimulation (a 50-ms tone) was presented either near (<5 cm) or far (140 cm) from the stimulated hand (Fig. 1, Paradigm). In newborns, superadditive responses to bimodal stimuli (ERPs exceeding the sum of unimodal responses) would indicate that MSI effects are already present at birth. More crucially, the spatial modulation of such superadditivity, with a larger MSI effect in the near space, would suggest a primitive coding of body boundaries. To identify a time period demonstrating MSI, we first extracted EEG global field power (GFP) in adults (4). Bimodal conditions showed greater GFP as compared to the sum of unimodal inputs (i.e., audio + tactile), indicating superadditivity in multisensory responses in a time window between 222 and 338 ms post-stimulus onset, corresponding to the latency of the P2 component (the greatest positive deflection following N140). To investigate MSI effects on ERPs, we extracted the ERP mean amplitude within this time window, as well as the latency of the P2 peak. In newborns, ERP mean amplitude of the same component (P2) that shows MSI in adults was extracted between 280 and 400 ms (different ERP latency between newborns and adults is often observed, as confirmed here in the latency analyses). In each group (i.e., adults and newborns), the ERP mean amplitude of our window of interest was entered in a 2*2 repeated measures ANOVA

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The authors declare no competing interest.

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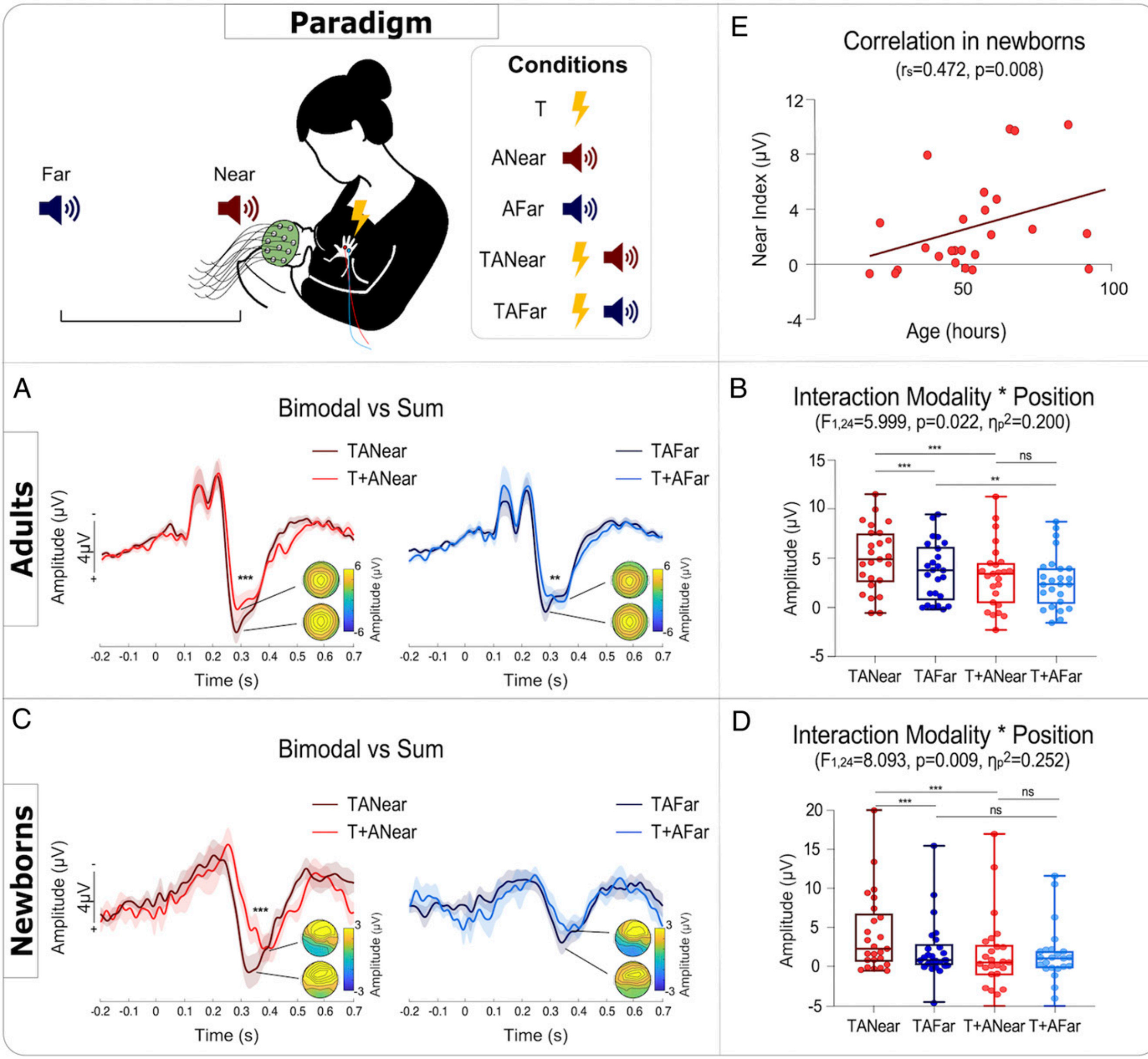

Fig. 1. Experimental paradigm and EEG results. (*Top Left*) Experimental paradigm. T: tactile (electrical) stimulation; ANear: auditory stimulation delivered near to the body; AFar: auditory stimulation delivered far from the body; TANear: tactile and auditory bimodal-near condition; TAFar: tactile and auditory bimodal-far condition. (*Top Right*) (*E*) Results of the correlation analysis between EEG data (MSI index in near position) and newborns' postnatal age (the hours since birth). (*Bottom*) EEG results. (*Left side*) Adults' (*A*) and newborns' (*C*) ERP responses and scalpmaps in near vs. far position. *x* axis: time (seconds); *y* axis: amplitude (microvolts). Shades represent SEM. (*Right side*) Adults' (*B*) and newborns' (*D*) position by modality interaction on ERP mean amplitude. Note also that the main effect of position (near > far; adults: $F_{1,24} = 15.061$; $P < 0.001$ $\eta_p^2 = 0.386$; newborns: $F_{1,24} = 5.362$; $P = 0.029$; $\eta_p^2 = 0.183$) and modality (bimodal > sums; adults: $F_{1,24} = 18.360$; $P < 0.001$; $\eta_p^2 = 0.433$; $\eta_p^2 = 0.386$; newborns: $F_{1,24} = 10.819$; $P = 0.003$; $\eta_p^2 = 0.310$) are significant. In *A* and *C* a latency shift between earlier bimodal responses and later sums can be observed in both near and far conditions (main effect of modality: adults: $F_{1,24} = 11.662$; $P = 0.002$; $\eta_p^2 = 0.33$; newborns: $F_{1,24} = 22.253$; $P < 0.001$; $\eta_p^2 = 0.48$). The dots in *B*, *D*, and *E* represent single-subject values. ns, not significant; $^{**}P < 0.005$; $^{***}P < 0.0005$.

with position (two levels: near; far) and modality (two levels: bimodal; sum) as within subject factors. See extended methodology in *SI Appendix*.

Results and Discussion

Very similar results were found in both groups (Fig. 1), with the EEG pattern of newborns (*A* and *B*) paralleling that of adults (*C* and *D*), namely 1): the presence of superadditive multisensory responses even in newborns, with significantly greater and earlier responses in bimodal conditions vs. the sum of unimodal conditions; 2) the spatial modulation of such superadditive responses, with a significantly larger MSI effect for the near space, where the auditory input occurs close to the body. Importantly, in both samples, no significant differences emerged between the two summed conditions (i.e., audio + tactile in near vs. far space), thus indicating that the spatial modulation of superadditive bimodal responses was specifically related to MSI effects and not merely driven by some features of unimodal stimulation (e.g., loudness). Note that the averaged data are reflective of the individual trend, since most participants show greater values in the bimodal near condition than in all the other conditions. Furthermore, we found a significant positive correlation (*E*) between the amplitude of MSI responses in the near (but not in the far) condition and the postnatal age (i.e., the hours since birth), thus suggesting that older newborns show a larger MSI effect. See statistical results in Fig. 1.

These findings represent electrophysiological evidence for the presence of MSI effects in human newborns, expressed by specific superadditive responses to bimodal stimulation. This superadditivity effect encompasses the time window of the P2 component in both adults and newborns. Such latency is compatible with converging evidence from both scalp (4) and intracranial (5) EEG recordings showing that MSI responses occur at middle latencies, likely reflecting MSI processes in associative areas. This result differs from a recent electrophysiological study, which found a linear integration of audiotactile responses in full-term newborns (i.e., responses to bimodal stimuli did not differ from fake sums) (8). Although the different types of sensory stimulations (i.e., voices instead of tones and air puffs instead of electrical stimulation) prevents a direct comparison between the two studies, it is possible that the more salient and punctuate nature of the electrical stimulation provided here allowed for more reliable evoked responses, thus possibly accounting for the greater expression of MSI effects. On the other hand, previous behavioral studies in human newborns, showing longer eye fixations for congruent rather than incongruent multisensory stimuli (7), support the present finding that indicates a functioning MSI mechanism a few hours after birth.

This result in humans may appear surprising considering that studies in other mammalians (i.e., cats) reported that postnatal experience is necessary to develop MSI (9). However, while the somatosensory cortical structures are already mature at birth in both species, in cats, auditory neurons fully develop only postnatally, whereas in humans functional hearing is already present within the third trimester of gestation (9, 10). Once the neural circuitry is mature, the mere exposure to congruent cross-modal input is able to initiate MSI (11). Thus, it is possible that the early tactile and auditory stimulation experienced by the newborns within the first (52.5 on average) hours of life, while parents hold them, touch them, and speak to them, can rapidly trigger MSI. This hypothesis seems also to be confirmed by the significant positive correlation between the amplitude of MSI responses in the near condition and the postnatal age. Therefore, the prenatal experience of diffuse tactile and auditory cues during the long and sensory-enriched gestation characterizing human pregnancy likely prepares the system for the development of MSI soon after birth. An additional interesting question for future studies is whether this superadditivity is also present for visuotactile interactions in newborns, given that in humans the full function of visual processing only develops postnatally (10), even though the neural circuitry necessary to elaborate elementary visual configurations appears already mature since birth (12).

Concerning the spatial modulation of MSI responses, results in our adult sample, showing significantly greater superadditive responses close to as opposed to far from the body, fully parallel the results of previous electrophysiological studies, which highlight a spatial modulation of ERPs consistently affecting long-latency components both in visuotactile and audiotactile tasks (4, 5, 13). More importantly, even in newborns, superadditive responses are spatially modulated by proximity to the body, with superadditive responses and significant correlations with postnatal age in near condition only, thus suggesting a primitive coding of the nearby space. The neural representation of this portion of space has been proposed to serve different functions, such as orienting goal-directed actions (interactive purpose) (1, 2, 14), supporting the body protection (defensive purpose) (2, 14), and contributing to the emergence and maintenance of a coherent multimodal bodily self-representation (self-consciousness purpose) (3, 4). Thus, it would seem adaptive to have a mechanism present very early in life for supporting these functions. We propose that, in newborns, this mechanism relies on a somatotopic reference frame, mainly grounded in somatosensory (tactile and proprioceptive) inputs. On the other hand, the development of a spatiotopic reference frame may happen much later in infancy and is related to the maturation of the visual channel, as demonstrated by studies on touch remapping in external coordinates (15).

Taken together, the present findings demonstrate that genuine MSI rapidly emerges soon after birth, as proven by a distinctive electrophysiological pattern, and is modulated by the proximity to the body. This suggests that a primitive coding of the bodily self boundaries, built from multisensory signals, can be observed within the first hours of life.

Data Availability. Anonymized EEG data have been deposited in Mendeley (http://dx.doi.org/10.17632/vpbm2w7njn.1).

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