

An EEG/ERP investigation of the development of empathy in early and middle childhood

Yawei Cheng^{a,b,*}, Chenyi Chen^{a,1}, Jean Decety^c

^a Institute of Neuroscience and Brain Research Center, National Yang-Ming University, Taipei, Taiwan, ROC

^b Department of Rehabilitation, National Yang-Ming University Hospital, Yilan, Taiwan, ROC

^c Department of Psychology and Department of Psychiatry and Behavioral Neuroscience, The University of Chicago, IL, USA

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ABSTRACT

Empathic arousal is the first ontogenetic building block of empathy to appear during infancy and early childhood. As development progresses, empathic arousal becomes associated with an increasing ability to differentiate between self and other, which is a critical aspect of mature empathetic ability (Decety and Jackson, 2004). This allows for better regulation of contagious distress and understanding others mental states. In the current study, we recorded electroencephalographic event-related potentials and *mu* suppression induced by short visual animations that depicted painful situations in 57 typically developing children aged between 3 and 9 years as well as 15 young adults. Results indicate that the difference wave of an early automatic component (N200), indexing empathic arousal, showed an age-related decrease in amplitude. In contrast, the difference wave of late-positive potentials (LPP), associated with cognitive appraisal, showed an age-related gain. Only early LPP was detected in children, whereas both early and late LPP were observed in adults. Furthermore, as compared with adults, children showed stronger *mu* suppression when viewing both painful and non-painful stimuli. These findings provide neurophysiological support for the development of empathy during childhood, as indicated by a gradual decrease in emotional arousal and an increase in cognitive appraisal with age.

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1. Introduction

Empathy, the affective response that stems from the apprehension or comprehension of another's emotional state or condition, allows for the understanding of what another person is feeling or would be expected to feel (Eisenberg and Eggum, 2009; Zahn-Waxler and

Radke-Yarrow, 1990). The experience of empathy is a powerful interpersonal phenomenon necessary in everyday social interaction. It facilitates parental care of offspring and enables us to live in groups, cooperate, and socialize. It paves the way for the development of moral reasoning and motivates prosocial behavior (Decety and Cowell, 2014). Children's capacities to respond emotionally to the joys and sorrows of others and to express empathic concern are present during the first year of life (Davidov et al., 2013).

Empathic arousal (or affective sharing) is the first element of empathy to appear during ontogeny with deep evolutionary roots (Decety, 2010a,b, 2013; Decety and Svetlova, 2012). For example, neonates contagiously cry in response to the distress of conspecifics that are in their proximity (Martin and Clark, 1982). This reaction is

* Corresponding author at: Institute of Neuroscience, National Yang-Ming University, No. 155, Sec. 2, St. Linong, Dist. Beitou, Taipei 112, Taiwan, ROC. Tel.: +886 2 28267912; fax: +886 2 28264903.

E-mail addresses: ywcheng2@ym.edu.tw, yaweicheng@gmail.com (Y. Cheng).

¹ These authors contributed equally to the study.

heightened specifically in response to hearing the cry of another as opposed to the child hearing his own crying (Dondi et al., 1999). Such affective response to another's distress is postulated to be one of the earliest forms of empathy (Geangu et al., 2010), which is also shared in many non-human animal species (Ben-Ami Bartal et al., 2011; Church, 1959; Langford et al., 2010).

Later in development, this initial empathic arousal becomes associated with growing differentiation between self and other, allowing for reactions that are more attuned to another's state than one's own (Bischof-Köhler, 1991; Geangu et al., 2011; Nichols et al., 2009). With the development of top-down regulatory capacities during childhood that are associated with executive function, emotion regulation, and language, the modulation of empathic arousal occurs, leading to more adaptive responses (Decety and Michalska, 2010). In childhood, these arousal-based reactions also become the foundation for outward prosocial behaviors, such as helping, altruistic behavior, and compassionate behavior (Decety and Meyer, 2008; Decety and Svetlova, 2012; Li et al., 2013). Empathetic responses continue to increase throughout infancy, with the earliest forms appearing anywhere from 8- to 16-months and continuing to develop into the second year (Roth-Hanania et al., 2011). By 18- to 36-months, empathic arousal becomes more specific, as children show more differential emotional and personal distress in response to another's sadness than another's pain (Bandstra et al., 2011). Importantly, individual differences in the tendency to experience empathic concern versus personal distress vary as a function of dispositional differences in the ability to regulate emotions (Eisenberg et al., 1996). Moreover, older children are more likely to show empathic concern than personal distress toward another in pain (Bandstra et al., 2011; Zahn-Waxler et al., 1992; Williams et al., 2014).

While the development of empathy has been explored for decades in behavioral studies, due to methodological constraints, few functional neuroimaging experiments have been conducted with very young children. One study used functional near-infrared spectroscopy to measure hemodynamic responses while stories eliciting affective and cognitive empathy were presented to children aged 4–8 years (Brink et al., 2011). Increased signal with age was detected over the medial orbitofrontal cortex and dorsolateral prefrontal cortex in older children. A cross-sectional functional MRI (fMRI) study measured the neuro-hemodynamic activity in response to empathy-eliciting stimuli while participants, ranging from 7 to 40 years of age, viewed visual scenarios depicting people being accidentally or intentionally hurt by another individual (Decety and Michalska, 2010). Subjective ratings of the stimuli indicated a gradual decrease of pain sensitivity as participants' age increased, with younger participants rating the scenarios as significantly more painful. Interestingly, the younger the participants, the more strongly the amygdala, insula, and ventromedial prefrontal cortex were activated when viewing the stimuli. A negative correlation between age and the degree of neuro-hemodynamic response was found in posterior insula, whereas a positive correlation was detected in the anterior insula. Another fMRI study with 4–37 year-old participants

reported stronger empathic sadness in young subjects, and this was associated with enhanced neural activity in the amygdala and insula when viewing intentional harm (Decety et al., 2012a,b). An age-related increase in functional connectivity between the ventromedial prefrontal cortex and the amygdala was also found. This convergent pattern of results indicates a developmental change from a visceral emotional resonance to a more evaluative cognitive understanding of the emotional situations presented to the participants.

However, it is important to note that activation of the neural regions involved in the first-hand experience of pain such as the anterior cingulate cortex and insula (often called the pain matrix) when perceiving or even imagining another person in pain or emotional distress (Lamm et al., 2011 for a meta-analysis) is not specific to the sensory qualities of pain. Rather, this pattern of response is associated with more general survival mechanisms such as aversion and withdrawal when exposed to danger and threat, and triggers protecting and defensive behaviors (Decety, 2010a,b, 2011a). Furthermore, the neural overlap between the first-hand experience of pain and its perception supports neural reuse theories which posit as a fundamental principle of brain evolution that neural circuits continue to acquire new use after an initial or original function is established (Decety and Jackson, 2004; Anderson, 2010; Decety et al., 2012a,b; Eisenberger, 2011; Tucker et al., 2005).

To our knowledge, no study has used electroencephalographic event-related brain potentials (EEG/ERP) to examine age-related changes in response to the perception of another's distress or pain from early to middle childhood. Previous studies with adults viewing someone being injured have documented the elicitation of specific ERP components, including an early automatic component (EAC, N200) and late positive potential (LPP) (Chen et al., 2012; Cheng et al., 2012; Escobar et al., 2014; Ibanez et al., 2011; Fan et al., 2014; Perry et al., 2010). The EAC within a time window of 200–300 ms is generally found to be dependent on the contextual reality of stimuli whereas the LPP within 500–700 ms was modulated by attention to pain cues (Fan and Han, 2008; Han et al., 2008). The EAC is often interpreted to reflect information processing associated with valence, whereas the LPP seems modulated by cognitive appraisal (Li and Han, 2010). One recent study reported that adolescents relative to young adults exhibited an earlier EAC to other's pain and greater LPP to neutral stimuli, indicating the development of empathy during adolescence (Mella et al., 2012). Moreover, convergent electrophysiological evidence supports that the LPP response relates to cognitive appraisal in typically developing children (Batty and Taylor, 2006; Cordon et al., 2009; Dawson et al., 2004; Dennis and Hajcak, 2009; Dennis et al., 2009; Hajcak and Dennis, 2009; Hajcak et al., 2010; Kujawa et al., 2012a,b; Wessing et al., 2011). In one study, the early LPP was modulated by both intrinsic (i.e., the stimulus type) and extrinsic (i.e., the re-appraisal description type) manipulations of the emotional significance of the stimuli, whereas the late LPP only reflected extrinsic emotion regulation (Macnamara et al., 2009). Furthermore, the linear decline with age of LPP in response to negative stimuli (Kisley et al., 2007) suggests that the LPP increase seems

to be a valid index to examine the maturation of cognitive appraisal in childhood (Hajcak and Dennis, 2009; Hajcak et al., 2010).

In addition, μ (8–13 Hz band) suppression, considered to represent sensorimotor resonance (Fan et al., 2010; Perry and Bentin, 2010; Perry et al., 2010), could be an index of the early component of empathic arousal. In adult participants, the perception of others in painful relative to non-painful situations is associated with the increased suppression of μ oscillations (Chen et al., 2012; Cheng et al., 2012; Fan et al., 2014; Yang et al., 2009). EEG μ suppression elicited by empathy has been reported in adult participants (Gutsell and Inzlicht, 2010). However, whether μ suppression associated with empathy exhibits developmental changes during childhood remains to be determined.

To investigate the developmental trajectories of empathic response to the pain of others during from early to middle childhood, we modified an EEG/ERP paradigm commonly used with adults for children aged between 3 and 9 years old. Based on prior behavioral knowledge about the development of empathy (Decety, 2010a,b; Decety and Svetlova, 2012), it was hypothesized that self-oriented affective arousal when witnessing another individual in physical pain would be associated with a greater EAC response, as indexed by a more negative deflection in the waveform 200–300 ms post-stimulus for Pain vs. No-pain pictures, in very young children compared to older children. As children's self-regulation, self-awareness, and perspective-taking abilities become more mature, we anticipated an increase in the LPP response. Moreover, μ suppression indexing sensorimotor resonance (or attention) was expected to be stronger in children than in adults.

2. Materials and methods

2.1. Participants

Seventy-nine typically developing children, 2–9 years old, and fifteen healthy adults, 23–25 years old, participated in this study. Due to insufficient artifact-free trials (<20), data from 22 children (three 2-year-olds, five 3-year-olds, nine 4-year-olds, three 6-year-olds and two 8-year-olds) were excluded from further analyses (i.e., three fell asleep, four dropped out before behavioral data were collected, and fifteen others failed to concentrate on experimental procedures). The final sample consisted of 57 children (24 girls) and 15 adults (12 females, mean age 22.8 ± 0.8 years). The children were divided into three age groups: 18 4- to 5-year-olds (61.2 ± 6.8 months), 18 6- to 7-year-olds (85.7 ± 7.0 months), and 18 8- to 9-year-olds (108.6 ± 6.6 months). Due to small sample size, the three 3-year-olds were only included in the correlation analyses. All participants provided assent and their parents gave informed written consent for the study, which was approved by the local Ethics Committee (Yang-Ming University Hospital).

2.2. Stimulus materials

There were a total of 70 dynamic visual stimuli that have been used with adults and children in previous fMRI

(Akitsuki and Decety, 2009; Decety and Michalska, 2010; Fan et al., 2014) and EEG/ERP studies (Chen et al., 2012; Cheng et al., 2008, 2012; Fan et al., 2014). Half of the stimuli depicted an individual's limb in painful situations (Pain) and the other half depicted matched non-painful situations (No-pain). Each series of animated stimuli consisted of three consecutive pictures, edited to the same size (512×384 pixels) and presented in a successive manner to imply motion. The durations of presentation of the first, second, and third pictures were 1000 ms, 50 ms, and 1000 ms respectively.

2.3. Procedure

Before EEG recordings, the parents of each child filled out the Chinese version of Vineland Adaptive Behavior Scales (Wu et al., 2004). The VABS assesses adaptive performance for children aged 3- to 12-years-old in the domains of communication, daily living skills, socialization, and motor skills. Specifically, the socialization domain provides a broad estimate of a child's social development with good test-retest ($r=0.86$) and inter-rater reliability ($r=0.81$), including the items assessing interpersonal relationships, play and leisure time and coping skills. Each item was rated on a 3-point scale, with a higher score indicating increased adaptive performance. The raw scores of each domain can be standardized to allow for comparisons across wide age ranges. According to the standard scores, there are five adaptive levels: low (<69), moderately low (70–84), moderate (85–115), moderately high (116–130) and high (>131).

During the EEG recordings, children were seated in front of a 17-in. color monitor at a distance of approximately 75 cm. The stimuli were presented in the center of a gray background on the monitor with visual angles of 12° horizontally. After a brief description of the experiment, EEG sensors were attached. The experiment contained 8 blocks (20 trials each). The participants were allowed to take a break between the blocks for as long as they needed. Fig. 1 demonstrates the stimulus event of a single trial. Each trial started with a fixation mark at the center of the screen for a jittered duration between 500 ms and 1500 ms. After the fixation marker, the dynamic animations were presented for 2050 ms, followed by a blank screen for 200 ms. The order of the stimulus condition was randomized within each block. Participants were asked to attend to the screen whenever visual stimuli were presented. Eye tracking was simultaneously recorded with EEG in order to monitor whether participants were paying attention to the stimuli.

2.4. Apparatus and recordings

Eye tracking data were recorded with a Tobii X120 Eye Tracker. EEG signals were continuously recorded from the scalp using the NuAmps (NuAmp, Neuroscan, Inc.). F3, Fz, F4, C3, Cz, C4, P3, Pz, and P4 were selected from the 32-channel cap for signal recording. Scalp impedance for each sensor was kept below 5 k Ω . Signal was recorded at a rate of 512 Hz, with the linked bilateral mastoids as the reference. A ground electrode was placed on the forehead. Eye blinks and vertical eye movements were monitored with

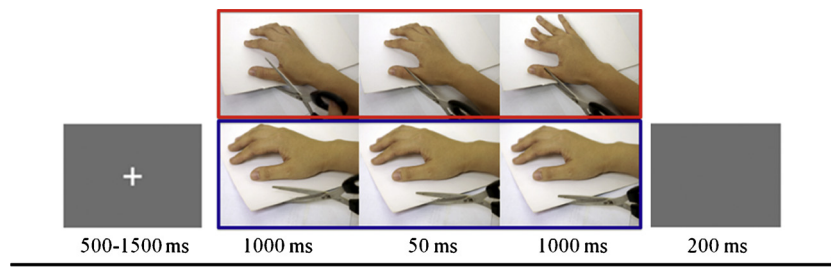


Fig. 1. Paradigm structure and examples of visual stimuli used in the study.

electrodes located approximately 1 cm above and below the left eye. Horizontal eye movement was recorded from electrodes placed approximately 1 cm lateral to the left and right external canthi. Furthermore, careful visual inspection in every trial and application of appropriate digital low-pass filters at 100 Hz ensured that muscle artifacts did not significantly contaminate even the most lateral electrodes. After visual inspection, trials that contained non-ocular artifacts were excluded from averaging. The algorithm designed to reduce ocular artifacts was then used for eye blinking correction. On average, each child had 106 valid trials (54 pain-trials; range: 44–67 trials) and each adult had 149 valid trials (74 pain-trials; range: 69–80 trials).

The paradigm was run with E-Prime (Psychology Software Tools, USA), in which every (visual) event was associated with a digital code (trigger) that was sent to the continuous EEG, allowing off-line segmentation and averaging of selected EEG periods for analysis by Neuroscan 4.4 (Compumedics Ltd., Australia). The EEG data were epoched over an analysis time of 2300 ms, including a pre-stimulus 250 ms for the baseline correction. An IIR filter of 0.1–30 Hz was applied before epoching. An automated artifact rejection system excluded any trials that contained transients exceeding $\pm 100 \mu\text{V}$ at any recording electrodes, including the electro-oculogram. Abnormal data that did not meet the transiency criterion (e.g., abnormal slopes, low activity, etc.) was excluded from further visual inspection.

2.5. Statistical analyses

The ERP components were chosen according to visual inspection of the grand-averaged data as well as prior knowledge. For the ERP time-locked to the presentation of the first picture, EAC was selected within a time window of 100 ms (200–300 ms) based on previous ERP studies using similar stimuli (Chen et al., 2012; Cheng et al., 2012). For the ERP time-locked to the third picture, according to previous child studies (Dennis and Hajcak, 2009; Hajcak et al., 2009), early and late LPP was defined within a time window of 250-ms centered at the peak latency of the difference wave (500–700 ms). The difference wave was obtained by subtracting the No-pain from the Pain condition. Statistical analysis, using four-way mixed ANOVA with two between-subject factors: (1) age group (4–5 year vs. 6–7 years vs. 8–9 years vs. adults) and (2) gender (boys vs. girls); and two within-subject factors: (1) stimulus (Pain vs. No-pain) and (2) electrode (Fz, Cz, Pz) was computed. The dependent

variable was the mean amplitudes of the EAC, early and late LPP. Degrees of freedom were corrected using the Greenhouse–Geisser method. Tukey's test was conducted only when preceded by significant effects. Finally, correlation analyses were calculated to test to what extent the difference waves (Pain vs. No-pain) of the EAC and LPP co-vary with age.

2.6. EEG μ power spectrum analysis

To assess sensorimotor resonance for pain empathy, the power of μ rhythm was computed from the adjacent frequencies (± 2 Hz) of the individualized largest power around 6–10 Hz for children and 8–12 Hz for adults and from the mean of electrodes C3, Cz, and C4 despite data being obtained from all electrodes (Berchicci et al., 2011; Yang et al., 2009). The power spectrum densities were computed with a fast Fourier transform (FFT) and then averaged epochs for the third picture. Reflection (i.e., symmetrical extension) extended the data in the pre-stimulus baseline (250 ms) to match the data set in the Pain and No-pain conditions (1000 ms). This approach eliminates the discontinuity by tacking on the end points in reverse order (Semmlow, 2004). Segments with equal data length were calculated for comparisons among conditions. Hamming window was applied to smooth the truncation for reducing the ripple effect. The ratio of the power density during each condition (Pain vs. No-pain) relative to the power density during the pre-stimulus baseline was used to control variability in absolute μ power resulting from individual differences, e.g., scalp thickness and electrode impedance, as opposed to pain empathy-related activity. The log transformation (the logarithm to the base e) was calculated for each ratio to correct for the inherent non-normality of ratio data as a result of lower bounding. Statistical analysis, using two-way mixed ANOVA with one between-subject factor: age group (4–5 years vs. 6–7 years vs. 8–9 years vs. adults) and one within-subject factor: stimulus (Pain vs. No-pain), was computed with the dependent variable as the log transformed μ power ratio in response to the stimuli. Bonferroni tests were conducted only when preceded by significant effects.

3. Results

3.1. Behavioral performance

The participants' demographics and VABS scores are listed in Table 1. Standard score of the socialization domain

Table 1

Demographics of study children participants.

Age groups	4–5 years-old (N = 18)		6–7 years-old (N = 18)		8–9 years-old (N = 18)	
Age (months)	61.2 ± 6.8		85.7 ± 7.0		108.6 ± 6.6	
Gender (M/F)	11/7		9/9		11/7	
VABS	4–5 years-old (N = 18)		6–7 years-old (N = 18)		8–9 years-old (N = 18)	
	M ± SD	Range	M ± SD	Range	M ± SD	Range
IR	27.4 ± 5.4	21–31	27.2 ± 6.0	14–33	29.0 ± 2.6	25–34
PT	26.0 ± 6.6	15–36	30.2 ± 5.6	20–36	31.7 ± 3.8	26–36
CS	14.9 ± 4.5	9–24	20.8 ± 6.8	9–35	24.8 ± 4.7	18–33
SL	66.3 ± 11.4	46–91	78.4 ± 13.4	44–104	85.4 ± 8.5	70–103

Abbreviations: VABS, Vineland Adaptive Behavior Scale; IR, interpersonal relationship; PL, play and leisure time; CS, coping skills; SL, socialization.

for all subjects were within moderate level, above the lower limit of normal ranges (70, 2 SD below the mean of the norms of their age level), indicating that all participants were typical in socialization.

3.2. Electrophysiological data

The grand-averaged waveforms of ERPs evoked by Pain vs. No-pain across age groups are illustrated in Fig. 2.

For EAC, a four-way mixed ANOVA with the stimulus (Pain vs. No-pain) and region (Fz, Cz, Pz) as within-subject variables and the age group (4–5 year-olds vs. 6–7 year-olds vs. 8–9 year-olds vs. adults) and gender (boys vs. girls) as between-subject variables showed significant main effects of the stimulus [$F(1, 61) = 8.12, p = 0.006, \eta^2 = 0.12$] and age group [$F(3, 61) = 7.34, p < 0.001, \eta^2 = 0.27$]. The interaction for age group \times electrode was significant [$F(6, 122) = 4.36, p = 0.004, \eta^2 = 0.18$], but the stimulus \times age group, stimulus \times electrode and stimulus \times age group \times electrode were not ($p > 0.1$). The Pain relative to No-pain condition elicited a more positive-going EAC response. Gender and gender-related interactions were not significant ($p > 0.1$). The follow-up analyses indicated that children displayed greater amplitudes than adults at electrode Pz ($p = 0.009$), but not at Fz and Cz ($p = 0.12; p = 0.17$).

For early LPP, the main effect of stimulus reached significance [$F(1, 61) = 17.87, p < 0.001, \eta^2 = 0.23$], but the age group did not [$F(3, 61) < 1.00, p > 0.1$]. There were significant interactions for age group \times electrode [$F(6, 122) = 4.61, p = 0.002, \eta^2 = 0.19$] and stimulus \times electrode [$F(2, 122) = 5.87, p = 0.005, \eta^2 = 0.09$], and a marginal interaction for stimulus \times age group \times electrode [$F(6, 122) = 2.02, p = 0.078, \eta^2 = 0.09$], but none for the stimulus \times age group and stimulus \times age group \times electrode ($p > 0.1$). Gender and gender-related interactions were not significant ($p > 0.1$). The follow-up analyses showed that children exhibited larger amplitudes than adults did at Fz and Cz ($p = 0.032; p = 0.018$), but not at Pz ($p = 0.25$). The Pain vs. No-pain differentiation was found at Cz and Pz ($p = 0.031; p = 0.019$), but none at Fz ($p = 0.19$). The effect size for the stimulus \times age group at Pz tended to be medium ($\eta^2 = 0.054$), whereas those at Fz and Cz were small ($0.009; 0.025$).

For late LPP, the stimulus [$F(1, 61) < 1.00, p > 0.1$] and age group [$F(3, 61) < 1.00, p > 0.1$] did not reach significance. The interaction of age group \times electrode was significant [$F(6, 122) = 2.79, p = 0.031, \eta^2 = 0.12$], but the stimulus \times electrode, age group \times stimulus, and age group \times stimulus \times electrode were not significant ($p > 0.1$). Gender and gender-related interactions were not significant ($p > 0.1$). Children differed from adults at electrode Pz ($p = 0.035$), but not at Fz and Cz ($p = 0.19; p = 0.33$).

3.3. Correlations with age

In 3- to 9-year-old children, the difference wave of EAC (Pain vs. No-pain) was negatively correlated with age [Fz: $r(57) = -0.35, p = 0.009$; Cz: $r(57) = 0.34, p = 0.012$; C3: $r(57) = -0.42, p = 0.001$; C4: $r(57) = -0.33, p = 0.013$] (Fig. 3a). When children and adult participants were included, the relationship between the EAC difference and age became linear [Cz: $r(72) = -0.29, p = 0.028$] and quadratic [$F(2, 69) = 3.72, p = 0.02$] (Supplementary Fig. s1). In 3- to 9-year-old children, the difference wave of early LPP (Pain vs. No-pain) was positively correlated with age [Pz: $r(57) = 0.29, p = 0.029$] (Fig. 3b). When children and adult participants were combined, the relationship between the early LPP difference and age became linear [$F(1, 70) = 3.69, p = 0.046$] and quadratic [$F(2, 69) = 4.01, p = 0.021$] (Supplementary Fig. s2). Neither EAC nor LPP had a quadratic relationship during childhood. Furthermore, to examine the robustness of the age effects, the number of trials dropped was modeled as a nuisance regressor and all the above correlations remained significant [EAC/C3: $r(57) = -0.39, p = 0.002$; EAC/Cz: $r(57) = -0.31, p = 0.019$; EAC/C4: $r(57) = -0.30, p = 0.023$]; early LPP/Pz: $r(57) = 0.26, p = 0.05$]. Hence, as age increased, EAC differences diminished and LPP differences increased in response to perceiving the Pain relative to the No-pain condition.

3.4. Mu suppression indicative of sensorimotor resonance or attention

The sensorimotor resonance for pain empathy in each age group (4–5 years vs. 6–7 years vs. 8–9 years vs. adults) is illustrated in Fig. 4. The age group had a main effect

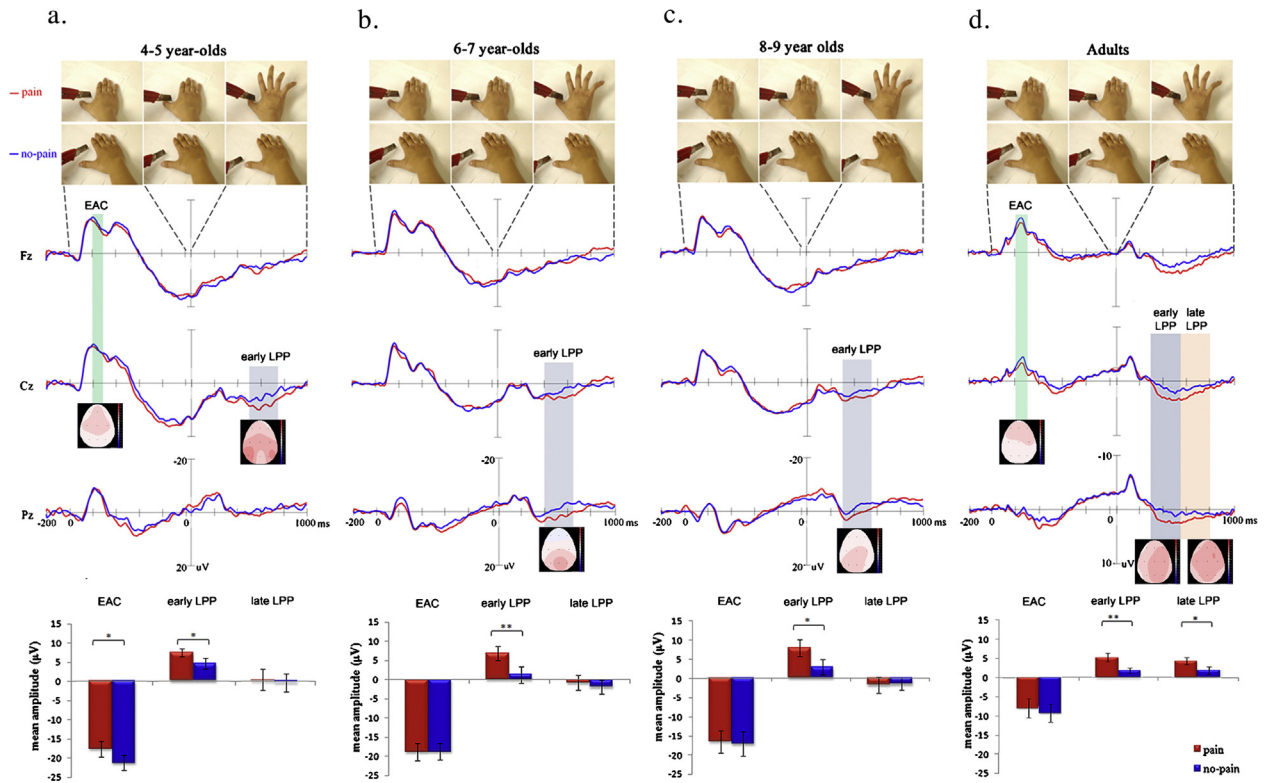


Fig. 2. Grand-averaged ERPs (EAC vs. early LPP vs. late LPP) in response to perceiving individuals in painful and non-painful situations (Pain, red vs. No-pain, blue) at electrode sites Fz, Cz, and Pz across age groups. For the sake of clarity, different scales are used for the ERP waves in children and adults (*, $p < 0.05$). The ERP components that showed significant stimulus effects are highlighted in different colors (EAC, green; early LPP, gray; late LPP, orange). The bar graphs present the averaged amplitudes across electrodes that were statistically significant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$[F(3, 65) = 8.46, p < 0.001]$, indicating that children showed stronger μ suppression than adults did [familywise error rate (FWER) < 0.05]. In spite of no significant interaction $[F(3, 65) = 1.47, p > 0.05]$, the age group \times stimulus had a medium to large effect size ($\eta^2 = 0.64$). When three age groups of children participants were combined for direct comparison between children and adults, the age

$[F(1, 31) = 47.81, p < 0.001]$ and the stimulus $[F(1, 31) = 8.70, p = 0.006]$ had main effects in addition to the interaction of age \times stimulus $[F(1, 31) = 7.67, p = 0.009]$ (Supplementary Fig. s3). The post hoc test, using *Bonferroni* correction, revealed that the stimulus effect (Pain vs. No-pain) mainly came from the adult group (FWER < 0.05), not from the child group ($p > 0.1$).

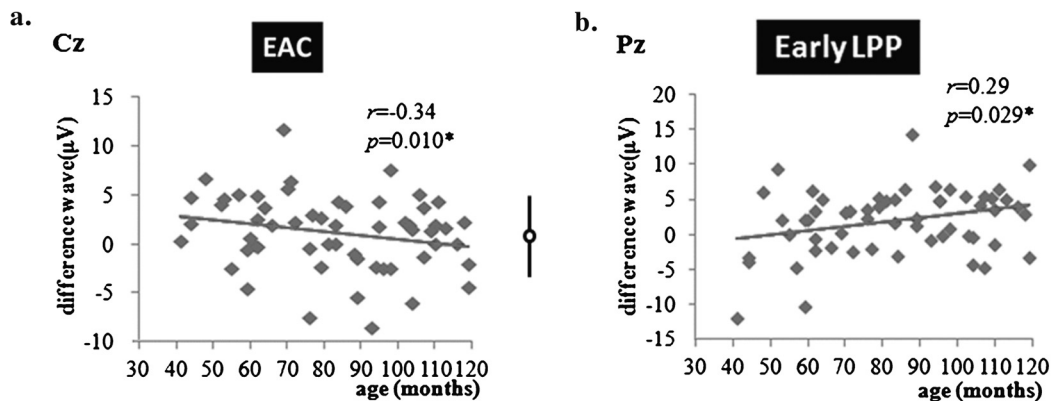


Fig. 3. Correlations between the ERP difference wave (Pain vs. No-pain) and age. (a) Early automatic component (EAC). (b) Early late positive potential (LPP). Open dots on the right side of the plot represent the data from adults' mean amplitudes of ERP difference wave, and lines above and below the dots correspond to 95% confidence intervals.

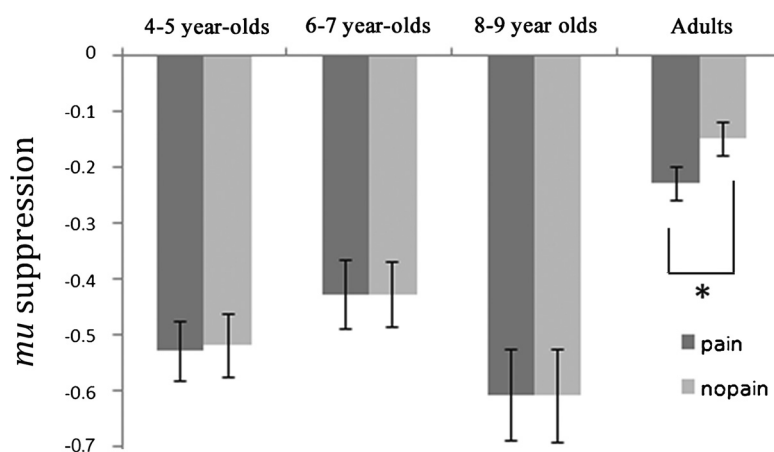


Fig. 4. Mu suppression in each age group.

4. Discussion

While a large body of developmental work has explored how infants and children respond to the distress of another person (Bandstra et al., 2011; Knafo et al., 2008; Roth-Hanania et al., 2011; Zahn-Waxler and Radke-Yarrow, 1990), relatively few studies have examined the neural underpinnings of these reactions as children develop, and none has included very young children as early as 3 years of age. Such studies are important to advance our understanding not only of typical development but also neurodevelopmental disorders associated with socioemotional deficits.

Using EEG/ERP, this study documents neurophysiological markers of the development of empathy in typically developing children between the ages of 3–9 years. Results indicate that, as children age, the difference in the EAC amplitudes between Pain and No-pain, as an index of affective arousal or affective sharing, decreased. In an opposite pattern, the difference wave of LPP, reflecting cognitive appraisal, increased with age. Interestingly, as compared to previous EEG/ERP studies with adults (Chen et al., 2012; Cheng et al., 2012), the stimuli induced stronger *mu* suppression in children with no differentiation between painful and non-painful stimuli. These findings provide neurophysiological evidence, as indicated by a decrease of affective arousal but an increase of cognitive appraisal, for the developmental course of empathy in childhood. They also support a shift from affective arousal to more empathic understanding, which has been theorized on the basis of behavioral observations (Eisenberg et al., 1996; Zahn-Waxler and Radke-Yarrow, 1990). Based on an ontogenetic framework, empathy begins with a primitive affective resonance mechanism and gradually matures into other-oriented responses (Decety and Michalska, 2010; Eisenberg and Eggum, 2009). Children who display more mature mental abilities and executive control tend to be relatively more empathetic, and are more likely to engage in prosocial behaviors (Bischof-Köhler, 1991; Li et al., 2013; Nichols et al., 2009). Infants in their first year begin to show signs of concern

for others when they are in distress and are already responding in socially appropriate ways when viewing others in distress or pain (Zahn-Waxler et al., 1992). This basic emotional motivation requires not only an affective reaction elicited by someone else's emotional state, but also a basic attribution of mental states. These early signs of empathy require only minimal mindreading and perspective taking capacities. Rather, they merely necessitate the capacity for emotional contagion and the capacity to attribute distress to another (Davidov et al., 2013). Not only do very young children make pain attributions, but also studies on comforting behavior demonstrate that they also respond to a variety of distress cues, and they direct their comforting behavior in ways that are appropriate to the target's distress. For example, in experimental studies of one-year olds, crying also elicited comforting behaviors, as did coughing and gagging (Roth-Hanania et al., 2011). Furthermore, in these studies, the children often comfort the target in appropriate ways and actually make pain attribution in conjunction with their comforting behavior and recognize what the target is distressed about.

Consistent with previous findings from adults (Chen et al., 2012), the stimulus effect was seen for the EAC in children, as indicated by more positive deflections in response to the Pain than No-pain at a time window of 200–300 ms. Specifically, this component had the peak latency around 200–300 ms in 4–5 year-olds, which was obscured in 6–7 and 8–9 year-olds. The age-related decrease of the EAC difference wave reflects that aversive responses at the sight of an imminent harm to others declines with age. Behavioral studies point out an age-related decline of emotional distress in response to others' distress in childhood (Bandstra et al., 2011; Eisenberg et al., 1996; Knafo et al., 2008). An fMRI study in participants aged 7–40 years old reported compatible results: an age-related decrease was noted in the subjective evaluations of pain intensity and the neuro-hemodynamic response in the amygdala and posterior insula when perceiving others being hurt (Decety and Michalska, 2010).

Only early LPP was detected in children, whereas both late and early LPP were observed in adults. Early LPP

was evident at Cz in 4–5 year-olds but at Cz and Pz in older children. Being the gateway to conscious recognition (Luck et al., 2000; Schupp et al., 2006), LPP reflects stimulus representation in working memory (Schupp et al., 2006) and facilitates attention to emotional stimuli for later processing (Cuthbert et al., 2000; Schupp et al., 2000). Being sensitive to the manipulation of cognitive appraisals (Foti and Hajcak, 2008; Hajcak and Nieuwenhuis, 2006), LPP may index emotional regulation and reappraisal. The appraisal modulation of LPP was associated with parent-report measures of emotion regulation in children (Dennis and Hajcak, 2009). Stronger LPP amplitudes elicited by the perception of others' pain have been associated with higher scores in the perspective taking subscale of interpersonal reactivity index (Chen et al., 2012). Age-related changes in LPP during adolescence have been proposed to reflect the cognitive aspects of empathy (Mella et al., 2012). Furthermore, in line with previous studies that showed that LPP to affective picture processing might end earlier during childhood (Hajcak and Dennis, 2009; Kujawa et al., 2013), we found an absence of a late LPP to others' pain among young children. While one NIRS study demonstrated that older compared to younger children displayed stronger activation in prefrontal cortex in response to empathy-eliciting stories (Brink et al., 2011), the present results extend to show an age-related increase of LPP for pain empathy from early to middle childhood.

The present study did not find any gender difference in both the EAC and LPP response to pain empathy. Although several studies of young children have found gender differences (e.g., Knafo et al., 2008; Volbrecht et al., 2007; Zahn-Waxler, 1992), other studies have not (e.g., Volbrecht et al., 2007). One cross-sectional developmental fMRI study with 4–17 year-old participants did not find gender-related differential activation in the regions associated with affective sharing (anterior insula and anterior cingulate cortex) and no interaction between gender and age, but female participants scored higher than males on self-reported dispositional empathy, a difference that increased with age (Michalska et al., 2013). The results of that latter study suggest a dissociation between explicit ratings and neurophysiological measures of empathic arousal.

Unlike adults, children aged 3–9 years old showed *mu* suppression sensitive to action observation, but not specific to the empathy condition. The age-related decrease of *mu* suppression, as evidenced by the smaller scale in adults (see Fig. 4), is in line with one developmental study (Oberman et al., 2013). The sensorimotor recruitment, as indicated by *mu* suppression, involved during the observation and execution of hand actions, emerges early in human infancy (Nystrom, 2008). Previous studies with adults and adolescents demonstrated that the perception of others in Pain versus No-pain induces stronger *mu* suppression (Chen et al., 2012; Cheng et al., 2008, 2012; Yang et al., 2009). Here, children showed no differential *mu* suppression for Pain vs. No-pain, suggesting that the neural mechanisms underpinning sensorimotor resonance of pain empathy may be immature in childhood. Alternatively, this finding may be attributed to a heightened attentional response to potential danger with regard to some of the No-pain

stimuli picturing a knife or a scissor close to a hand (see Fig. 1). It is worthy of note that this result supports the view that affective sharing is not mediated by sensorimotor resonance (Blair, 2011; Cheng et al., 2012; Decety, 2011a,b, 2013; Decety et al., 2013).

There are several limitations that need to be acknowledged. First, many of the participants aged 2–3 years old were excluded from data analysis because of insufficient artifact-free trials for the ERP analysis. Three 3-year-olds included in the correlation analysis do not provide sufficient power and may not be representative of this age. Second, the averaged number of trials for grand-averaged ERP increased with age because older children were generally more cooperative than younger children. This might confound the age-related ERP results. Third, the EAC, whose source localization is located at prefrontal cortex, reflects negative arousal concordant with anticipatory processes about imminent harm delivered to others (Chen et al., 2012). It is worth mentioning that the prefrontal cortex is not functionally mature until early adulthood (Sowell et al., 1999; Steinberg, 2005). The age-related decrease of EAC differences to others' pain during childhood might negate the anticipatory effect of aversive responses. In addition, physiological development during childhood and adolescence could partially contribute to the age-related ERP changes. In this study, these electrophysiological results could be the first step. More neurodevelopmental works from early childhood to adulthood is warranted to clarify the complex interrelationships between anticipatory and emotional processes underlying the neuro-cognitive components of empathy, particularly measuring trial-by-trial valence and arousal.

In conclusion, our study provides the first neurophysiological evidence for important developmental changes in empathic processing in children aged 3–9 years old. The difference wave of EAC, detected in young children when they viewed others in physical pain decreased with age. The difference wave of early LPP increased with age. These age-related changes may reflect a decrease in affective sharing/arousal and an increase in cognitive appraisal as empathy develops.

Conflict of interest

None declared.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.dcn.2014.08.012>.

References

- Akitsuki, Y., Decety, J., 2009. Social context and perceived agency affects empathy for pain: an event-related fMRI investigation. *Neuroimage* 47, 722–734.
- Anderson, M.L., 2010. Neural reuse: a fundamental organizational principle of the brain. *Behav. Brain Sci.* 33, 245–266.
- Bandstra, N.F., Chambers, C.T., McGrath, P.J., Moore, C., 2011. The behavioural expression of empathy to others' pain versus others' sadness in young children. *Pain* 152, 1074–1082.
- Batty, M., Taylor, M.J., 2006. The development of emotional face processing during childhood. *Dev. Sci.* 9, 207–220.
- Ben-Ami Bartal, I., Decety, J., Mason, P., 2011. Empathy and pro-social behavior in rats. *Science* 334, 1427–1430.
- Berchicci, M., Zhang, T., Romero, L., Peters, A., Annett, R., Teuscher, U., Bertollo, M., Okada, Y., Stephen, J., Comani, S., 2011. Development of mu rhythm in infants and preschool children. *Dev. Neurosci.* 33, 130–143.
- Bischof-Köhler, D., 1991. The development of empathy in infants. In: Lamb, M.E., Keller, H. (Eds.), *Infant Development: Perspectives from German-Speaking Countries*. Lawrence Erlbaum Associates, Hillsdale, NJ, pp. 245–273.
- Blair, R.J.R., 2011. Should affective arousal be grounded in perception-action coupling? *Emot. Rev.* 3, 109–110.
- Brink, T.T., Urton, K., Held, D., Kirilina, E., Hofmann, M.J., Klann-Delius, G., Jacobs, A.M., Kuchinke, L., 2011. The role of orbitofrontal cortex in processing empathy stories in 4- to 8-year-old children. *Front. Psychol.* 2, 80.
- Chen, C., Yang, C.Y., Cheng, Y., 2012. Sensorimotor resonance is an outcome but not a platform to anticipating harm to others. *Soc. Neurosci.* 7, 578–590.
- Cheng, Y., Hung, A.Y., Decety, J., 2012. Dissociation between affective sharing and emotion understanding in juvenile psychopaths. *Dev. Psychopathol.* 24, 623–626.
- Cheng, Y., Yang, C.Y., Lin, C.P., Lee, P.L., Decety, J., 2008. The perception of pain in others suppresses somatosensory oscillations: a magnetoencephalography study. *Neuroimage* 40, 1833–1840.
- Church, R.M., 1959. Emotional reactions of rats to the pain of others. *J. Comp. Physiol. Psychol.* 52, 132–134.
- Cordon, I.M., Georgieff, M.K., Nelson, C.A., 2009. Neural correlates of emotion processing in typically developing children and children of diabetic mothers. *Dev. Neuropsychol.* 34, 683–700.
- Cuthbert, B.N., Schupp, H.T., Bradley, M.M., Birbaumer, N., Lang, P.J., 2000. Brain potentials in affective picture processing: covariation with autonomic arousal and affective report. *Biol. Psychol.* 52, 95–111.
- Davidov, M., Zahn-Waxler, C., Roth-Hanania, R., Knafo, A., 2013. Concern for others in the first year of life: theory, evidence, and avenues for research. *Child Dev. Perspect.* 7, 126–131.
- Dawson, G., Webb, S.J., Carver, L., Panagiotides, H., McPartland, J., 2004. Young children with autism show atypical brain responses to fearful versus neutral facial expressions of emotion. *Dev. Sci.* 7, 340–359.
- Decety, J., 2010a. The neurodevelopment of empathy in humans. *Dev. Neurosci.* 32, 257–267.
- Decety, J., 2010b. To what extent is the experience of empathy mediated by shared neural circuits? *Emot. Rev.* 2, 204–207.
- Decety, J., 2011a. Dissecting the neural mechanisms mediating empathy. *Emot. Rev.* 3, 92–108.
- Decety, J., 2011b. Promises and challenges of the neurobiological approach to empathy. *Emot. Rev.* 3, 115–116.
- Decety, J., 2013. The neuroevolution of empathy and caring for others: why it matters for morality. In: Decety, J., Christen, Y. (Eds.), *New Frontiers in Social Neuroscience*. Springer Verlag, Berlin, p. 127–151.
- Decety, J., Cowell, J.M., 2014. The complex relation between morality and empathy. *Trends Cogn. Sci.* 18, 337–339.
- Decety, J., Jackson, P.L., 2004. The functional architecture of human empathy. *Behav. Cogn. Neurosci. Rev.* 3, 71–100.
- Decety, J., Meyer, M., 2008. From emotion resonance to empathic understanding: a social developmental neuroscience account. *Dev. Psychopathol.* 20, 1053–1080.
- Decety, J., Michalska, K.J., 2010. Neurodevelopmental changes in the circuits underlying empathy and sympathy from childhood to adulthood. *Dev. Sci.* 13, 886–899.
- Decety, J., Michalska, K.J., Kinzler, K.D., 2012a. The contribution of emotion and cognition to moral sensitivity: a neurodevelopmental study. *Cereb. Cortex* 22, 209–220.
- Decety, J., Norman, G.J., Berntson, G.G., Cacioppo, J.T., 2012b. A neuro-behavioral evolutionary perspective on the mechanisms underlying empathy. *Prog. Neurobiol.* 98, 38–48.
- Decety, J., Skelly, L.R., Kiehl, K.A., 2013. Brain response to empathy-eliciting scenarios in incarcerated individuals with psychopathy. *JAMA Psychiatry* 70, 638–645.
- Decety, J., Svetlova, M., 2012. Putting together phylogenetic and ontogenetic perspectives on empathy. *Dev. Cogn. Neurosci.* 2, 1–24.
- Dennis, T.A., Hajcak, G., 2009. The late positive potential: a neurophysiological marker for emotion regulation in children. *J. Child Psychol. Psychiatry* 50, 1373–1383.
- Dennis, T.A., Malone, M.M., Chen, C.C., 2009. Emotional face processing and emotion regulation in children: an ERP study. *Dev. Neuropsychol.* 34, 85–102.
- Dondi, M., Simion, F., Caltran, G., 1999. Can newborns discriminate between their own cry and the cry of another newborn infant? *Dev. Psychol.* 35, 418–426.
- Eisenberger, N.I., 2011. Why rejection hurts: What social neuroscience has revealed about the brain's response to social rejection. In: Decety, J., Cacioppo, J.T. (Eds.), *The Oxford Handbook of Social Neuroscience*. Oxford University Press, New York, NY, pp. 586–598.
- Eisenberg, N., Eggum, N.D., 2009. Empathic responding: sympathy and personal distress. In: Decety, J., Ickes, W. (Eds.), *The Social Neuroscience of Empathy*. MIT Press, Cambridge, pp. 71–83.
- Eisenberg, N., Fabes, R.A., Murphy, B., Karbon, M., Smith, M., Maszk, P., 1996. The relations of children's dispositional empathy-related responding to their emotionality, regulation, and social functioning. *Dev. Psychol.* 32, 195–209.
- Escobar, M.J., Huepe, D., Decety, J., Sedeno, L., Messow, M.K., Baez, S., Rivera-Rei, A., Canales-Johnson, A., Morales, J.P., Gomez, D., Schröder, J., Manes, F., López, V., Ibañez, A., 2014. Brain signatures of moral sensitivity in adolescents with early social deprivation. *Sci. Rep.* 4, 5354.
- Fan, Y., Han, S., 2008. Temporal dynamic of neural mechanisms involved in empathy for pain: an event-related brain potential study. *Neuropsychologia* 46, 160–173.
- Fan, Y.T., Chen, C., Chen, S.C., Decety, J., Cheng, Y., 2014. Empathic arousal and social understanding in individuals with autism: evidence from fMRI and ERP measurements. *Soc. Cogn. Affect. Neurosci.* 9, 1203–1213.
- Fan, Y.T., Decety, J., Yang, C.Y., Liu, J.L., Cheng, Y., 2010. Unbroken mirror neurons in autism spectrum disorders. *J. Child Psychol. Psychiatry* 51, 981–988.
- Foti, D., Hajcak, G., 2008. Deconstructing reappraisal: descriptions preceding arousing pictures modulate the subsequent neural response. *J. Cogn. Neurosci.* 20, 977–988.
- Geangu, E., Benga, O., Stahl, D., Striano, T., 2010. Contagious crying beyond the first days of life. *Infant Behav. Dev.* 33, 279–288.
- Geangu, E., Benga, O., Stahl, D., Striano, T., 2011. Individual differences in infants' emotional resonance to a peer in distress: self-other awareness and emotion regulation. *Soc. Dev.* 20, 450–470.
- Gutsell, J.N., Inzlicht, M., 2010. Empathy constrained: prejudice predicts reduced mental simulation of actions during observation of outgroups. *J. Exp. Soc. Psychol.* 46, 841–845.
- Hajcak, G., Dennis, T.A., 2009. Brain potentials during affective picture processing in children. *Biol. Psychol.* 80, 333–338.
- Hajcak, G., Dunning, J.P., Foti, D., 2009. Motivated and controlled attention to emotion: time-course of the late positive potential. *Clin. Neurophysiol.* 120, 505–510.
- Hajcak, G., MacNamara, A., Olvet, D.M., 2010. Event-related potentials, emotion, and emotion regulation: an integrative review. *Dev. Neuropsychol.* 35, 129–155.
- Hajcak, G., Nieuwenhuis, S., 2006. Reappraisal modulates the electrocortical response to unpleasant pictures. *Cogn. Affect. Behav. Neurosci.* 6, 291–297.
- Han, S., Fan, Y., Mao, L., 2008. Gender difference in empathy for pain: an electrophysiological investigation. *Brain Res.* 1196, 85–93.
- Ibanez, A., Hurtado, E., Lobos, A., Escobar, J., Trujillo, N., Decety, J., 2011. Subliminal presentation of other faces (but not own face) primes behavioral and evoked cortical processing of empathy for pain. *Brain Res.* 1398, 72–85.
- Kisley, M.A., Wood, S., Burrows, C.L., 2007. Looking at the sunny side of life: age-related change in an event-related potential measure of the negativity bias. *Psychol. Sci.* 18, 838–843.
- Knafo, A., Zahn-Waxler, C., Van Hulle, C., Robinson, J.L., Rhee, S.H., 2008. The developmental origins of a disposition toward

- empathy: genetic and environmental contributions. *Emotion* 8, 737–752.
- Kujawa, A., Hajcak, G., Torpey, D., Kim, J., Klein, D.N., 2012a. Electro-cortical reactivity to emotional faces in young children and associations with maternal and paternal depression. *J. Child Psychol. Psychiatry* 53, 207–215.
- Kujawa, A., Klein, D.N., Hajcak, G., 2012b. Electro-cortical reactivity to emotional images and faces in middle childhood to early adolescence. *Dev. Cogn. Neurosci.* 2, 458–467.
- Kujawa, A., Weinberg, A., Hajcak, G., Klein, D.N., 2013. Differentiating event-related potential components sensitive to emotion in middle childhood: evidence from temporal–spatial PCA. *Dev. Psychobiol.* 55, 539–550.
- Lamm, C., Decety, J., Singer, T., 2011. Meta-analytic evidence for common and distinct neural networks associated with directly experienced pain and empathy for pain. *Neuroimage* 54, 2492–2502.
- Langford, D.J., Tuttle, A.H., Brown, K., Deschenes, S., Fischer, D.B., Mutso, A., Root, K.C., Sotocinal, S.G., Stern, M.A., Mogil, J.S., Sternberg, W.F., 2010. Social approach to pain in laboratory mice. *Soc. Neurosci.* 5, 163–170.
- Li, Y., Li, H., Decety, J., Lee, K., 2013. Experiencing a natural disaster alters children's altruistic giving. *Psychol. Sci.* 24, 1686–1695.
- Li, W., Han, S., 2010. Perspective taking modulates event-related potentials to perceived pain. *Neurosci. Lett.* 469, 328–332.
- Luck, S.J., Woodman, G.F., Vogel, E.K., 2000. Event-related potential studies of attention. *Trends Cogn. Sci.* 4, 432–440.
- Macnamara, A., Foti, D., Hajcak, G., 2009. Tell me about it: neural activity elicited by emotional pictures and preceding descriptions. *Emotion* 9, 531–543.
- Martin, G.B., Clark, R.D., 1982. Distress crying in neonates: species and peer specificity. *Dev. Psychol.* 18, 3–9.
- Mella, N., Studer, J., Gilet, A.L., Labouvie-Vief, G., 2012. Empathy for pain from adolescence through adulthood: an event-related brain potential study. *Front. Psychol.* 3, 501.
- Michalska, K.J., Kinzler, K.D., Decety, J., 2013. Age-related sex differences in dispositional empathy do not predict brain responses. *Dev. Cogn. Neurosci.* 3, 22–32.
- Nichols, S.R., Svetlova, M., Brownell, C.A., 2009. The role of social understanding and empathic disposition in young children's responsiveness to distress in parents and peers. *Cogn. Brain Behav.* 13, 449–478.
- Nystrom, P., 2008. The infant mirror neuron system studied with high density EEG. *Soc. Neurosci.* 3, 334–347.
- Oberman, L.M., McCleery, J.P., Hubbard, E.M., Bernier, R., Wiersema, J.R., Raymaekers, R., Pineda, J.A., 2013. Developmental changes in mu suppression to observed and executed actions in autism spectrum disorders. *Soc. Cogn. Affect. Neurosci.* 8, 300–304.
- Perry, A., Bentin, S., 2010. Does focusing on hand-grasping intentions modulate electroencephalogram mu and alpha suppressions? *Neuroreport* 21, 1050–1054.
- Perry, A., Bentin, S., Bartal, I.B., Lamm, C., Decety, J., 2010. "Feeling" the pain of those who are different from us: modulation of EEG in the mu/alpha range. *Cogn. Affect. Behav. Neurosci.* 10, 493–504.
- Roth-Hanania, R., Davidov, M., Zahn-Waxler, C., 2011. Empathy development from 8 to 16 months: early signs of concern of others. *Infant Behav. Dev.* 34, 447–458.
- Schupp, H.T., Cuthbert, B.N., Bradley, M.M., Cacioppo, J.T., Ito, T., Lang, P.J., 2000. Affective picture processing: the late positive potential is modulated by motivational relevance. *Psychophysiology* 37, 257–261.
- Schupp, H.T., Flaisch, T., Stockburger, J., Junghofer, M., 2006. Emotion and attention: event-related brain potential studies. *Prog. Brain Res.* 156, 31–51.
- Semmlow, J.L., 2004. *Biosignal and Biomedical Image Processing: Matlab-Based Applications*. CRC Press, Boca Raton, FL.
- Sowell, E.R., Thompson, P.M., Holmes, C.J., Jernigan, T.L., Toga, A.W., 1999. In vivo evidence for post-adolescent brain maturation in frontal and striatal regions. *Nat. Neurosci.* 2, 859–861.
- Steinberg, L., 2005. Cognitive and affective development in adolescence. *Trends Cogn. Sci.* 9, 69–74.
- Tucker, D.M., Luu, P., Derryberry, D., 2005. Love hurts: the evolution of empathic concern through the encephalization of nociceptive capacity. *Dev. Psychopathol.* 17, 699–713.
- Volbrecht, M.M., Lemery-Chalfant, K., Aksan, N., Zahn-Waxler, C., Goldsmith, H.H., 2007. Examining the familial link between positive affect and empathy development in the second year. *J. Genet. Psychol.* 168, 105–129.
- Wessing, I., Furniss, T., Zwitserlood, P., Dobel, C., Junghofer, M., 2011. Early emotion discrimination in 8- to 10-year-old children: magnetoencephalographic correlates. *Biol. Psychol.* 88, 161–169.
- Williams, A., O'Driscoll, K., Moore, C., 2014. The influence of empathic concern on prosocial behavior in children. *Front. Psychol.* 5, 425.
- Wu, W.-T., Cheng, C.-F., Lu, H.-H., Chiu, S.-C., 2004. *Vineland Adaptive Behavior Scale – Chinese Version*. Psychological Publishing, Taipei.
- Yang, C.Y., Decety, J., Lee, S., Chen, C., Cheng, Y., 2009. Gender differences in the mu rhythm during empathy for pain: an electroencephalographic study. *Brain Res.* 1251, 176–184.
- Zahn-Waxler, C., 1992. Development of concern for others. *Dev. Psychol.* 28, 126–136.
- Zahn-Waxler, C., Radke-Yarrow, M., 1990. Origins of empathic concern. *Motiv. Emot.* 14, 107–130.
- Zahn-Waxler, C., Robinson, J.L., Emde, R.N., 1992. The development of empathy in twins. *Dev. Psychol.* 28, 1038–1047.