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Somatosensory modulation of affective pictures' processing in adults with cerebral palsy and healthy controls: a case-control study

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Abstract

Background Brain processing of both somatosensation and emotion is altered in individuals with cerebral palsy. This paper aims at further exploring the interaction between the somatosensory system and affective processing in individuals with cerebral palsy.

Methods Somatosensory thresholds and emotion knowledge were assessed in 18 adults with cerebral palsy and compared with 15 age and sex-matched controls. EEG event-related potentials elicited by viewing affective pictures were recorded. During event-related potentials acquisition, a continuous cutaneous electrical stimulus was applied either at supra- or sub-threshold intensity.

Results Adults with CP had higher pain sensitivity and increased emotion difficulties, as well as lower event related potential amplitudes than controls. Moreover, the modulatory effects of the somatosensory stimuli on the brain processing of affective pictures differed between adults with CP and controls. Sex was an important factor affecting somatosensory modulation in affective picture brain processing.

Conclusions In adults with CP the interaction of abnormal processing of somatosensory and emotional inputs may give rise to a more basic interpretation of emotional cues in complex contexts. Pain sensitivity and sex appear as relevant factors that influence the processing of emotions in CP and should be taken into account in research and clinical settings.

Keywords Emotion, Somatosensory, Cerebral palsy, Visual-evoked potentials, Affective pictures, Pain, Sex

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Background

Somatosensory perception is a driver of multiple aspects of functional performance, not only as a sensory-discriminative event but also as an integrative part of affective processing [1]. How (somato-)sensory processing and emotion influence one another, is apparent in many research paradigms. As an example, magnetoencephalography research shows that gentle naturalistic touch rapidly activates somatosensory areas in the brain, as well as brain areas linked to emotion processing, such as the amygdala and cingulate regions [2]. As another example of sensory processing affecting emotion-regulating brain areas: the initial visual processing of others' human faces is followed by the activation of non-visual somatosensory areas contributing to emotion recognition, discrimination, and embodiment [3–5]. Furthermore, growing evidence points towards a contribution of the somatosensory cortex in the long-term memory storage of aversive conditioning [6]. On the other hand, emotions influence the processing of subsequent somatosensory stimuli [7–8]. For instance, negative emotional pictures increase the pain intensity and the amplitude of evoked potentials elicited by laser stimuli [9]. As another example, functional MRI research has shown that placebo improvements of painful and pleasant touch are mediated by activation of emotion appraisal brain circuitry which down- or up-regulates early sensory processing [10].

Experimental studies investigating the interaction between somatosensory processing and emotions have used affective stimuli, such as emotional faces [11] or affective pictures [7–8]. These studies showed distinct somatotopic activation of the somatosensory brain cortex and changes in somatosensory evoked potential amplitudes in function of the emotional load of stimuli [3, 8]. The functional coupling between brain areas integrating somatosensory and emotional information could reflect adaptive attention mechanisms to motivationally relevant stimuli and modulation of appraisal regions [8, 10]. In this context, sex could be a relevant factor modulating this interaction, as biological and psychosocial variables (e.g. sex steroid hormones or gender identity) may affect brain connectivity during emotion processing [12]. Thus, women may have faster valence recognition and stronger reactions to negative images [13], whereas men have a more evaluative brain response during negative emotion processing [12]. In the same line, women show higher excitability of the somatosensory cortex than men, and a characteristic attentional modulation of the somatosensory processing, based on whether attention is directed towards or away from the sensory stimulus [14].

Somatosensory processing and emotion regulation both are significantly impaired in cerebral palsy (CP). Individuals with CP exhibit deficits in stereognosis, proprioception and touch that could be attributable to altered somatosensory brain functioning [15–19]. Abnormal findings such as weaker somatosensory cortical activity hypergating to the second stimulus in paired-pulse stimulation, decreased cerebral cortical thickness, anomalous connectivity within S1 and between S1 and S2, and atypical somatotopic organization are commonly found in brain studies of individuals with CP [19–22]. From the reduction of ERP amplitudes at early latencies, it has been suggested that even the detection of emotionally relevant stimuli is altered in persons with CP [23]. Also, abnormal functional connectivity has been shown between the prefrontal cortex and the parietal regions implicated in prosocial and emotion regulation skills [24]. From a more clinical perspective, a high proportion of the adults with CP show signs of emotional dysregulation, in particular depression, anxiety and stress [25–26]. It appears that alterations in emotion perception due to somatosensory impairments, may have consequences in real-life for adults with CP, as, for example, fast automatic encoding of emotions is important for social interactions [27]. In children with CP, adapted behavior and positive socioemotional responses related to sensory processing have been linked with psychological well-being [28]. Despite the benefits of somatosensory intervention for normalizing somatosensory perception shown in adults with CP [29], from our knowledge, no research on the modulatory effects of somatosensory stimulation on affective processing in individuals with CP has been conducted.

In the neurotypical population, simultaneous tactile stimuli affect brain activity when viewing affective pictures, with a shift in attentional resources and a reduction in the brain's responsiveness to emotional content in the presence of distractors [8, 30–31]. This interaction between somatosensory and affective processing appears to be altered in patients with chronic pain [32–33]. In neurological conditions, such as autism spectrum disorders, it appears that emotion processing may significantly modulate somatosensory brain activity [34]. Also, it has been shown that simultaneous tactile tapping can reduce the recruitment of the somatosensory system during the discrimination of affective faces in autism [5]. For now, the interaction between somatosensory and affective processing remains unstudied in persons with CP.

The objective of the present study was to explore how somatosensory stimulation may bias affective processing in individuals with CP in comparison with healthy controls. In a double stimulus paradigm, EEG brain activity was recorded in response to affective pictures while a continuous mild somatosensory stimulus was applied to the forearm (supra- or sub-threshold level). Based on previous work suggesting that somatosensory information could interfere with affective brain processing [8, 30–31], we hypothesized that somatosensory stimulation

at the supra-threshold intensity level could reduce brain responses to affective stimuli differently in patients CP compared to healthy controls.

Methods

Aim, design and setting

The aim of this case-control study was to explore how somatosensory stimulation affects affective processing in individuals with CP in comparison with healthy controls. The study was developed in the laboratory of neuroscience of the University of the Balearic Islands, Spain.

Table 1 Clinical characteristics of individuals with cerebral palsy ($n = 17$). Gross motor function classification system (Palisano et al., 1997), Manual ability classification system (Eliasson et al., 2006), communication function classification system (Hidecker et al., 2011), visual function classification system (Baranello et al., 2019). These scales classify the person into 5 levels of function, lower scores indicating higher function

	n
Gross motor function classification system	
Level I	7
Level II	1
Level III	0
Level IV	8
Level V	1
Manual Ability Classification System	
Level I	7
Level II	3
Level III	2
Level IV	2
Level V	1
Communication Function Classification System	
Level I	5
Level II	4
Level III	5
Level IV	3
Level V	0
Visual Function Classification System	
Level I	9
Level II	6
Level III	2
Level IV	0
Level V	0
Cognitive level	
Not impairment	8
Mild impairment	5
Moderate impairment	4
Subtype of cerebral palsy	
Bilateral spastic	8
Unilateral spastic	1
Dyskinetic	2
Ataxic	1
Mixed	5

Participants

A group of adults with CP and/or their legal representatives, users of the Comprehensive Adult Life Development Services of the Cerebral Palsy Association (ASPACE) of the Balearic Islands (Majorca, Spain) were selected and invited to participate in the study according to the following criteria: inclusion criteria – diagnosis of cerebral palsy, age older than 18 year.; exclusion criteria - recent surgery or presenting an acute process at the moment of the study. Eighteen individuals with CP (mean age = 46.25yrs, SD = 18.04, 7 females) agreed to participate in the study. Written informed consent was obtained from those participants with the legal capacity to agree. In the case of participants without legal capacity, their verbal consent to participate was requested and their legal representatives signed the informed consent. In addition, 15 controls of similar age and sex (mean age = 44.15yrs, SD = 16.23, 7 females) were recruited among the staff of the ASPACE Balearic Foundation and their relatives. They gave their written consent to participate in the study. The study was developed in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the ASPACE Balearic Foundation and the Ethics Committee on Research from the University of the Balearic Islands (ref. 127CER19).

Clinical measures

All participants provided their age and sex. They also reported any existence of chronic pain (defined as recurring or persisting pain lasting more than 3 months). Clinical data of individuals with CP, such as type of cerebral palsy, levels of gross and fine motor function, visual function, communication, and cognitive impairment were obtained from the clinical history provided by the care center (Table 1). One individual with CP was excluded for having severe communicative impairment that could bias the study results.

All participants completed the *Emotion Matching Task* (EMT) [35]. This task measures the emotional knowledge of happiness, sadness, anger and fear/surprise through the labeling of facial emotions in four different tasks: EMT1 expression matching, EMT2 emotion situation knowledge (detecting the adequate facial expression for a given situation), EMT3 expressive emotion knowledge (naming the emotion corresponding to a facial expression), and EMT4 receptive emotion knowledge (choosing the face expressing a given emotion). The score of each task is computed by adding up the number of correct hits (maximum hits, score = 12). Both the original version and the Spanish version of the EMT present good psychometric properties [35–36]. Although conceived for a pediatric population, this this task-based assessment was used in an exploratory manner to evaluate emotion knowledge deficits in this population of adults with CP.

As EMT scores correlate strongly with verbal ability [35], only individuals with CP with CFCS < 3 were included in the data analysis.

Somatosensory thresholds

Each participant was assessed by the same experienced investigator. Tactile, warm, cold, and pressure pain thresholds were determined on the left thenar eminence and the dorsal part of the left forearm, according to the quantitative sensory testing protocol of Backonja et al. (2013) [37]. As individuals with CP have higher response time, response intervals were adjusted according to the behavior of each individual. For example, if no response was obtained after the usual response time of a particular subject, the stimulation was repeated or performed in a different location. Thenar and forearm locations allowed for exploring evoked potential differences between C fiber-related areas (forearm, related to the affective dimension of touch) and non-C fiber-related areas (thenar eminence, related to the discriminative dimension of touch) [38]. None of the participants expressed distress during the assessment. A professional with expertise in the daily care of the participants assured the tasks were understood and acted as an additional observer of non-verbal signs (e.g. facial expression, body behavior) in response to the somatosensory stimuli in those participants with communication difficulties. Several trials were performed until obtaining coherent measures and the mean of the 3 more similar trials was taken as the threshold value. The total duration of the assessment was twenty minutes. None of the participants expressed distress during the assessment. A detailed description of the assessment procedure for each threshold can be found in Riquelme et al., 2023 [39].

Tactile thresholds were measured with Von Frey monofilaments [40] with a diameter ranging from 0.14 to 1.01 mm according to the method of limits [37]. This procedure has previously been used to assess tactile thresholds in adults with CP [29].

Thermal detection thresholds (warm and cold detection thresholds) were measured with a computer-controlled contact thermal stimulator (Cold/warm plate AHP-301CPV, Teca, Schubert, IL, USA). Lower thermal thresholds for warmth correspond to greater warmth sensitivity. Lower thermal thresholds for cold correspond to lower cold sensitivity. As soon as participants detected the thermal stimulus, the temperature of the thermal stimulator returned to the baseline temperature.

Cold pain thresholds were measured at the same body locations with the same thermal stimulator. Participants were instructed to keep the skin in contact with the thermal plate. Temperature was decreased from the baseline temperature at a mean rate of 1°C/s to a minimum temperature of 0°C; the cold pain threshold was considered the temperature at which the participant removed the hand. Lower cold pain thresholds correspond to lower pain sensitivity. This procedure has previously been used to assess thermal pain thresholds in individuals with developmental disorders [41].

Pressure pain thresholds (expressed in Newtons) were measured with a digital dynamometer. The average of the three stimuli was calculated as the pressure pain thresholds for each location. Lower pressure pain thresholds correspond to higher pain sensitivity. The reliability of this procedure for assessing pressure pain sensitivity has been demonstrated in previous studies in adults with CP [29].

EEG recording and data processing

EEG was continuously acquired while participants viewed affective pictures. Ninety affective stimuli were selected from the International Affective Picture System (IAPS) [42]. Stimuli were identical to those used in a previous study in children with CP [23]. Affective stimuli were grouped into three categories according to valence ratings from normative adult data: 30 pleasant, 30 neutral and 30 unpleasant pictures. Pleasant and unpleasant pictures were comparable in arousal and valence levels. The EEG part of the experiment consisted of 2 blocks of presentation of affective pictures. After ending the EEG acquisition, the same set of 90 pictures was projected in a random order, and participants were asked to rate each picture for valence and arousal on a numerical scale ranging between 0 (low pleasantness, or low arousal) and 10 (high pleasantness, or high arousal).

A computer using Presentation software (Neurobehavioral Systems, Inc.; Albany, CA) controlled the stimulus timing and the presentation order. Affective pictures were randomly displayed in color on a screen, following the parameters used in Belmonte et al., 2019 [23]. Each picture was presented during 6000 ms (picture duration), followed by a white fixation cross on a black screen for 1000 ms (fixed inter-stimulus interval). Concomitantly with the presentation of the affective pictures, somatosensory stimulation was applied to the left forearm using a transcutaneous electrical nerve stimulator (TENS, Enraf-Nonius, Rotterdam, The Netherlands). The somatosensory stimulation consisted in successive bursts of 2 Hz with a duration of 180 μs, separated by interstimulus intervals of 50 μs, that were continuously provided along all the picture presentation. The somatosensory stimulation was applied in one of two modalities: at a subthreshold intensity or a suprathreshold intensity. For this purpose, before the start of the experiment, perceptive thresholds for the intensity of the TENS stimulus were determined individually. In individuals with CFCS level IV, this intensity was determined with the same procedure used for determining sensitivity thresholds.

Suprathreshold stimulus intensity was defined as sufficiently intense to be consciously perceived without being painful. The subthreshold intensity was set at -20% of the lowest perceived stimulus intensity. The EEG experiment consisted of 2 blocks of 90 affective images presented: (1) one block where affective pictures were displayed together with a continuous suprathreshold TENS stimulation and (2) one block where affective pictures were displayed together with a continuous subthreshold TENS stimulation. The order of presentation of blocks was randomized across subjects. None of the participants expressed distress during the EEG recording or the TENS threshold determination.

Electroencephalography (EEG) was recorded from 32 scalp electrodes placed following the international 10/20 system and EEG waveforms were pre-analyzed following the parameters described in Belmonte et al., 2019 [23]. Only recordings of right hemispheric electrodes were kept for statistical analysis, as tactile stimulation was applied on the left forearm. EEG epochs containing artifacts (maximal allowed voltage step/sampling point = 100μV, minimal allowed amplitude = – 100μV, maximal allowed amplitude = 100μV, or maximal allowed absolute difference in the epoch = 100μV) were automatically rejected. EEG waveforms were averaged per brain region (frontal: average of F4 andFC4-, centroparietal: average of C4, CP4 and P4, occipital: O2). For each subject, ERPs were averaged per emotional condition (pleasant, neutral, and unpleasant) and per intensity modality (suprathreshold TENS, subthreshold TENS). Thus, 30 epochs were used to construct each averaged waveform. Six waveforms were obtained for each subject. EEG analysis was performed locked to the visual stimulus onset. After visual inspection of averaged waveforms, amplitudes of following ERP components were identified for each participant and computed for each waveform: (a) P100, defined as an early positive peak around 100 ms after stimulus onset (latency range 50–180 ms). It has been suggested that the P100 is related to the automated detection and encoding of stimuli that are emotionally relevant [43]; (b) N200, defined as a negative peak into the latency range 180–250 ms after stimulus onset. The N200 is associated with early visual processing of affective stimuli; (c) P300, defined as a major positive peak in the latency range 250–450 ms after stimulus onset which is supposed to reflect emotional cue extraction [41]; (d) Late Positive Potential (LPP) which appears in the time-window ranging from 400 to 900 ms (late positive potential, LPP), and is associated with the emotional regulation of attentive resources [41].

Table 2 Clinical and behavioral characteristics of individuals with cerebral palsy and individuals with typical development. ** $p<.01$, *** $p>.001$

	Individuals with cerebral palsy	Controls
	Mean (SD)	Mean (SD)
Presence of chronic pain	*n* = 8	*n* = 6
Emotion knowledge task		
Expression matching	8.59 (1.54)	11.07 (1.14)***
Emotion situation knowledge	6.294 (2.54)	9.14 (1.56)**
Expression emotion knowledge	7.71 (3.18)	11.14 (1.16)***
Receptive emotion knowledge	8.41 (1.97)	11.14 (1.10)***

Statistical analyses

Descriptive statistics were computed. Kolmogorov-Smirnov tests confirmed a normal distribution of all variables (all $p>.05$). Sociodemographic and EMT data were compared between groups (individuals with cerebral palsy vs. controls) using chi-square and t-tests. For temperature, tactile and pain thresholds, a two-way ANOVA was computed with a between-subjects factor GROUP (individuals with cerebral palsy vs. controls) and a within-subject factor LOCATION (thenar eminence vs. forearm). For subjective ratings of affective pictures, a two-way ANOVA with a between-subjects factor GROUP and a within-subject factor EMOTION (pleasant vs. neutral vs. unpleasant) was used.

Statistical analyses of ERP were performed with ANOVAs with a between-subjects factor GROUP (individuals with cerebral palsy vs. controls) and within-subject factors EMOTION (pleasant vs. neutral vs. unpleasant) and INTENSITY (suprathreshold tactile stimuli vs. subthreshold tactile stimuli) for each brain location and time window. Analyses were repeated using the between-subjects factor SEX (men vs. women) as a covariate. Greenhouse–Geisser correction was applied for the violation of sphericity assumptions and Bonferroni corrections were applied for post-hoc comparisons. A significance level of 0.05 was used.

Results

Clinical measures and questionnaires Groups (CP vs. controls) were similar in sex, age, and presence of chronic pain. Eight participants with CP reported chronic pain in lower limbs, lumbar area and abdomen; six controls reported pain in lower limbs, lumbar and cervical areas. Participants with CP had lower scores for all the tasks of the ***Emotion Knowledge Task*** (all $t>2.96$, all $p<.003$). This corresponded to a lower emotion knowledge than controls. Table 2 displays the scores of the different subscales of the task in both groups.

Somatosensory thresholds Table 3 displays the somatosensory thresholds in both groups. Main effects of GROUP revealed less warmth and cold sensitivity ($F(1,26) = 28.69$, $p<.001$ and $F(1,26) = 6.78$, $p=.015$ respectively), as well as higher cold pain sensitivity ($F(1,25) = 51.60$, $p<.001$) and

Table 3 Somatosensory thresholds in adults with cerebral palsy and in controls. * $p<.05$, *** $p>.001$

	Individuals with cerebral palsy	Controls
	Mean (SD)	**Mean (SD)**
Tactile detection threshold (g/mm^2)		
Thenar eminence	0.98 (1.62)	0.03 (0.03)
Forearm	0.95 (2.38)	0.01 (0.01)
Warm detection threshold (ºC)		
Thenar eminence	37.01 (2.36)	31.75 (3.29)***
Forearm	35.94 (2.04)	31.99 (2.18)***
Cold detection threshold (ºC)		
Thenar eminence	32.85 (2.41)	29.97 (2.22)*
Forearm	31.74 (3.89)	29.71 (2.38)*
Cold pain thresholds (ºC)		
Thenar eminence	21.58 (10.93)	-0.42 (1.28)***
Forearm	20.32 (11.71)	-0.55 (1.98)***
Pressure pain thresholds (N)		
Thenar eminence	18.16 (15.79)	69.97 (16.45) ***
Forearm	18.14 (9.94)	61.94 (12.19)***

Table 4 Valence and arousal ratings of pleasant, neutral and unpleasant affective pictures in adults with cerebral palsy and in controls. * $p<.05$

	Individuals with cerebral palsy	Controls
	Mean (SD)	**Mean (SD)**
Valence		
Pleasant	5.92 (3.33)	7.95 (0.71)
Neutral	4.35 (3.05)	4.96 (0.60)
Unpleasant	2.08 (2.02)	2.38 (1.19)
Arousal		
Pleasant	4.35 (3.44)	6.68 (1.55)*
Neutral	3.67 (3.44)	4.25 (1.60)*
Unpleasant	4.17 (3.48)	6.36 (1.79)*

greater pressure pain sensitivity ($F(1,29)=122.78$, $p<.001$) in participants with CP, indicating greater pain sensitivity than in controls. A non-significant trend in the main effect GROUP ($F(1,29)=3.95$, $p=.057$) revealed less tactile sensitivity in individuals with CP than in controls. No significant effects were found for LOCATION or the interaction GROUP * LOCATION.

Subjective ratings of valence and arousal Table 4 displays the valence and arousal ratings in both groups. A significant main effect of EMOTION ($F(2,28)=68.00$, $p<.001$) on ***valence*** ratings was found among the 3 types of images (pleasant > neutral > unpleasant). No main effects due to GROUP or EMOTION * GROUP were found. Regarding ***arousal***, significant main effects of EMOTION ($F(2,28)=6.77$, $p=.004$) and GROUP ($F(1,39)=5.53$, $p=.026$) indicated that pleasant affective pictures elicited higher arousal ratings than neutral pictures ($p=.002$), and that individuals with CP reported lower arousal ratings than controls. No significant interaction of GROUP * EMOTION was found.

Visual ERPs

Event-related potentials (ERPs) elicited by affective pictures showed an early positive peak at 100 ms (P100) followed by a negative peak at 200 ms (N200) and a positive peak at 300 ms (P300). ERP data from 2 participants with CP had to be eliminated from statistical analyses because their EEG recordings did not meet the criteria specified above. The grand-average ERP for each group and each modality is shown in Fig. 1. ERP descriptive data and a summary of the statistical results are displayed in Tables 5 and 6, respectively.

Latency

Statistical analyses revealed significant main effects of EMOTION over the frontal and centroparietal regions in P300 ($F(2,26)=3.37$, $p=.046$ and $F(2,26)=7.64$, $p=.002$), respectively), indicating higher peak latencies in response to unpleasant than to neutral or pleasant pictures ($ps<0.038$). No significant main effects GROUP or INTENSITY or interaction effects were found. No significant effects were found in P100 or N200.

Amplitude

P100 The statistical analyses of *P100* amplitudes revealed significant main effects of EMOTION over the centroparietal and occipital regions (both $F>3.72$, both $p<.037$), showing higher amplitudes in response to pleasant than to neutral pictures. No significant main GROUP or INTEN-

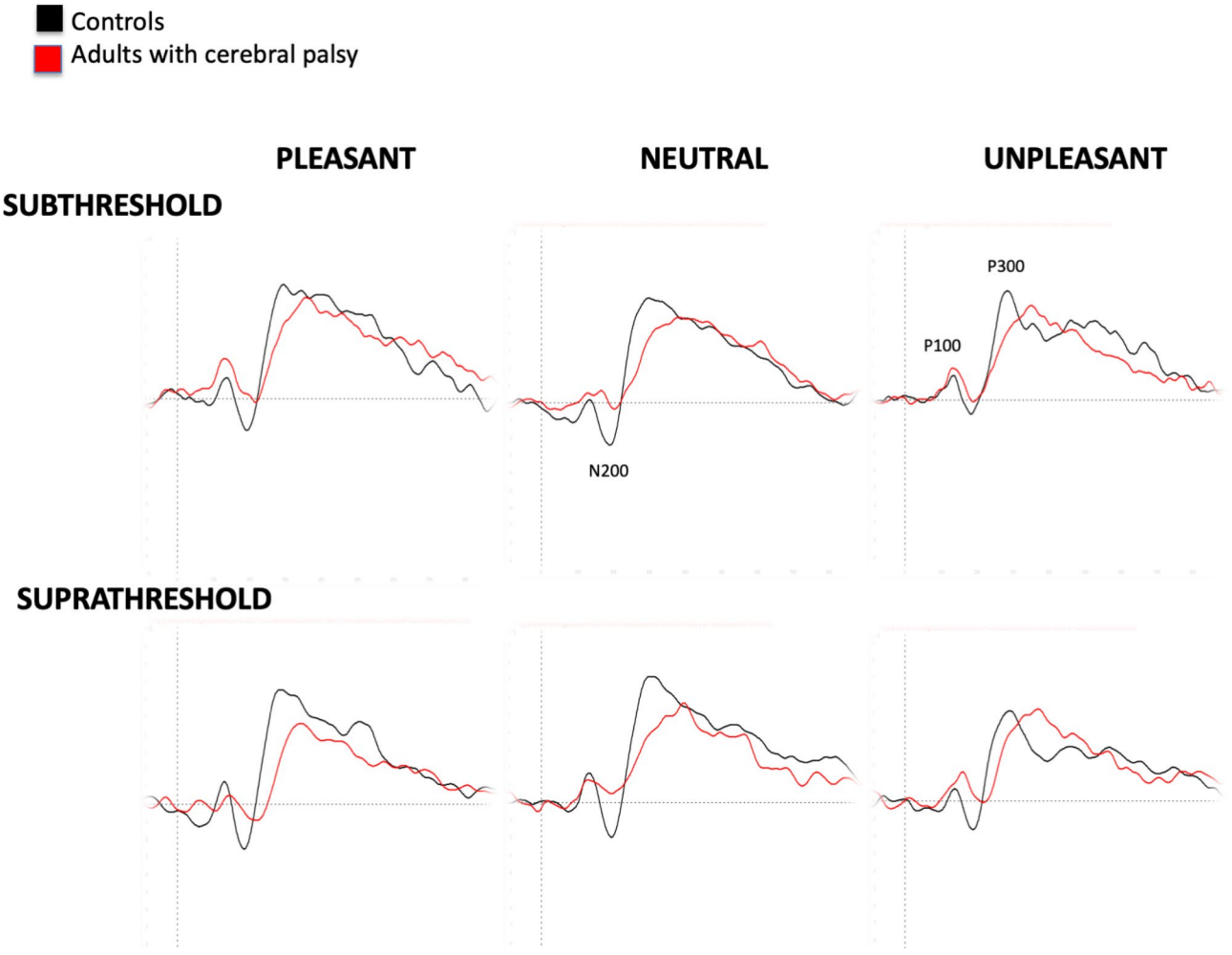

Fig. 1 Visual-evoked potentials elicited by pleasant, neutral and unpleasant pictures at the rigth occipital cortex during concomitant supra- and subthreshold stimuli in individuals with cerebral palsy and individuals with typical development

SITY effects or interaction effects GROUP*EMOTION were found.

N200 A significant GROUP*INTENSITY interaction effect was found on *N200* amplitudes over occipital electrode locations ($F(2,26) = 5.18$, $p = .031$). N200 amplitudes were lower during suprathreshold stimulation than during subthreshold stimulation in controls ($p = .031$), while no significant differences were observed in adults with CP. No significant effects of the factor EMOTION were found.

P300 A significant EMOTION main effect was found on *P300* amplitudes over occipital ($F(2,26) = 9.35$, $p = .001$) and over centroparietal electrodes ($F(2,26) = 3.77$, $p = .047$), indicating that pleasant pictures elicited higher amplitudes than neutral and unpleasant pictures ($ps < 0.05$). A significant GROUP*INTENSITY interaction effect was found on *P300* amplitudes over occipital electrode locations ($F(2,26) = 4.58$, $p = .031$). P300 amplitudes were lower during suprathreshold stimulation than during subthreshold stimulation in controls ($p = .031$), while no significant differences were observed in adults with CP. A significant GROUP * EMOTION interaction effect was yielded on *P300* amplitudes over frontal electrodes ($F(2,26) = 5.42$, $p = .013$), revealing that both pleasant and unpleasant pictures elicited higher amplitudes than neutral pictures in controls ($ps < 0.01$), but not in individuals with CP.

LPP A significant EMOTION main effect ($F(2,26) = 4.76$, $p = .013$) was yielded on *LPP* amplitudes over centroparietal electrodes, revealing that neutral images overall elicited higher LPP amplitudes than unpleasant pictures. A significant GROUP*EMOTION*INTENSITY interaction effect on *LPP* amplitudes over centroparietal electrodes ($F(2,26) = 3.84$, $p = .03$) further revealed that this effect (neutral > unpleasant) appeared in controls during suprathreshold stimulation ($p = .014$), but not in adults with CP

Table 5 Visual ERP amplitudes in the right occipital cortex in adults with cerebral palsy and controls. LPP: long positive potential

	Individuals with cerebral palsy		**Controls**	
	Suprathreshold intensity Mean (SD)	**Subthreshold intensity Mean (SD)**	**Suprathreshold intensity Mean (SD)**	**Subthreshold intensity Mean (SD)**
P100				
Pleasant	4.63 (3.60)	5.39 (3.34)	5.73 (3.67)	5.35 (3.42)
Neutral	3.49 (1.57)	3.80 (2.11)	4.08 (2.12)	2.72 (0.60)
Unpleasant	2.99 (2.54)	4.11 (2.36)	3.26 (2.18)	4.18 (3.11)
N200				
Pleasant	-4.17 (5.10)	-2.90 (5.04)	-3.74 (3.48)	-4.89 (5.08)
Neutral	-3.78 (2.61)	-4.19 (4.71)	-2.35 (2.22)	-4.73 (5.29)
Unpleasant	-4.33 (4.31)	-3.09 (4.33)	-3.45 (2.27)	-4.07 (4.68)
P300				
Pleasant	9.38 (0.35)	7.84 (0.21)	5.21 (3.67)	6.90 (2.35)
Neutral	6.44 (2.64)	8.20 (2.02)	3.09 (0.80)	4.35 (1.19)
Unpleasant	6.37 (2.82)	7.60 (1.70)	3.90 (2.37)	5.22 (3.25)
LPP (area)				
Pleasant	3068.8 (2373.3)	3509.7 (2553.2)	3256.0 (2327.1)	3529.2 (1872.3)
Neutral	3575.6 (2668.5)	2705.3 (3428.1)	3478.1 (2280.7)	3700.2 (2223.6)
Unpleasant	3394.7 (2344.3)	2781.0 (2258.4)	2707.4 (1642.4)	2964.7 (1360.7)

Table 6 Statistical results of ERP comparisons

	Frontal F, *p*	**Centroparietal F, *p***	**Occipital F, *p***
P100			
Main effect Group	1.43, 0.243	0.25, 0.619	0.10, 0.750
Main effect Emotion	0.28, 0.696	**3.72**, **0.037**	**6.84**, **0.008**
Main effect Intensity	0.18, 0.673	1.36, 0.254	0.41, 0.530
Group*Emotion	1.70, 0.201	0.009, 0.99	0.33, 0.631
Group*Intensity	1.63, 0.212	3.17, 0.086	2.60, 0.118
Group*Emotion*Intensity	0.99, 0.356	0.56, 0.570	0.70, 0.492
N200			
Main effect Group	0.02, 0.879	0.15, 0.706	0.006, 0.94
Main effect Emotion	0.70, 0.501	0.40, 0.640	0.03, 0.974
Main effect Intensity	0.05, 0.830	0.09, 0.768	0.74, 0.397
Group*Emotion	0.24, 0.726	0.37, 0.659	0.37, 0.626
Group*Intensity	3.88, 0.059	2.56, 0.121	**5.18**, **0.031**
Group*Emotion*Intensity	0.04, 0.845	0.21, 0.760	0.08, 0.898
P300			
Main effect Group	0.34, 0.563	0.18, 0.678	0.70, 0.411
Main effect Emotion	1.91, 0.168	**3.77**, **0.047**	**9.35**, **0.001**
Main effect Intensity	0.19, 0.669	0.06, 0.809	1.03, 0.319
Group*Emotion	**5.42**, **0.013**	1.91, 0.171	2.22, 0.133
Group*Intensity	3.90, 0.059	2.09, 0.160	**4.58**, **0.042**
Group*Emotion*Intensity	0.10, 0.848	0.32, 0.575	0.02, 0.886
LPP			
Main effect Group	0.87, 0.359	0.002, 0.97	0.005, 0.95
Main effect Emotion	2.92, 0.075	**4.76**, **0.013**	2.10, 0.139
Main effect Intensity	1.32, 0.260	0.24, 0.627	0.45, 0.508
Group*Emotion	0.66, 0.502	1.54, 0.224	0.40, 0.643
Group*Intensity	0.43, 0.518	0.24, 0.498	0.06, 0.806
Group*Emotion*Intensity	1.64, 0.206	**3.84**, **0.031**	0.77, 0.431

or during subthreshold stimulation. No significant main GROUP effects were found.

Sex-related effects

To analyze the effects of participants' sex on ERPs elicited by affective stimuli and somatosensory stimulation, ANOVAs were repeated using the between-subjects factor SEX as a covariate. Previous statistical results involving GROUP, INTENSITY, and EMOTION were confirmed when the influence of SEX was taken into account. In addition, a significant interaction effect of SEX*EMOTION*INTENSITY was found on the P100 and LPP amplitudes (all $F < 0.6.22$, all $ps < 0.005$), revealing sex-related effects during emotion processing that depended on the intensity level of TENS stimulation. Indeed, post-hoc mean comparisons revealed that women (in both groups) displayed higher P100 amplitudes than men over the occipital region when processing unpleasant and neutral pictures during suprathreshold stimulation ($p = < 0.05$). Furthermore, it appeared that differences due to stimulation intensity (sub-threshold > supra-threshold) appeared in response to unpleasant pictures in men, whereas they appeared in response to pleasant pictures in women (all $p < .05$). Finally, LPP amplitudes over centroparietal electrodes were higher in response to pleasant than to unpleasant pictures in men ($p = .045$), whereas no differences were found in women. No further effects due to SEX were found in the questionnaire scores, somatosensory thresholds, or subjective ratings of affective pictures.

Discussion

This study aimed at examining the interaction between somatosensory perception and emotion regulation in individuals with cerebral palsy (CP). For this purpose, we analyzed the modulatory effects of somatosensory stimulation at sub- and supra-threshold intensity levels on event-related brain responses elicited by affective pictures. Brain responses were characterized by an amplitude enhancement to pleasant affective pictures between 100 and 300 ms after stimulus onset in both groups. The brain responses of adults with CP had lower peak amplitudes than age-and sex-matched controls; this effect was not influenced by differences in the valence of affective visual stimuli. Moreover, individuals with CP and controls significantly differed in the modulatory effects of somatosensory stimulation on visual event-related potentials (ERP) to affective stimuli, with a significant change in ERP peak amplitude in controls, which was not observed in adults with CP. Finally, we observed that sex was an important factor affecting somatosensory modulation in emotion brain processing.

Results of the present study are in line with previous work describing an altered affective processing in adults and children with CP, reporting emotion knowledge problems, as well as reduced ERP amplitudes in early latencies, alterations in the detection of emotionally relevant stimuli and abnormal functional connectivity between the prefrontal cortex and the parietal regions implicated in prosocial and emotion regulations skills [23–26, 45–48]. We found that individuals with CP had significantly lower amplitudes of the middle- and late-latency components (between 200 ms and 800 ms after stimulus onset) of the event-related potentials during affective processing over centroparietal and occipital electrodes and, to a lesser extent, in frontal electrodes as compared to controls. We also found that participants with CP showed an atypical brain response to affective stimuli, with an overall reduction of ERP amplitudes (P300, LPP) to pleasant and unpleasant as compared to neutral pictures. Previous research in healthy adults has suggested that ERP amplitudes to both pleasant and unpleasant stimuli in these latencies might reflect the activation of neural circuitries responsible for the capture of automatic attention toward relevant stimuli that require rapid approach or avoidance responses [49–52]. Therefore, reduced brain responses as observed here in individuals with CP could be linked to altered encoding and attentional mechanisms involved in the processing of emotionally relevant stimuli [23, 44, 47, 53]. This is also in agreement with our behavioral data showing significant impairments in affective processing, such as reduced emotion knowledge in adults with CP than in controls. In short, it appears that brain processing and behavioral data in individuals with CP points towards abnormal functional alterations in emotion regulation and detection of emotionally relevant stimuli [23–24]. We further believe that these results, in addition to revealing that cerebral palsy presents important alterations in affective processing, point to the need to carry out studies on specific therapeutic interventions that improve emotional competence in this population.

The present study aimed at taking an additional step in this line of research by introducing a double stimulation ERP paradigm, what allowed explore the interactions between the brain processing of somatosensation and emotion. In this sense, we found that simultaneous suprathreshold rather than subthreshold somatosensory stimulation was able to reduce evoked potentials amplitudes (N200, P300, LPP) elicited by affective pictures (particularly, unpleasant stimuli) in controls, but not in individuals with cerebral palsy. We believe that these amplitude reductions after suprathreshold somatosensory stimulation could be due to a distraction effect caused by the simultaneous presentation of both types of sensory stimuli (somatosensory and visual). Taking into account previous works that analyze the interaction of somatosensory and affective processing [8, 30–31], it

could be argued that this type of double stimulation tasks required subjects to extract information from both sensory modalities and to reallocate attentional resources for the adaptive processing of the information that reaches the brain. Thus, although controls in our study have shown differential adaptive brain processing for reallocating attention and extracting information from emotional signals when these are in competence with parallel somatosensory inputs, these adaptive mechanisms seem to be absent in individuals with CP.

One of the reasons that may explain the lack of modulation of emotion processing by tactile stimuli in individuals with CP could be the abnormal processing of somatosensory stimuli in this population. Thus, abnormal brain processing of somatosensory information has been widely reported in individuals with CP, with weaker activation of somatosensory brain regions, atypical power oscillations in several frequency bands, and abnormal phase synchronization within the primary somatosensory cortex, and between the primary and the secondary somatosensory cortices [15, 18–19, 21, 54]. As selective attention to a stimulus can be biased by the occurrence of distractors that involuntary attract attention [30], the attenuated processing of tactile stimuli in individuals with CP may have reduced attention interference to emotional processing. In this sense, the lack of adaptive attentional discrimination during competing stimuli has been reported in other populations with abnormal somatosensory processing and emotion, such as women with fibromyalgia [33, 55] or individuals with autism [5]. As the somatosensory cortex plays a major role in emotion understanding and the storage of emotional memory [2–6, 11], further research is warranted to elucidate how reduced somatosensory processing may impact emotional problems in individuals with CP.

Moreover, we observed here that individuals with CP had enhanced pain sensitivity to pressure and cold than controls, as we had previously reported in CP [19] and other neurodevelopmental disorders [39]. Thus, it seems that these populations could be characterized by enhanced pain sensitivity associated with emotional and behavior problems, suggesting that deficits in somatosensory processing might impact the interpretation of body signals and be involved in the incidence of emotional and behavioral disorders [56–57]. As pain stimuli are known to affect focal attention and disrupt the automatic encoding of facial emotions [27] and individuals with chronic pain have shown maladaptive affective attention modulation [58], it seems plausible that pain, as a more arousal somatosensory perception, may modulate emotional processing in higher extent than tactile stimuli. Further investigation in the interference of pain sensitivity in all the aspects of emotion processing is extremely important, mostly in a population with high rates of pain prevalence, such as individuals with CP [59].

Finally, sex appeared as a crucial factor modulating the competitive processing of emotion and somatosensory signals. Although beyond the interest of this study, the sex-related processing of emotions should be deeply addressed, in line with the principles of personalized medicine, given that affective disorders, such as mood and anxiety are predominant in women [60]. Thus, it has been reported that men and women may elicited different cognitive strategies and distinct brain connectivity for the processing of emotional stimuli [12–13]. In line with this research, our study suggests differences between women and men in the brain processing adaptation to simultaneous stimuli when detecting and interpreting emotional cues, even though the absence of sex-related differences on behavioral measures. In the same line, mental representations of touch at a socio-affective level, measured with the modulation of central Rolandic rhythms when viewing affectionate touch, appear at being less effortful in women than in men [61]. Sex has been reported as a risk factor of socioemotional problems in children with CP, with boys manifesting more disruptive and social behavior problems [45, 62]. However, sex-related differences in somatosensory and emotion processing have been scarcely studied in individuals with CP and could proportionate important clues for tailoring interventions in this population.

Limitations

Although the sample size was low, it was comparable to the sample size in previous studies analyzing brain processing in this population. To overcome this limitation, we ran the ANOVA with a reduced number of factors and separated analyses for each brain location. Communication impairment could have affected results in participants with CP. For instance, previous research has revealed the association between language skills and emotion knowledge or quantitative sensory testing [37, 63]. Communication impairment might have also affected the determination of TENS stimuli used in the EEG recording, what could have implied the stimulation of nociceptive fibers in individuals with poorer communication (CFCS = 4, $n = 3$), even if careful procedure control measures were contemplated to perform threshold detection and none individual expressed distress along the experiment. Although the inclusion of participants with more severe forms of CP may better reflect the epidemiology of the condition, the interpretation and generalization of the findings must take into account the characteristics of the sample. Although proxy consent is usually admitted in individuals without legal capacity, and although noxious tests were restricted to thresholds, aversive testing in individuals with extremely limited

communication abilities may arise some ethical considerations. A discussion on the balance of research benefits and personal costs in vulnerable population is warranted.

In conclusion, the present study may advance the understanding of the interaction between the somatosensory system and affective processing in cerebral palsy, opening new possibilities for specific interventions that take into account their characteristic somatosensory and affective deficits. In individuals with CP the interaction of abnormal processing of somatosensory and emotional inputs may lead to a more basic interpretation of emotional cues in complex contexts, as those of real life. Pain sensitivity and sex may be relevant factors influencing emotion understanding and must be considered in future research, as a previous step for its implementation in the design of personalized interventions for improving emotional problems in this population.

Abbreviations

CP	Cerebral palsy
EEG	Electroencephalography
EOG	Electrooculography
ERP	Event-related potentials
LPP	Late positive potential
TENS	Transcutaneous electrical nerve stimulation
VEPs	Visual evoked potentials

Author contributions

IR and PM conceived and designed the study, analyzed the data and wrote the first version of the manuscript. AS and EM recruited the participants, recorded the EEG data and performed the clinical and behavioral examinations. SMH was a major contributor in writing the manuscript. All authors revised and the different drafts and read and approved the final manuscript.

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Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Written informed consent was obtained from participants or their legal representatives, in the case of participants without legal capacity. The study was approved by the Ethics Committee of the ASPACE Balearic Foundation and the Ethics Committee on Research from the University of the Balearic Islands (ref. 127CER19).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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