Body-Space Interactions: Same Spatial Encoding but Different Influence of Valence for Reaching and Defensive Purposes

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Abstract

The space around our body, the so-called 'Peripersonal Space' (PPS), is where interactions with nearby objects may occur. 'Defensive space' and 'Reaching space', respectively, refer to two opposite poles of interaction between our body and the external environment: protecting the body and performing a goal-directed action. Here, we hypothesized that mechanisms underlying these two action spaces are differentially modulated by the valence of visual stimuli, as stimuli with negative valence are more likely to activate protective actions while stimuli with positive valence may activate approaching actions. To test whether such distinction in cognitive/evaluative processing exists between Reaching and Defensive spaces, we measured behavioural responses as well as neural activations over sensorimotor cortex using electro-encephalography (EEG), while participants performed several tasks designed to tap into mechanisms underlying either Defensive (e.g., respond to touch) or Reaching space (e.g., estimate whether object is within reaching distance). During each task, pictures of objects with either positive or negative valence were presented at different distances from the participants' body. We found that Defensive space was smaller for positively compared to negatively valenced visual stimuli. Furthermore, sensorimotor cortex activation (reflected in modulation of beta power) during tactile processing was enhanced when coupled with negatively rather than positively valenced visual stimuli regarding Defensive space. On the contrary, both the EEG and behavioural measures capturing the mechanisms underlying Reaching space did not reveal any modulation by valence. While valence encoding thus had differential effects on Reaching and Defensive spaces, the distance of the visual stimulus modulated behavioural measures as well as activity over sensorimotor cortex (reflected in modulations of mu power) in a similar way for both types of spaces. Our results are compatible with the idea that Reaching and Defensive spaces involve the same distance-dependent neural representations of sensory input, whereas task goals and stimulus valence (i.e., contextual information) are implemented at a later processing stage and exert an influence on motor output rather than sensory/space encoding.

Keywords: Defensive space; Reaching space; Peripersonal Space; Valence; Mu; Beta.

Introduction

Peripersonal space (PPS) refers to the region of space directly surrounding our body that may serve as a sensory-motor interface between our body and the external world (Rizzolatti et al., 1981, 1997, Graziano & Cooke, 2006). Integration of visual and tactile stimuli is enhanced when the visual stimulus is closer to the body rather than far away from it, as revealed by electrophysiological studies in monkey (Fogassi et al., 1996, Duhamel et al., 1997, Graziano et al., 1999) as well as humans (Bernasconi et al., 2018, Noel et al., 2019). In humans there is also considerable behavioural evidence for multisensory enhancement within PPS (Làdavas et al., 1998, Makin et al., 2009, Brozzoli et al., 2011, Serino et al., 2015, Spaccasassi et al., 2019, Spaccasassi et al., 2021).

The role of PPS is not merely to integrate stimuli coming from different modalities, but rather to regulate body-objects interactions (di Pellegrino & Làdavas, 2015). This means that objects located inside PPS are represented in terms of potential actions (Bufacchi & Iannetti, 2018). As suggested by de Vignemont & Iannetti (2015), when an appetitive object is close to our body, we can actively try to take it by implementing an approaching, goal-directed, voluntary action. Therefore, a reaching movement, among other actions, acts inside rather than outside PPS. However, as is evident from the above-mentioned previous literature, PPS size does not overlap with that covered by our reaching movement. Indeed, PPS is not solely a metrical representation of the space around us but includes a more complex (operational) representation of it (di Pellegrino & Làdavas, 2015).

PPS properties are not fixed, but can be altered by motor plans, emotional stimuli and social context (Canzoneri et al., 2013, Patané et al., 2017, Spaccasassi & Maravita, 2020, Teneggi et al., 2013). For instance, visuo-tactile interactions can be extended in space after the active use of a tool which allows reaching far locations (Maravita et al., 2001, Farnè et al., 2005). Behavioral measures of PPS based on the strength of multisensory integration were also found to be modulated by the valence of

visual stimuli (Ferri et al., 2015, Spaccasassi et al., 2019). However, although stimulus valence influences action (Saraiva et al., 2013) and it modifies neural activations associated with visual processing (Conroy & Polich, 2007, Schupp et al., 2004, Codispoti et al., 2001), neural modulations that reflected the valence of a visual stimulus were not influenced by whether or not the stimulus was estimated to be within reaching distance (Valdés-Conroy et al., 2014).

Here, we hypothesized that these discrepancies in earlier findings are related to differences between 'Defensive' space and 'Reaching' space, which, respectively, refer to two opposite poles of interaction between our body and the external environment: protecting the body and performing a goal-directed action. Whether these two spatial systems rely on the same or different neural maps is currently under debate (for a review based on PPS perspective see de Vignemont & Iannetti, 2015). There are recent attempts to characterize the Defensive space through EEG (Naro et al., 2019) as well as to distinguish it from the Interpersonal space (i.e., the space between individuals) at neuronal level (Vieira et al., 2020), but a direct comparison between the Defensive and Reaching spaces is lacking. Here we provide such direct comparison, recording behavioural as well as neurophysiological measures sensitive to the mechanisms underlying Defensive and Reaching spaces. Reasoning that stimuli with negative valence are more likely to activate protective actions while stimuli with positive valence likely activate approaching actions (Saraiva et al., 2013), we hypothesized that mechanisms associated with Defensive space are more strongly activated when objects have negative compared with positive valence, whereas the opposite is true for mechanisms associated with Reaching space.

In a psychophysical experiment, we used explicit questions inquiring into the evaluative components of both Defensive and Reaching spaces. In particular, by adopting a staircase procedure (Cornsweet, 1962), we investigated whether the cognitive/evaluative aspects of Defensive and Reaching space extend to similar regions of space around the body and whether this is similarly

modified by stimulus valence. We expect that negative visual stimuli extend Defensive space relative to positive visual stimuli (Ferri et al., 2015, de Haan et al., 2016), while the opposite holds for the Reaching space (Balcetis & Dunning, 2010, Valdés-Conroy et al., 2012, 2014).

Regarding Reaching space, participants were asked to explicitly estimate their own reaching capabilities. This question is used in the scientific literature about PPS as an explicit measure of Reaching space (Valdès-Conroy et al., 2012, 2014, Wamain et al., 2016, Patanè et al., 2017, D'Angelo et al., 2019). Regarding Defensive space, participants were asked whether they were comfortable with an object at a certain distance from their body. This method was adopted from research on Interpersonal space, where it is used in reference to humans instead of objects. It was shown that this "comfort" question is sensitive to the valence of avatar facial expression (Ruggiero et al., 2017) and parallels the electrodermal physiological activity pattern (Cartaud et al., 2018, 2020). Specifically, an expansion of Interpersonal space as well as a stronger electrodermal response was found when facing an angry face compared to a neutral or happy face, thus revealing the efficacy of the "comfort" question in capturing defensive reactions. In addition, regarding Defensive space we asked participants to indicate whether they would like to retract their hand away from an object at a certain distance from their body. With the "retract" question the focus is centred on the motor component of defensive reactions like withdrawal movements (Graziano & Cooke, 2006).

We also recorded activity in sensorimotor cortex using EEG to assess whether tactile anticipation and motor imagery, respectively associated with the mechanisms underlying Defensive and Reaching spaces, are affected by stimulus valence. The same participants performed a tactile discrimination task (i.e., reporting where on their hand they felt a tactile stimulus) and a reaching estimation task (i.e., estimating whether they could reach an object) while they looked at images of valence-connoted objects located at different distances from their hand. While the former task

relates to the multisensory perception of space (based on PPS perspective: Graziano & Cooke, 2006; Serino, 2019), the latter, relying on reachability judgments, relates to the motor properties of the action space (de Vignemont & Iannetti, 2015). We reasoned that these cognitive evaluations of valence-connoted visual stimuli tap into both Defensive and Reaching spaces, respectively.

We analyzed modulation of beta rhythm (15-25 Hz) and mu rhythm (8-12 Hz) over sensorimotor cortex, as these have been associated with tactile processing, tactile anticipation, movement execution, motor preparation and motor imagery (beta: Pfurtscheller, 1981/1986; McFarland et al., 2000, Gaetz & Cheyne, 2006; mu: Babiloni et al., 1999, Llanos et al., 2013, Salenius et al., 1997; Braadbaart et al., 2013, Hari, 2006, Muthukumaraswamy et al., 2004; Pfurtscheller & Lopes Da Silva, 1999, Neuper et al., 2005; Coll et al., 2005, Gonzalez-Franco et al., 2014). Specifically, synchronization and desynchronization of these rhythms over central areas are generally interpreted as an index of sensorimotor cortex inhibition and activation, respectively (Pfurtscheller et al., 1996, McFarland et al., 2000).

Regarding Defensive space, we expect to find stronger somatosensory cortex activation for negatively than positively valenced visual stimuli when occurring close to the body, reflecting actions to protect the body from aversive objects close to the body (Ferri et al., 2015, de Haan et al., 2016). This hypothesis is supported by previous studies showing that somatosensory sensation elicits a defensive response when coupled to a threatening or negative stimulus (Taffou et al., 2014, Ferri et al., 2015, de Haan et al., 2016, Ellena et al, 2020). In addition, we expect to find modulations of somatosensory activation by visual stimulus valence prior to delivery of the tactile stimulus, considering that tactile expectation alone is capable of producing somatosensory activations that are associated with upcoming sensory processing (van Ede et al., 2010, 2011; Babiloni et al., 2008, 2010). Regarding Reaching space, we expect enhanced sensorimotor activity

concomitant with visual processing of positively compared to negatively valenced visual stimuli when occurring close to the body, reflecting preparation of goal-directed action towards appetitive nearby objects (Valdés-Conroy et al., 2012, 2014; Wamain et al., 2016).

Methods

Participants. 30 healthy right-handed volunteers (21 females, mean age (M) ± standard deviation (SD): 26.3 ± 6.8 years) participated in the study. They had normal or corrected to normal vision and normal sense of touch as assessed by a self-report questionnaire. Participants had no (history with) neurological or psychiatric disorders, no abuse of alcohol or drugs and they gave written informed consent prior to participation. Five additional participants were excluded from the analysis because of technical problems during EEG recording. Recruitment and testing of participants conformed to the Helsinki Declaration and was approved prior to data collection by the local Ethics Committee the Faculty of Social and Behavioral Sciences of Utrecht University (study number: FETC17-117). The number of participants was based on a priori power analysis (30 sample size, 0.22 effect-size, 0.05 error probability, 0.95 power, 8 measurements) conducted by G*Power Software (Faul et al., 2009).

Figure 1. Images of every-day objects used as visual stimuli. Each of 20 pairs of objects consisted of 1 object with positive valence (on the left) and 1 object with negative valence (on the right), which were roughly matched on overall shape and semantic value. The 2 groups of objects with positive and negative valence were carefully matched on arousal value and difficulty to grasp, but the valence and likability to touch differed between the objects. The 2 sets of images were also carefully matched on overall luminance, contrast, colour content and colour contrast.

Visual Stimuli. Visual stimuli consisted of 20 pairs of images obtained from the internet showing every-day objects. Each pair consisted of 1 object with positive valence and 1 object with negative valence, which were roughly matched on overall shape and semantic value (Figure 1). The 2 groups of objects (with positive and negative valence) were carefully matched on arousal value and difficulty to grasp (see method in section 'Behavioural experiment: Validation of visual stimuli'). Also, the 2 sets of images were carefully matched on overall luminance, contrast, colour content and colour contrast (using Adobe Photoshop CC 19.1.9). A gamma correction was applied (Using MATLAB 2016A, MathWorks Inc.). Mean luminance of the images as well as the midgrey

background was (71.1 cd/m^2). The images were displayed at varying distance from the participant's body along the vertical midline of a big monitor (PH BDL 5530 EL, 133 x 75 cm display size, 1920 x 1080 resolution, 60 Hz refresh rate) that was positioned flat in front of participant's body midline (equivalent to a table surface, see Figure 2). Size of the images was adjusted such that their longest cardinal axis (i.e., height/width) was 12.50 cm.

In the experiments described below each presentation of an object image was preceded by a fixation stimulus that participants were instructed to fixate on and that consisted of a 21.5-mm wide black dot with a 14.6-mm wide grey dot and a 7.6-mm wide white dot presented concentrically on top it (Figure 2A). The centre of the fixation stimulus was displayed at the same location, i.e., distance from the participant's body, as the subsequent object image. The fixation dot appeared 500-800 ms prior to the visual stimulus, meaning the eye movement toward it was made before the appearance of the visual and tactile stimuli. During the visual and tactile stimuli, the participants were instructed to maintain strict fixation.

General procedure. Participants were seated in a comfortable chair in a dark room that was acoustically shielded. During all experiments, participants were instructed to place their right hand on the monitor with the dorsal side up, positioning the end of their middle finger on the vertical midline of the monitor, 18 cm from the edge that was close to their body (this position was close to where the nearest object images would appear). Participants put their chin in a chinrest and placed their left hand on a keyboard or computer mouse located out of sight underneath the monitor. In case the keyboard was used, participants positioned their left middle and index fingers on two response buttons (key 1 and key 2) of which the corresponding meanings were randomly assigned across participants (see following sections). In all experiments the participants' right hand was used for the experimental manipulation (i.e., tactile imagery/anticipation/stimulation or reaching imagery/estimation) and their left hand was used for responding.

Before starting the experiments, the reaching distance of the participants' right hand was measured to determine which distances were within and outside this real reaching distance. This distance was measured from the edge of a table at which the participants were sitting (their abdomen touched the table) to the end of their right middle finger while they were asked to stretch their right arm as far as they can. Then, the experiments that are described in the following sections were completed. Participants first completed two experiments during which EEG was recorded: the 'Tactile task' involved tactile anticipation and stimulation and was designed to tap into mechanisms underlying Defensive space, while the 'Reaching task' involved a reaching estimation and was designed to tap into mechanisms underlying Reaching space. With these tasks we particularly aim to test cognitive/evaluative processing of everyday objects that may occur within and outside Reaching and Defensive space. Whether the Tactile task or the Reaching task was completed first was determined randomly per participant. Then, they completed a behavioural experiment in which the boundaries of Defensive and Reaching spaces were determined through explicit evaluative judgements (as described below). After that, they completed another behavioural experiment in which the valence, arousal level, difficulty to grasp and likability to touch of each of the 40 object images was assessed. All statistical testing was performed using Jamovi 1.2 (The Jamovi Project, https://www.jamovi.org) and included repeated-measures Analysis Of Variance (ANOVA) or paired t-tests (unless indicated otherwise; further details are described per experiment below). A Welch's t-test was performed for post-hoc testing of significant 2-way interactions resulting from an ANOVA. Response accuracy during the EEG experiments was analysed using Wilcoxon test.

EEG experiments: General procedure and recording. Before starting the Tactile task and Reaching task participants were equipped with an elastic cap (Quickcap, Neuromedical supplies of Neurosoft inc.). EEG was measured using an Active Two system (Biosemi, Amsterdam, The Netherlands, www.biosemi.com) with 32 silver/silver-chloride (Ag/AgCl) flat type active electrodes

positioned at standard locations on the elastic cap. EEG was recorded continuously with a sampling rate of 2048 Hz and referenced to an additional active electrode (Common Mode Sense) during recording. Two electrodes in the cap provided an active ground. Electro-oculogram (EOG) was also recorded from sub- and supraorbital regions of the right eye as well as the skin temporal to the outer canthi of the two eyes.

During both the Tactile task and the Reaching task participants were instructed to minimize their movements and to maintain fixation on the fixation stimulus. Both tasks included the images of objects with either positive or negative valence, displayed with its centre at 1 out of 9 possible distances from the participant's body. Distances were defined relative to the real reaching distance of each participant's right arm as measured before the start of the experiment. Specifically, the distances of the centre of the object images were 150.0%, 142.5%, 135.0%, 110.0%, 100.0%, 90.0%, 65.0%, 57.5% and 50.0% of the real reaching distance. Considering that the averaged reaching distance was 65.83 cm, the shortest (50.0%) and longest (150.0%) distances on average corresponded to 32.92 and 98.75 cm from the participant's abdomen, respectively. The closest edge of the nearest visual stimuli was, therefore, on average 8.67 cm away from the end of participant's right middle finger (as this was placed 18 cm from the edge of the monitor and image size was 12.50 cm). The nearest 3 distances and furthest 3 distances were analysed in conjunction and will be referred to as 'near space' and 'far space', respectively. The middle 3 distances were included to increase difficulty and unpredictability of the tasks but were not analysed.

EEG experiment: Tactile stimulus used in Tactile task. The tactile stimulus was delivered on the more distal phalanx of either the right little finger or the right thumb by means of attaching vibrotactile stimulators to these locations using adhesive tape (Figure 2). The vibrotactile stimulators produced a vibration like that of a mobile phone (eccentric rotating mass in cylindrical casing; Precision Microdrives, model: 308–00, 8 mm diameter, 3.4 mm thick). Per trial one or none

of the stimulators was activated for 100 ms (see trial types in next section). Due to the gradual rise and decay of vibration amplitude in response to onset and offset of the activation, the resulting vibration was perceivable (i.e., >50% of the maximum amplitude) approximately in the time-interval 55-280 ms relative to activation onset. In this time interval vibration frequency was ~67 Hz (measured with Bosh Sensortec BST-BMI160 inertial measuring unit). Therefore, when interpreting neural activity relative to onset of the activation of the tactile stimulator (Figure 5), note that the delay between activation and producing a perceivable vibration amplitude was ~55 ms. The stimulators produced negligible sound, which was masked by white noise that the participants listened to throughout both the Tactile task and the Reaching task in the EEG experiment using headphones. After completing the Tactile task, participants indicated whether they used audition or touch to determine the location of the vibration on a visual analogue scale that went from 'touch only' on the left end to 'audition only' on the right end. All participants reported that they discriminated the tactile stimulus mostly by touch (M ± SD = 92 ± 11; 0 for audition only, 100 for touch only). They also indicated the pleasantness of the tactile stimulus, evidencing that it was not perceived as aversive (visual analogue scale ranging from 'very unpleasant' on the left end (score 0) to 'very pleasant' on the right end (score 100): M ± SD = 64 ± 18).

EEG experiment: Procedure during Tactile task. The Tactile task was designed to tap into the evaluative mechanisms underlying Defensive space, particularly with respect to multisensory integration. Participants completed 3 sessions that were identical and each lasted 10.5 minutes. Sessions were separated by a short break. Each trial started with the fixation stimulus at one of the nine possible distances from the participant's body (see above). After a delay with random duration between 500 to 800 ms the fixation stimulus was replaced by one of the 40 possible object images displayed at the same distance for a random duration between 1000 and 1300 ms. After that, the sequence of events depended on the trial type. In NO GO trials, there was no tactile stimulation, thus they ended here. For both NO GO trials with tactile stimulation and GO trials with tactile

stimulation (Figure 2A), the tactile stimulator was now activated, and the object image remained visible for an extra 300 ms (the tactile stimulus was perceivable approximately 55-280 ms after activation of the stimulator, see above). A NO GO trial with tactile stimulation was then ended, but on GO trials with tactile stimulation a GO stimulus that included the object image with a red square around it was then presented for 1200 ms (Figure 2C). The red square had a line thickness of 1.04 cm and subtended 14.65 cm horizontally and vertically. Only on these GO trials participants had to indicate as fast as possible whether the tactile stimulus was delivered to the right little finger or right thumb using the keyboard that they operated with their left hand. All GO trials were accompanied by tactile stimulation. Note that NO GO trials were just shorter versions of a GO trial. Thereby, during a NO GO trial the participant did not know yet whether it was a NO GO trial, or whether a tactile/GO stimulus would follow. It has been shown that a low number of GO trials is sufficient to elicit task/response-related processing also on NO GO trials (e.g., Wamain et al., 2016). The stimuli were delivered using Presentation (Neurobehavioral Systems, www.neurobs.com).

Per space (near/far space), per valence value (positive/negative), there were in total 18 GO trials, 72 NO GO trials with tactile stimulation and 108 NO GO trials without tactile stimulation, amounting to 792 trials that were entered in the analysis, which reflected visual stimulation alone (i.e., visual epochs – which stopped at 1000 ms from visual stimulus onset; see Analysis of the EEG data for further details). All trials were collapsed in this analysis, because they were identical up to this timepoint, irrespective of whether they were GO or NO GO with/without tactile stimulation. For the analysis of tactile processing with simultaneous visual stimulation (i.e., tactile epochs; see Analysis of the EEG data for further details) only GO trials and NO GO trials with tactile stimulation were considered, amounting to 360 trials that were entered in the analysis. As the tactile stimulation increased trial duration, we did not include more NO GO trials with tactile stimulation in the experiment than needed to obtain a sufficient amount of trials for analysing neural oscillation

related to tactile processing. As specified above, in both near and far space there were 3 distances at which images could appear (near: 65.0%, 57.5% and 50.0% of the real reaching distance; far: 150.0%, 142.5% and 135.0% of the real reaching distance; Figure 2C). The trials were divided equally over these 3 distances and analysed in conjunction. As mentioned above, distances close to the real reaching distance (110.0%, 100.0% and 90.0%) were included to increase task difficulty and unpredictability but were not analysed. Therefore, these distances were presented fewer times (in total 36 GO trials, 18 NO GO trials with tactile stimulation and 18 NO GO trials without tactile stimulation; trial were divided equally over the 3 distances).

EEG experiment: Procedure during Reaching task. The Reaching task was designed to tap into evaluative mechanisms underlying Reaching space. The procedure during the Reaching task was the same as during the Tactile task, with a few exceptions. First, this task did not include tactile stimuli. Therefore, each session lasted somewhat shorter: 9.8 minutes. There were 2 trial types: NO GO trials and GO trials. On GO trials the GO stimulus appeared directly after the 1000-1300 ms period designated for the visual stimulus alone. Second, the instruction for GO trials was different: participants were instructed to estimate whether they could reach the displayed objects with their right hand (the same instruction as used for the assessment of Reaching space boundary, see above). The responded by pressing one of two response buttons that were assigned to a 'yes' or 'no' response, respectively. In total there were 18 GO trials and 180 NO GO trials per space (near/far space), per valence value (positive/negative), amounting to 792 trials that were entered in the analysis. Distances close to the real reaching distance were not analysed and therefore were presented fewer times (36 GO trials and 36 NO GO trials in total).
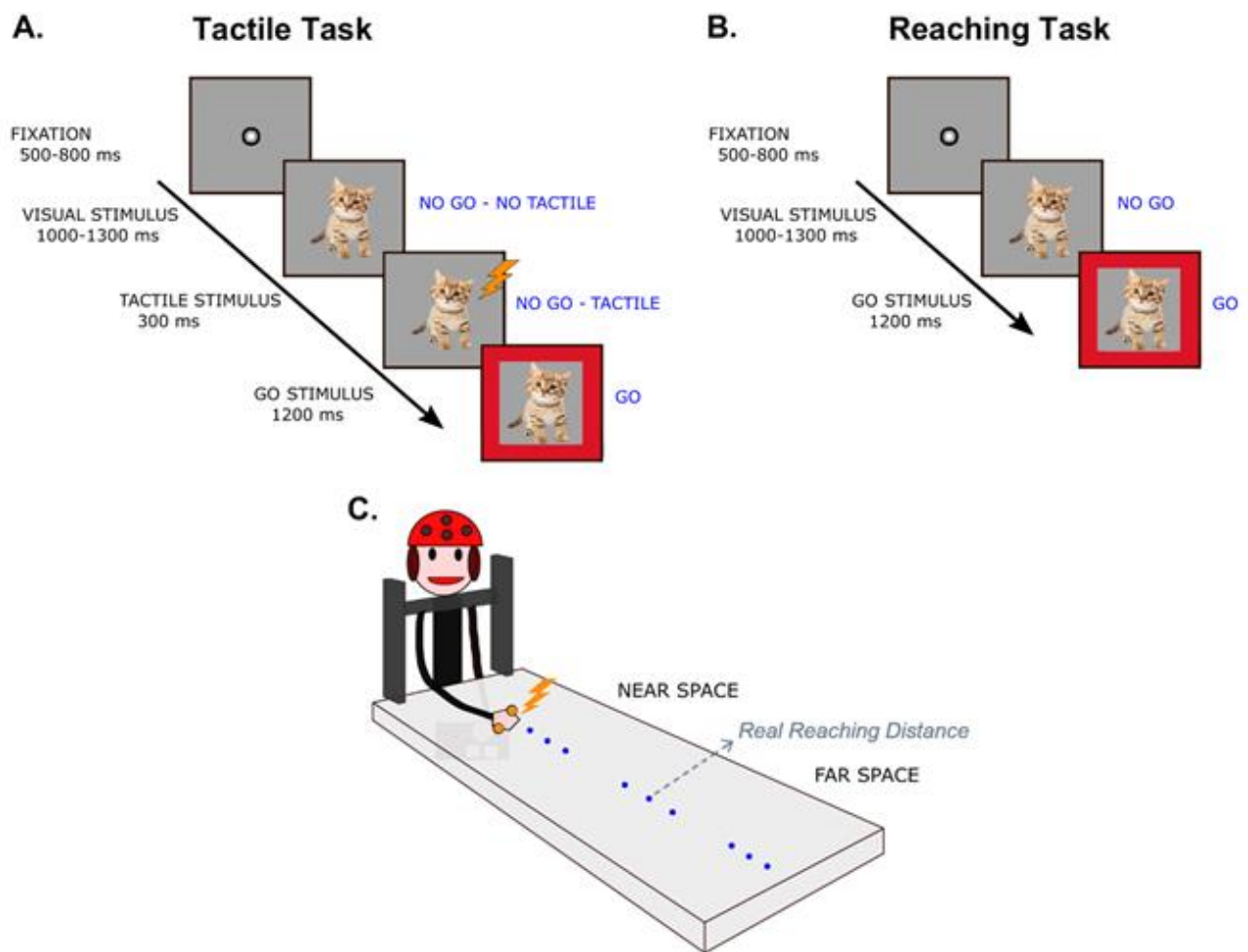
Figure 2. Trial types and experimental set-up during the EEG experiments. Panel A. Trial types and corresponding sequence of events in single trials during the Tactile task. For illustrational purposes the fixation stimulus and GO stimulus are depicted larger than they actually were. The tactile stimulus is indicated by the orange lightning. Blue text represents the names of the trial types. **Panel B.** Trial types and corresponding sequence of events in single trials during the Reaching task. Conventions as in panel A. **Panel C.** Illustration of the experimental set-up using during the Tactile task and Reaching task. Participants were seated in front of a big monitor that was positioned flat. On the monitor visual stimuli could appear in one of the nine distances indicated by the blue dots (trials with objects in near space and far space were analysed and compared; trials with objects close to the real reaching distance were included to increase unpredictability and difficulty of the task but were not analysed). Orange dots indicate the tactile stimulators used in the Tactile task. The same monitor was used during the behavioural experiments.

Analysis of EEG data. During offline analysis, the continuous EEG signal was down-sampled (1024 Hz), filtered (basic FIR filter, 1–100 Hz) and re-referenced to the average signal using EEGLAB software (Delorme & Makeig, 2004) running under MATLAB R2019b (MathWorks Inc.). ICA-based artefact correction was used in order to correct for blink artefacts (Delorme, Sejnowski, & Makeig, 2007) and ICA components falling outside the selection threshold of the EEGLAB plug-in SASICA were automatically removed (Chaumon et al., 2015). The signal was then divided into 'visual epochs' that contained the periods in which the object images appeared and 'tactile epochs' that contained the period in which tactile processing occurred (see specific time intervals used for epoching below). Epochs contaminated by muscular contractions or excessive deflections (± 75 µV) were excluded (total rejection rate was 11% in visual epochs and 8% in tactile epochs). For each participant, event-related changes in the oscillatory activity were quantified using a time-frequency wavelet decomposition of the EEG signals between 1 and 100 Hz (complex Morlet's wavelets, ratio $f_o/\sigma f = 7$) implemented in 'WTools' toolbox (Parise & Csibra, 2013). Baseline correction was performed over a -300 to -100 ms time interval relative to onset of the object image / tactile stimulator for visual / tactile epochs, respectively, using Fieldtrip toolbox (http://fieldtriptoolbox.org; Oostenveld et al., 2011) running under MATLAB R2019b (MathWorks Inc.). Then, the grand average was calculated and mean power of mu (8–12 Hz) and beta (15-25 Hz) rhythms were extracted from centro-parietal electrodes C3, CP1, CP5 and P3 on the left hemisphere and C4, CP2, CP6 and P4 on the right hemisphere (frequency ranges and electrodes of interest based on: Behmer & Jantzen, 2011, Nyström et al., 2011, Perry & Bentin, 2009, Perry & Bentin, 2011, Pfurtscheller et al., 2006, Pineda, 2005, Proverbio, 2012).

Visual epochs included the -700 to + 1500 ms time interval relative to onset of the object image (including the baseline period that started at -300 as well as the time interval of interest that lasted until +1000 ms (see below) and 500 ms extra before and after this interval to account for edge effects resulting from the time-frequency analysis. For the visual epochs, mu power was analysed in

a repeated-measures ANOVA with Distance (Near, Far), Valence (Positive, Negative), Hemisphere (Left, Right) and Task (Reaching, Tactile) as within factors, using the average mu power in the time window 500-1000 ms after visual stimulus onset for both tasks. The time window was chosen because it just precedes onset of the tactile stimulator and because mu power showed a robust increase within this time window. No statistical analysis was performed on beta power for the visual epochs because scalp maps revealed a clear occipital instead of sensorimotor localization (used scalp maps reflected beta power over the time interval after onset of the object image).

Tactile epochs included the -1900 to +1100 ms time interval relative to onset of the tactile stimulator. This interval started early because we wanted to enable visual inspection of the tactile epochs with baseline correction applied over the period prior to onset of the object image instead of the period prior to onset of the tactile stimulator (this inspection corroborated results described in the Results section regarding power differences that were present during tactile processing, but that already emerged prior to onset of the tactile stimulator). For the tactile epochs, mu and beta power were analysed in a repeated-measures ANOVA with Distance (Near, Far), Valence (Positive, Negative) and Hemisphere (Left, Right) as within factors. For mu and beta power, respectively, we used the average power in the time window 400-1000 ms and 300-700 ms after activation of the tactile stimulator. These time windows were based on previous literature (Cheyne et al., 2003, Hu et al., 2013, Singh et al., 2014). Note that on some trials the tactile epoch and the window used for mu rhythm lasted beyond the end of the trial (the shortest NO GO trials lasted only until 800 ms after onset of the tactile stimulator). However, when we repeated our analysis of mu power using a shorter time window (400-700 ms) we found equivalent results.

Behavioural experiment: Assessment of spatial boundary. We asked participants to make explicit judgments for both Defensive and Reaching spaces using a staircase procedure that included the 2 groups of object images (with positive and negative valence) and 3 different

experimental questions. To explicitly assess Reaching space, we asked participants to answer as fast as possible: 'Could you reach that object at that distance with your right hand?'. To explicitly assess Defensive space, we asked 2 questions in separated runs, one related to a feeling of comfort and the other related to action, in this case an avoidance response. The respective questions were: 'Do you feel uncomfortable with that object at that distance from your right hand?' and 'Would you like to retract your right hand away from that object at that distance from your right hand?'. For each question 4 runs with positively valenced images and 4 runs with negatively valenced images were completed. Per question, per valence value, the starting position of the object image on the first trial of a run alternated between being close to the participant's right hand (ascending series) or being far from the participant's right hand (descending series). The specific object that was displayed on a single trial within a run was selected randomly from the respective group of 20 images. Each trial started with 500-ms presentation of the fixation stimulus followed by presentation of an object image that lasted until response (using OpenSesame 3.1, Mathôt et al., 2012). Participants responded by pressing one of two possible response buttons on a computer mouse (left button for 'yes', right button for 'no'). A 'yes'/'no' answer resulted in the position of the object image on the following trial being further away / closer to their body, respectively. In the first run of each series, step size was 2.22 cm, while in the second run a more precise estimation of the extent of the respective space was obtained using a step size of 0.56 cm. The final runs ended when the participant's answer (and thereby the distance of the object image) went back-and-forth between the 2 possibilities for 12 times in a row (this was 6 times for the runs with 2.22 cm precision). The spatial boundary determined by explicit judgements was then computed by averaging all the object positions that elicited response change across the final run of both descending and ascending series. For statistical analysis, a repeated-measures ANOVA over participants was performed, with Space (Reaching, Defensive 'comfort', Defensive 'retract') and Valence (Positive, Negative) as within factors.

Behavioural experiment: Validation of visual stimuli. After the other experiments were completed, participants performed a short behavioural experiment in which they rated the valence, arousal level, difficulty to grasp and likability to touch regarding each of the 40 images of objects used in the completed experiments. Valence ('Rate how NEGATIVE/POSITIVE the picture just displayed is') and arousal level ('Rate how AROUSING the picture just displayed is') of the displayed object was rated using a 9-point Likert scale that ran from 'Completely Negative'/'Completely Unarousing' to 'Completely Positive'/'Completely Arousing' with the central point marked as 'Neutral'/'Medium Arousing' (using OpenSesame 3.1, Mathôt et al., 2012). The images were displayed at the centre of the same screen used for the EEG task for 1500 ms preceded by a 500 ms fixation stimulus, and the Likert scales remained visible until response. The response was made using a computer mouse held in the right hand. The procedure was then repeated with two different questions that assessed difficulty to grasp and likability to touch (respective instructions were: 'Rate if is it difficult or easy to GRASP/LIFT the object just displayed using only the right hand' and 'Rate if would you like or dislike to TOUCH the object just displayed'; Likert scale was labelled 'Very Easy'/'Dislike Very Much' on the left end and 'Very Difficult'/'Like Very Much' on the right end, with the label 'Neutral' in the middle). The 2 categories of 20 images (positive/negative valence) differed in rated valence and likability to touch but not in rated arousal value and difficulty to grasp (valence: $t_{(29)}= 17.0$; $p> 0.001$; likability to touch: $t_{(29)}= 20.4$; $p> 0.001$; arousal: $t_{(29)}= 1.1$; $p= 0.3$; difficulty to grasp: $t_{(29)}= -0.9$ $p= 0.4$). The 20 pairs of images used in the experiments were selected from a larger set of 81 pairs of images that was assessed in a pilot test using the same protocol as describe above. Based on the results of the pilot test 20 out of the 81 pairs of images were selected such that they differed in valence but not in arousal value and difficulty to grasp and this was confirmed for the current group of participants (see statistical results above).

Results

Explicit assessment of spatial boundary: *The boundary of Defensive space, but not Reaching space, is further from the body for objects with negative compared to positive valence.* A significant interaction between Space and Valence ($F_{(2,58)}$= 20.7; p< 0.001) revealed that valence had no effect in Reaching space ($t_{(81.9)}$= -0.21; p≈ 1.0), while it had a strong effect on Defensive space (Defensive 'comfort' space: $t_{(81.9)}$= -7.4; p< 0.001; Defensive 'retract' space: $t_{(81.9)}$= -7.3; p< 0.001; main effect of Valence: $F_{(1,29)}$= 54.8; p< 0.001) (Figure 3). The effect of valence on Defensive space was mainly expressed as a profound reduction of its threshold when positive visual stimuli were presented (objects with positive valence, Reaching space vs. Defensive 'comfort' space: $t_{(102.9)}$= 8.1; p< 0.001; Reaching PPS vs. Defensive 'retract' space: $t_{(102.9)}$= 8.1; p< 0.001; Real Reaching vs. Defensive 'comfort' space: $t_{(29)}$ = 11.266; p<0.001; Real Reaching vs. Defensive 'retract' space: $t_{(29)}$= 8.1; p< 0.001). Regarding negative visual stimuli, Defensive space was also slightly smaller than Reaching space but they did not significantly differ from each other (objects with negative valence, Reaching space vs. Defensive 'comfort' space: $t_{(102.9)}$= 1.7; p= 0.5; Reaching space vs. Defensive 'retract' space: $t_{(102.9)}$= 1.9; p= 0.4; overall main effect of Space: $F_{(2,58)}$= 24.3; p< 0.001). There were no differences between our two measures of Defensive space regarding these effects (difference between the two Defensive spaces: $F_{(1,29)}$= 0.02; p= 0.9; interaction with Valence: $F_{(1,29)}$= 0.01; p= 0.9) and, overall, the results of the two defensive staircases were positively correlated (r=0.620; p<0.001), thus suggesting they were indeed measuring the same type of space.
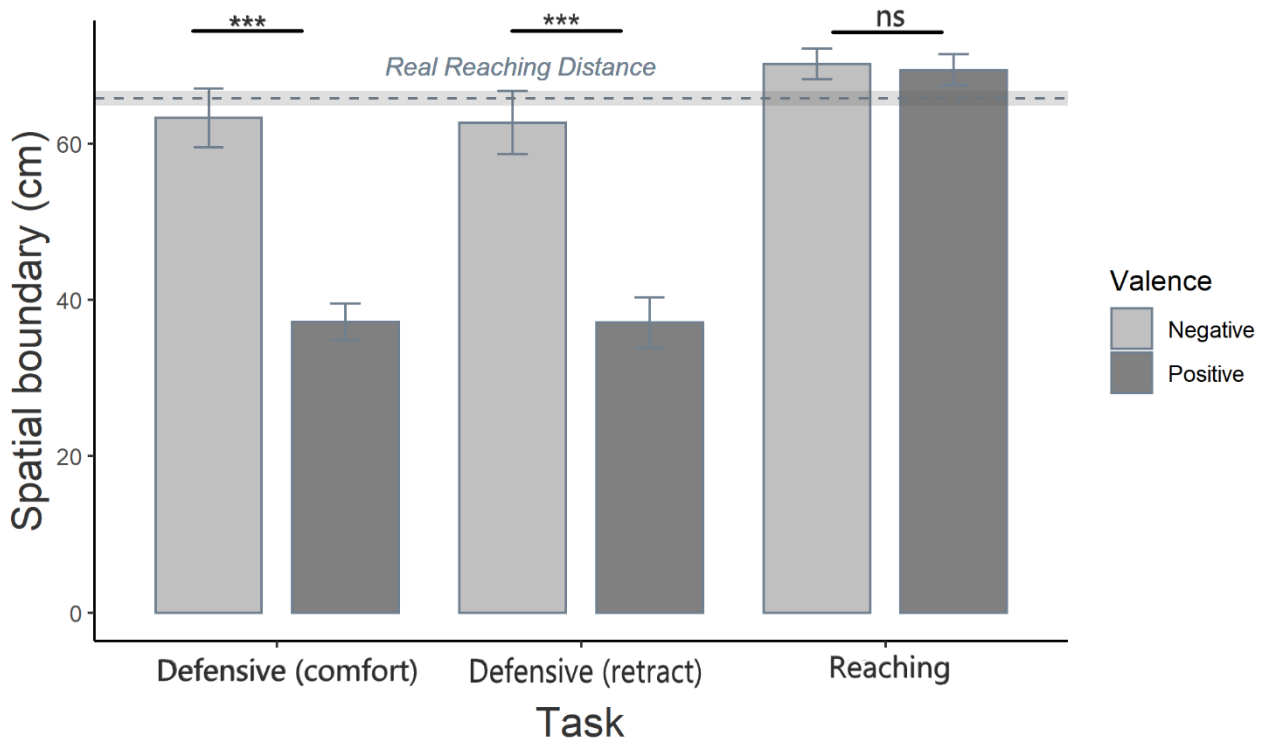
Figure 3. Explicit assessment of spatial boundary: *The boundary of Defensive space, but not Reaching space, is further from the body for objects with negative compared to positive valence.* The boundary of Defensive space (both Defensive 'comfort' and Defensive 'retract') was much closer to the body for objects with positive valence (dark grey bars) than for objects with negative valence (light grey bars). For the Defensive 'comfort' measure participants indicated whether they felt comfortable with objects at a certain distance from their hand. For the Defensive 'retract' measure participants indicated whether they wanted to retract their hand further away from the objects. The size of Reaching space, as assessed by asking participants to indicate whether objects were within reaching distance, was not influenced by the valence of the objects. Error bars indicate SEM. The dashed horizontal line indicates the actual reaching distance of the participants (shading indicates SEM). Asterisks represent the difference between objects with positive and negative valence (*** indicates p< 0.001; ns indicates no significant difference).

Behavioural results EEG experiment: *Responses are faster and more accurate for nearby objects, but they are not influenced by stimulus valence.* In both tasks, participants responded faster when objects were located near rather than far from the body ($F_{(1,29)}$= 15.4; p< 0.001). This difference between near and far space was even stronger in the Reaching task (69 ms difference; $F_{(1,29)}$= 17.4; p< 0.001) than in the Tactile task (22 ms; $F_{(1,29)}$= 4.9; p= 0.04; Distance*Task: $F_{(1,29)}$= 6.3; p= 0.02; overall mean reaction time was 622 ms). Reaction times were particularly fast for objects in near space in the Reaching task (difference between the tasks: 90 ms; $F_{(1,29)}$= 6.9; p=

0.01), while reaction times for objects in far space were more similar (42 ms; $F_{(1,29)}= 1.5$; p= 0.2; overall main effect of Task: $F_{(1,29)}= 4.3$; p< 0.05). No main effects of valence or interactions with valence were found (all $F_{(1,29)}< 1.2$; all p ≥ 0.3).

Responses were more accurate for near than for far objects in the Reaching task ($x^2_{(1)}= 6.0$; p=0.01; near: M ± SD: 96% ± 12%; far: 93% ± 9%), but not in the Tactile task ($x^2_{(1)}= 0.1$; p=0.7; near: 91% ± 9%, far: 90% ± 11%). Valence of the object did not influence response accuracy (Reaching task: $x^2_{(1)}= 0.2$; p=0.7; Tactile task: $x^2_{(1)}= 0.3$; p=0.6).

Visual processing: *Bilateral mu synchronization is weaker for nearby objects and this effect is not influenced by stimulus valence*. In both tasks, bilateral mu synchronization was larger when objects were far from the body than when objects were near the body (Figure 4; Distance: $F_{(1,29)}= 34.0$; p< 0.001; mu power relative to baseline for far: $t_{(29)}= 6.4$; p< 0.001; for near: $t_{(29)}= 23.8$; p= 0.008; Hemisphere: $F_{(1,29)}= 2.5$; p= 0.1; Distance*Hemisphere: $F_{(1,29)}= 1.3$; p= 0.3). The difference between near and far objects was significant in the Reaching task ($F_{(1,29)}= 17.8$; p< 0.001) as well as the Tactile task ($F_{(1,29)}= 41.9$; p< 0.001), but in the Tactile task the enhanced mu synchronization for far objects was particularly strong (Figure 4; difference between the tasks for far objects: $F_{(1,29)}= 20.6$; p< 0.001; for near objects: $F_{(1,29)}= 2.6$; p= 0.1; Distance*Task: $F_{(1,29)}= 11.0$; p= 0.002; Task: $F_{(1,29)}= 13.2$; p< 0.001). Object valence did not influence these effects (Distance*Valence: $F_{(1,29)}= 0.2$; p= 0.7; Valence: $F_{(1,29)}≈ 0.0$; p≈ 1.0; other interactions with Valence: all $F< 3.5$; all p> 0.07). Note that visual stimuli had a larger retinal size when closer to the body which might have contributed to the main effect of Distance.
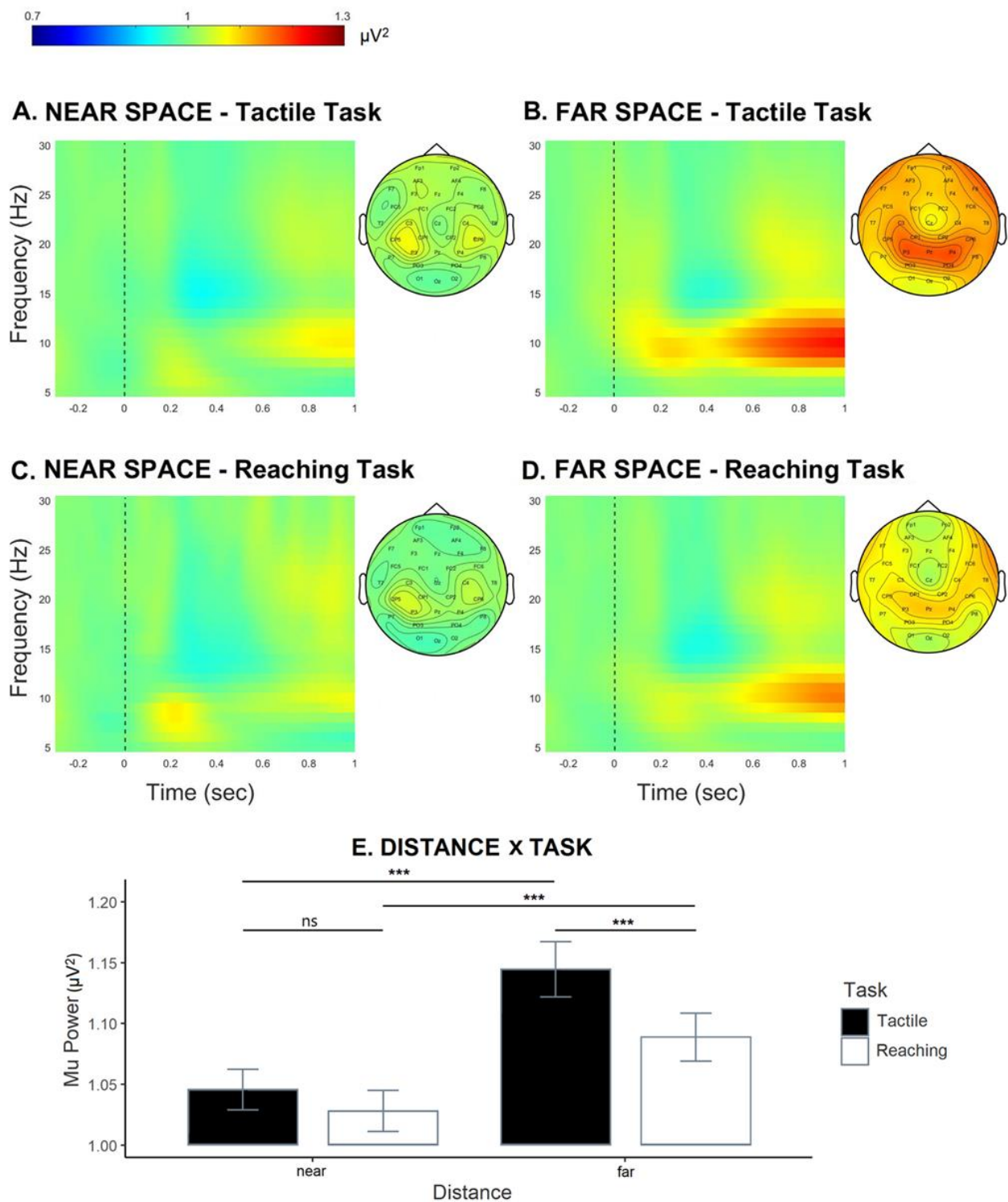
Figure 4. Visual processing: *Bilateral mu synchronization is weaker for nearby objects than for far objects in the Tactile task as well as the Reaching task*. **Panel A**. Time-frequency (TF) spectrum relative to onset of the visual stimulus and scalp map of mu power (8-12 Hz) for the time interval 500-1000 ms after visual stimulus onset for near space in the Tactile Task. Mu power is indicated by colours (see colour bar in upper left corner), with blue and red symbolizing μV^2 desynchronization and synchronization relative to baseline, respectively. **Panel B**. TF spectrum and scalp map for far space in the Tactile Task. **Panel C**. TF spectrum and scalp map for near space in the Reaching Task. **Panel D**. TF spectrum and scalp map for far space in the Reaching Task. **Panel**

E. Mu power (8-12 Hz) for the time interval 500-1000 ms after visual stimulus onset, illustrating the main effect of Distance in both tasks. Error bars represent SEM. Asterisks represent difference between conditions (*** indicates p< 0.001; ns indicates no significant difference).
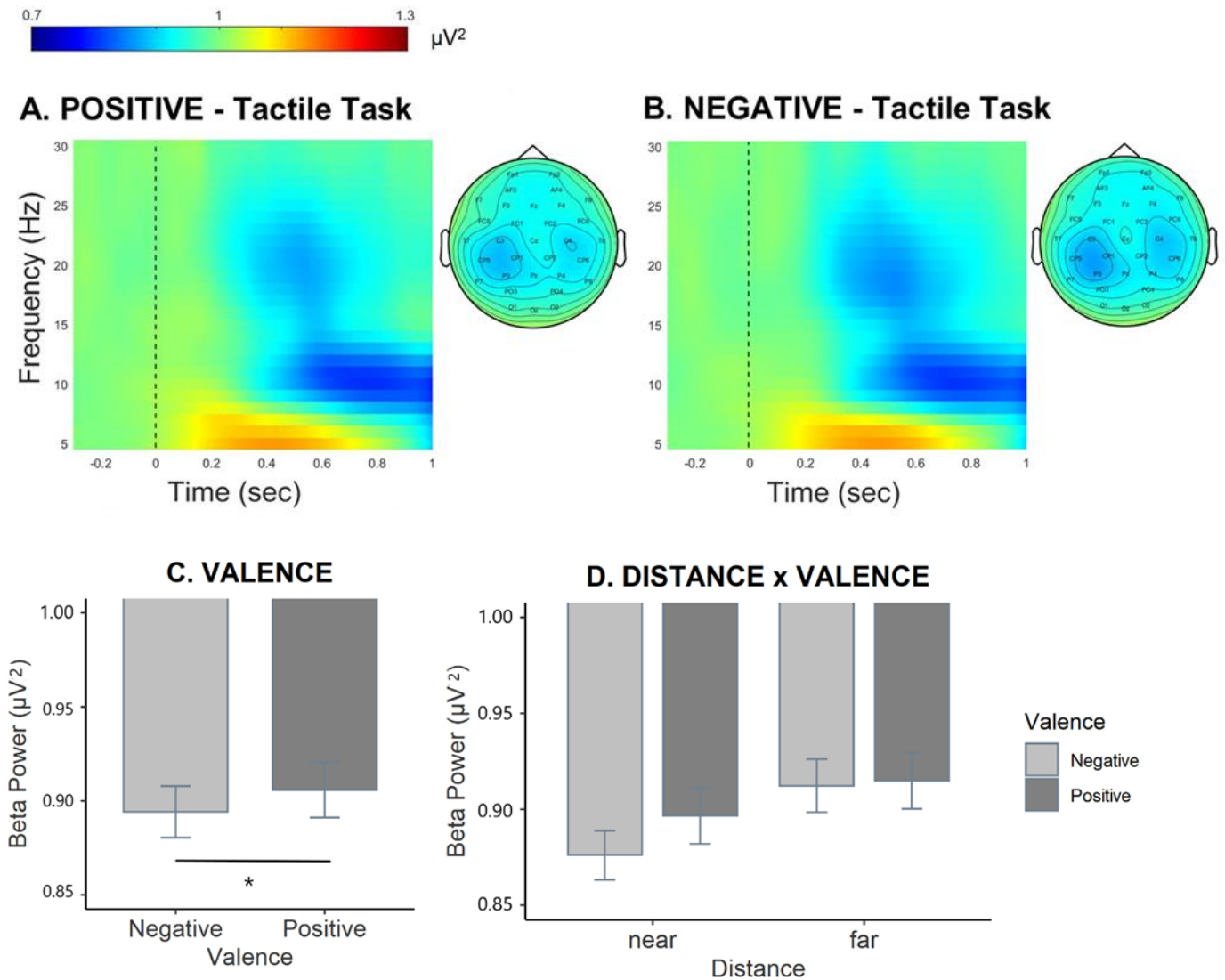
Figure 5. **Tactile processing:** *Beta desynchronization is enhanced for objects with negative compared to positive valence.* **Panel A**. Time-frequency (TF) spectrum relative to onset of the tactile stimulator and scalp map of beta power (15-25 Hz) for the time interval 300-700 ms after tactile stimulator onset for objects with positive valence (near and far spaces are averaged). Note that vibration amplitude increased gradually after onset of the tactile stimulator and that it reached a perceivable level after approximately 55 ms (see Methods). Beta power is indicated by colours (see colour bar in upper left corner), with blue and red symbolizing desynchronization and synchronization relative to baseline, respectively. **Panel B**. Same as panel A, but here for objects with negative valence. **Panel C**. Beta power (15-25 Hz) for the time interval 300-700 ms after

tactile stimulus onset, illustrating the main effect of Valence. There was also a main effect of Distance, but this was not related to tactile processing specifically, because it was already present prior to onset of the tactile stimulus. **Panel D**. Same data as in panel C, but here presented for near and far space separately (the two-way interaction Distance*Valence was only marginally significant). Error bars represent SEM. Asterisks represent difference between conditions (* indicates $p < 0.05$).

Tactile processing: *Beta desynchronization is enhanced for objects with negative compared to positive valence.* In line with expectation, there was a bilateral desynchronization of mu and beta power after the tactile stimulus was delivered, which was stronger in the contralateral than in the ipsilateral hemisphere (Hemisphere: mu: $F_{(1,29)}= 8.8$; $p= 0.006$; beta: $F_{(1,29)}= 5.6$; $p= 0.03$; contralateral and ipsilateral power for mu: M ± SD: $0.84 \mu V^2 \pm 0.14$ and $0.87 \mu V^2 \pm 0.13$; for beta: $0.89 \mu V^2 \pm 0.08$ and $0.91 \mu V^2 \pm 0.07$). In both hemispheres, desynchronization of beta rhythm was stronger when objects had negative compared to positive valence (Figure 5A-5B-5C; Valence: $F_{(1,29)}= 4.9$; $p= 0.03$; Valence*Hemisphere: $F_{(1,29)}= 0.3$; $p= 0.6$). There was a marginally significant Valence*Distance interaction ($F_{(1,29)}= 3.1$; $p= 0.09$; Valence*Distance*Hemisphere: $F_{(1,29)}= 0.9$; $p= 0.3$; Figure 5D). The effects of Hemisphere and Valence were not significant prior to onset of the tactile stimulus (analysis over 800-1000 ms time interval after visual stimulus onset, all $F_{(1,29)} \leq 1.5$; all $p > 0.2$), indicating they emerged during tactile processing. Note that vibration amplitude increased gradually after onset of the tactile stimulator and that it reached a perceivable level after approximately 55 ms (see Methods). Also note that, even if their onset was asynchronous, the tactile stimulus was delivered when the visual stimulus was still present. Therefore, these results may reflect coupling of visuo-tactile stimuli, rather than tactile stimulation alone.

There was a difference in beta power between objects in near and far space (Figure 5C; $F_{(1,29)}=$ 20.2; $p< 0.001$). However, this difference may, at least partly, reflect a difference in visual processing, because it was already present prior to onset of the tactile stimulus and may thereby have affected the time interval used for baseline correction (analysis over 800-1000 ms time interval after visual stimulus onset, $F_{(1,29)}= 5.1$; $p=0.03$; -0.014 $\mu V^2 \pm 0.006$ difference). Similarly, mu power also differed for objects in near and far space ($F_{(1,29)}= 16.2$; $p< 0.001$; near: M $\pm$ SD: 0.88 $\mu V^2 \pm 0.12$, far: 0.83 $\mu V^2 \pm 0.14$), but a difference with similar scalp location and magnitude was already present before onset of the tactile stimulus, indicating it probably reflected tactile anticipation rather than tactile processing (Figure 4). Desynchronization of mu rhythm was not influenced by object valence ($F_{(1,29)}= 0.01$; $p= 0.9$) and no other main effects or interactions were found (all $F\leq 0.8$; $p\geq 0.4$).

Discussion

Inspired by the literature on PPS, we aimed to explore the electrophysiological and behavioural signature of the mechanisms underlying the two spatial representations - Reaching and Defensive spaces - and their modulation by the valence of visual stimuli. We recorded electro-encephalograms (EEG) while participants performed a Reaching task (Reaching space) and a Tactile task (Defensive space) in which they viewed visual stimuli with positive or negative valence. In a separate experiment that included the same visual stimuli as the EEG experiment, spatial boundaries were probed using explicit judgments about evaluative mechanisms in a staircase procedure. We obtained three main results: (*i*) the boundary of Defensive space but not Reaching space was influenced by valence: the boundary was closer to the body for visual stimuli with positive compared to negative valence; (*ii*) Electrophysiological results support an influence of valence in Defensive space: during tactile processing in the Tactile task, desynchronization of beta rhythm over the sensorimotor cortex

was smaller for positively compared to negatively valenced visual stimuli; (*iii*) Visual processing in both Defensive and Reaching spaces was influenced by object distance but not valence: in both the Tactile task and the Reaching task, presentation of the visual stimulus elicited weaker synchronization of mu power when the visual stimulus was presented close to rather far from the body. Thus, to summarize, both EEG and psychophysical data reveal an effect of valence for Defensive space, while no effects of valence were found for Reaching space. Our results regarding Defensive space suggest that valence (i.e., contextual information) influences late processing stages rather than initial object/space encoding, because tactile processing (beta rhythm) and explicit measure of spatial boundary were influenced by valence, but visual processing was not.

Valence encoding modulates Defensive space boundaries and beta rhythm oscillations during tactile processing. Using two different questions that relate to Defensive space (i.e., 'Are you uncomfortable with that object at that distance?' and 'Would you like to retract your right arm with that object at that distance?') in a staircase procedure, we obtained a clear effect of valence on explicit judgements of Defensive space boundary. In particular, we found that positively valenced stimuli entail a smaller Defensive space than negatively valenced stimuli for both the questions used. This makes sense, considering that it is not necessary to implement protective actions when encountering pleasant stimuli. Valence of the visual stimulus did not influence the boundary of Reaching space ('Could you reach, with your right hand, that object located at that distance?').

While the estimation of own reaching capabilities is often used in the scientific literature to explicitly assess Reaching space (Valdès-Conroy et al. 2012, 2014, Wamain et al., 2016, Patanè et al., 2017, D'Angelo et al., 2019), to date, there is no standard explicit measurement of Defensive space. In the context of PPS, a physiological response to threat is typically employed when indexing Defensive space, measured both through the hand-blink-reflex (Sambo et al., 2012) and skin conductance (Rossetti et al., 2015). Therefore, we developed a novel paradigm to explicitly

characterize Defensive space by using two different questions tapping into the mechanisms underlying this space, the "comfort" question and the "retract" question.

So far, most studies about PPS investigated the influence of negatively valenced stimuli by comparing them to stimuli with neutral valence (Ferri et al., 2015, de Haan et al., 2016, Taffou et al., 2014). These studies, using multisensory stimulation paradigms, showed an expansion of PPS boundaries for visually threatening stimuli (Ferri et al., 2015, Taffou et al., 2014). The influence of stimuli with positive valence on PPS boundaries has received less attention. Using a visuo-tactile interaction task, Spaccasassi et al. (2019) showed faster reaction times to both positively and negatively valenced stimuli (regardless of their arousal value) compared to neutral stimuli in far space, while this distinction disappeared in near space. This was interpreted as evidence for high saliency of all visual stimuli that are close to the body as well as non-neutral stimuli further away from the body. However, this study did not assess changes in PPS boundary.

In the current study we assessed the influence of visual stimulus valence in relation to the distinction between Defensive and Reaching space and found that valence influenced the mechanisms underlying Defensive space but not those underlying Reaching space. Defensive space boundary measured by explicit judgements about positively valenced stimuli was much closer to the body than both explicit judgements about Reaching space and the actual reaching distance of the participants, while there were no significant differences regarding positively valenced stimuli (we did not include a neutral stimulus). Without claiming that Defensive space, Reaching space and actual reaching distance are the same for negatively valenced stimuli, these results suggest that the modulation of Defensive space by valence mainly comprises a reduction in Defensive space for positively valenced stimuli. It would be interesting to see whether this holds if affirmative questions are asked instead, i.e., asking whether the participant is 'comfortable' (instead of uncomfortable) and asking whether the participant would like to 'keep the hand in place' (instead of asking about

retraction). Neurolinguistic studies indicated that negative and affirmative sentences are processed differently, with the latter being associated with better mnemonic and semantic processing (Christensen, 2009; Cornish & Wason, 1970). Note that our staircase methodology inevitably resulted in a measure of a boundary, but this reflects the methodology used and we therefore consider the boundaries found in the current study not to be in contradiction with a recent proposal that PPS is a set of graded fields than as a sharp boundary (Buffacchi & Iannetti, 2018).

This influence of stimulus valence on the properties of Defensive space was supported by modulations of beta oscillations that occurred bilaterally centred on the sensorimotor cortices during tactile processing in the Tactile task (bilateral occurrence is in line with previous literature: Genna et al., 2017; using the same tactile stimulus as in the present study: de Jong & Dijkerman, 2019, see Figure S2D). Beta desynchronization was reduced for concurrent visual stimuli with positive compared to negative valence. Previous studies have shown a link between aversive tactile stimuli and modulations of beta oscillations (Mancini et al., 2012, Michail et al., 2016) as well as between processing unpleasant visual stimuli and modulations of beta oscillations (Güntekin & Başar, 2010). Our study extends these findings by showing that the valence of a *visual* stimulus modulates beta oscillations that reflect *tactile* processing. We suggest that the observed difference in beta desynchronization could be linked to unpleasant bodily consequences (Valentini et al., 2012) implied by negatively valenced visual stimuli (Kandula et al., 2015, Dijkerman & Medendorp, 2021). This interpretation relates to the influence of valence on the explicit judgements measuring Defensive space boundary that we found using the 'comfort'- question ('Are you uncomfortable with that object at that distance?'). Alternatively, the difference in beta desynchronization could be related to subthreshold motor activation like an avoidance response (DeLaRosa et al., 2014), considering the effect on Defensive space boundary observed using the 'retract'-question ('Would you like to retract your right arm with that object at that distance?').

Interestingly, the bilateral valence effect observed for beta oscillations was not (or only weakly) modulated by object distance. It could be that the influence of object distance would have been stronger if the objects had had a larger difference in valence or a higher arousal level (being threatening or dangerous), if the tactile stimulus would have been aversive or nociceptive (as in Sambo et al., 2012, and De Paepe et al., 2014) or if the experiment would have included more participants and/or more trials. However, even if object distance (marginally) influences the modulation of beta by object valence, our findings largely suggest that near space encoding occurs separately from - perhaps prior to - valence encoding as indicated by the different modulation of oscillations in near vs. far space prior to tactile stimulation. This is in line with the 'swiss army-knife model' of PPS (de Vignemont & Iannetti, 2015), which describes a single cortical map underlying Reaching PPS and Defensive PPS.

We had hypothesized that positively valenced stimuli evoke enhanced neural processing in the Reaching task and a more distant Reaching space boundary than negatively valenced stimuli because of their high desirability (Balcetis & Dunning, 2009, Valdès-Conroy et al., 2012). However, valence of the visual stimulus influenced neither behavioural measures nor electro-encephalograms related to Reaching space. This suggests that visual stimulus valence does not modulate the mechanisms underlying Reaching space when the arousal level of the visual stimuli is carefully matched, in line with a previous report that showed that event-related potentials recorded with EEG are not modulated by the valence of visual stimuli displayed either inside or outside Reaching space (Valdès-Conroy et al., 2014). Moreover, this result is also consistent with our validation ratings where the reachability scores of the stimuli with positive and negative valence were similar. We here considered Reaching space to be characterized best by asking for a subjective estimation of reaching ability (indicate if you *could* reach the object with your right arm; in line with Patanè et al., 2017, D'Angelo et al., 2019), as reaching is the most straight-forward way of pro-actively interacting with an object close to our hand. Note that this methodology does not

equate Reaching space to actual reaching space, because rather than an objective measure of reaching ability, we analysed subjective estimates and neural processing associated with concomitant motor imagery. Still, it could be that the lack of modulation by valence is inherent to the context of reaching ability ('could') rather than reaching preference ('would'). In addition, it would be interesting to more thoroughly test (with more GO trials) whether reaction times and accuracy in the EEG task are indeed not modulated by stimulus valence.

Near space encoding is supported by reaction times and mu rhythm oscillations. In the literature, PPS refers to the facilitated processing of (multi)sensory stimuli when they are located close to the body (for a review see di Pellegrino & Làdavas, 2015). In line with this we found faster reaction times in both the Tactile task and the Reaching task for objects in near compared to far space, as well as higher response accuracy for objects in near space in the Reaching task. Furthermore, we found bilateral synchronization of mu rhythm over sensorimotor cortex, which, in both tasks, was most profound when visual stimuli were located in far compared to near space. Mu synchronization occurred 500-1000 ms after visual stimulus onset, thus prior to potential presentation of the Go signal or the tactile stimulus. In this time interval participants presumably were engaged in motor imagery (Reaching task), tactile anticipation (Tactile task) and response preparation (both tasks). Interestingly, in both tasks objects in near space were associated with mu synchronization that was confined to electrodes over sensorimotor cortex, while objects in far space elicited more distributed mu synchronization, including more lateral and more posterior electrodes. Following previous interpretations of similar localization difference between processing of objects in near and far space (e.g., Weiss et al., 2000), this may be interpreted as engagement of the dorsal (motor encoding) and ventral (perceptual encoding) visual processing stream for near and far visual stimuli, respectively. Alternatively, it may indicate that visual attention (alpha oscillations) contributed to the results, particularly in far space (Jensen & Mazaheri, 2010, Clayton et al., 2018).

Based on previous literature about mu rhythm, we had expected desynchronization of mu rhythm in near space – rather than reduced synchronization (Wamian et al., 2016; Llanos et al., 2013; Salmelin and Hari, 1994; Braadbaart et al. 2013; Hari, 2006; Coll et al., 2014). The reduced synchronization over sensorimotor cortex observed here could reflect that the sensorimotor cortex is less inhibited when visual stimuli are present in near compared to far space (following Pfurtscheller et al., 1996). In the present study, inhibition rather than activation of sensorimotor cortex may have resulted from the inability to physically interact with objects that are presented as flat images on a computer monitor, as well as the instruction of participants to refrain from actually performing such interactions. Importantly, if mu synchronization reflected inhibition of sensorimotor cortex, our results indicate that sensorimotor cortex is less inhibited when objects are in near space. This change in engagement of the sensorimotor cortex depending on object distance, irrespective of task goals and object valence, is consistent with the PPS characterisation postulated by Noel & Serino (2019). Indeed, these authors emphasize the role of distance in defining PPS, claiming that proximity is more important than any other factor sensitive to PPS measures. Our results are also in line with the perspective of Bufacchi & Iannetti (2018) that (*i*) visual objects inside PPS are transformed into representations of potential actions and (*ii*) different PPS measures lead to different results. Related to (*i*), the weaker mu rhythm synchronization in far vs. near space found in both the Tactile and the Reaching task, could reflect transformation into actions that could respectively be aimed at protecting the body (as investigated in Gonzalez-Franco et al., 2014) or performing a goal-directed action (as investigated in Wamain et al., 2016). Concerning (*ii*), the Tactile task revealed different aspects of Defensive space than the two defensive staircases (e.g., touch is an important signal that the body is potentially in danger of being harmed as well as the "comfort" and "retract" questions provide info about cognitive processing related to preventing the body from harm). In the present EEG study, indeed, we compared two regions in space, near and far from the body. In a future study, it would be interesting to vary the analysed distances parametrically, particularly including distances near the actual reaching distance or PPS boundary,

also to see if there is a near-to-far space gradient in space encoding (as suggested regarding PPS by Bufacchi & Iannetti, 2018).

Despite the similar topography and temporal dynamics of mu rhythm synchronization recorded in both spaces, it is worth noting that the Reaching EEG task relies on explicit judgements while the Tactile task relies on multisensory processing. Even though multisensory processing and reaching potentialities are not completely detached from each other (Maravita et al., 2001, Farnè et al., 2005), in a future experiment, it would be interesting to add an irrelevant tactile stimulus during the Reaching task (for a similar procedure see Zanini et al., 2020). This could determine whether the greater desynchronization of beta oscillations found for negative visual stimuli after receiving the tactile input is indeed specific to Defensive space.

In both tasks, the observed mu synchronization was not lateralized. Previous reports of *de*synchronization of mu rhythm often report lateralization to the contralateral hemisphere (motor imagery: McFarland et al., 2000, Nam et al., 2011; tactile expectation: van Ede et al., 2010, 2011; response preparation: Deiber et al., 2012), though not under all circumstances (Pfurtscheller & Aranibar, 1979, Pfurtscheller & Berghold, 1989). The lack of lateralization in the present results could be due to the fact that both hands were relevant to the task: the right hand for reaching estimation or tactile anticipation and the left hand for preparing a button press.

Conclusion. Using literature on PPS as a theoretical framework, we here investigated behavioural and neural correlates of Defensive and Reaching spaces by looking at their modulation by visual stimulus valence. The explicit judgments of Defensive space revealed a closer boundary for positively compared to negatively valenced visual stimuli. Furthermore, sensorimotor cortex activation during tactile processing was enhanced when coupled with negatively rather than

positively valenced visual stimuli. On the contrary, both the EEG and psychophysical measures of Reaching space did not reveal any modulation by valence. Contrasting their difference regarding valence encoding, we found indications that spatial encoding is similar for Defensive and Reaching spaces. Reaching estimation as well as tactile anticipation were characterized by increased mu synchronization for far compared to near visual stimuli, which could indicate increased inhibition of sensorimotor cortex for far stimuli. In accordance, in both tasks we found slower reaction times for far compared to near stimuli. These findings parallel the swiss army knife model of PPS described by de Vignemont & Iannetti (2015) that postulates a single cortical map underlying Reaching PPS and Defensive PPS (contrasting a range of behavioural studies supporting a distinction between the two spaces, e.g., Zanini et al., 2020). Our results are thus compatible with the idea that Reaching and Defensive space (and possibly PPS) are processed by the same neural representation that integrates sensory input with encoding of space, whereas task goals and stimulus valence (i.e., contextual information) are implemented in a later processing stage and exert an influence on touch processing and motor output rather than object/space encoding.

Conflict of interests

The authors declare that there is not any conflict of interests regarding the publication of this paper.

Author Contribution

CS: Conceptualization, Funding Acquisition, Data Curation, Formal Analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing, Visualization. CD: Conceptualization, Funding Acquisition, Resources, Supervision, Project Administration, Writing – review & editing. AM: Conceptualization. OF: Formal Analysis. MdJ: Conceptualization, Funding Acquisition, Methodology, Software, Writing – review & editing, Supervision.

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