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Infant communicative signals elicit differential brain dynamics in fathers and non-fathers

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Abstract

Responses to infant signals are critical to infant development and well-being. However, brain mechanisms underlying paternal responses to infant crying are still largely unknown. Here using EEG, we investigated brain activations in two different groups, 10 fathers and 10 non-fathers, in response to infant-related sounds: typically developing infants' cry(TD), ASD infants' cry(ASD), infants' laughter(LAU), and white noise(WN). Event Related Potentials in the first second after stimuli onset were analyzed. Analysis revealed a significant interaction between group and stimulus type in the left dorsolateral frontal cluster of electrodes, a brain area involved in motor programming and communicative signals' processing. A main effect of group in response to all auditory stimuli, irrespective of stimulus duration, emerged in the right temporal and parietal clusters. The different levels of familiarity and distinct processing strategies found in response to infant vocalizations shed light on the physiological mechanisms underlying adaptive paternal responses to infants' behaviors.

Keywords: Fathers, brain responses, ERP, infant vocalizations, ASD cry

1. Introduction

Infant cry is the most relevant early communicative signal parents can rely on to understand and promptly respond to babies' needs. Prompt and adequate parental responses to babies' needs enhance the possibility for the infant to develop adaptively in several domains: social, emotional and cognitive (Bowlby, 1969; Waters et al., 2000). By contrast, slow or inadequate parental behaviors may diminish the adaptability of infant development, increasing the anxiety and decreasing emotional regulation abilities. Because parental behaviors are experienced in an early stage of life, their effects on infants' behaviors and physiology are strong and shape development in a long-term way, even into adulthood (Dalsant et al., 2015; Esposito et al., 2017; Rilling et Young, 2014; Truzzi et al., 2017; Truzzi et al., 2018). Infant cry seems to be a stimulus with a special valence because it elicits specific responses in both the central and peripheral nervous systems (Bornstein et al., 2017). An fMRI study showed that infant hunger cry decreases activity in the Default Mode Network (DMN) in adult women indicating that this kind of cry triggers and engages attention automatically (De Pisapia et al., 2013). Infant cry-specific responses have also been shown in the peripheral nervous system. Messina and colleagues (2016) measured EMG showing that the presentation of infant cry elicited muscle pre-activation in the lower right arm of nulliparous women. In both the fMRI and the EMG studies the same specific responses were not found in adult non-parent males. However, comparing different peripheral physiological responses between fathers and non-fathers, namely heart rate, galvanic skin responses, and right hand skin temperature, Esposito and colleagues (2015) showed that infant cries of both typically developing infants and infants late diagnosed with ASD elicited a slower heart rate and a higher right hand skin temperature in fathers compared to non-fathers. ASD infant cry triggered higher galvanic responses than typical cry in both fathers and non-fathers. The specificity of infant cry is given by a defined set of acoustic characteristics such as

fundamental frequency, length or pitch (Esposito & Venuti, 2009). If one of these acoustic characteristics is altered, the stimulus loses its special valence and does not trigger infant cry-related responses. In the previously described EMG study, for example, when the fundamental frequency of cries was artificially modified, the muscular pre-activation was not triggered (Messina et al. 2015). This, is also the case for ASD infant cry which has different acoustic characteristics from typical cry, such as longer cry bouts and a higher fundamental frequency (Esposito & Venuti, 2010; Sheinkopf et al, 2012). These acoustical differences elicit different brain activations in adults compared to responses to typical infant cry. Venuti and colleagues (2012) showed that cry of infants with ASD elicits different cerebral responses compared to typically developing infant cry by activating brain areas related to language processing, the Superior Temporal Gyrus, emotional processing, and motor behaviors, the supplementary motor cortex, and the precentral gyrus. Also, ASD cry is rated as more distressed and aversive compared to typical infant cry, and tree-based models show that the best predictor for adults' judgement of infant cry distress is its fundamental frequency, the higher the fundamental frequency the higher the perceived distress (Esposito et al., 2012; Esposito et al., 2013). Because a fast and univocal decoding is necessary for a prompt and adequate response, altered or atypical signal processing is likely to hinder parental responses to babies' needs, and this, in turn, will affect infant development. In the case of ASD, impairing effects of the lack of attunement between infants' needs and parental responses stand out. Also, as fathers nowadays are more involved in infants' care and nurture, their contribution in responding to infants' needs plays an increasingly important role in both typical and atypical infant development. Although results about males seems not to highlight infant cry-specific responses in males' brain, they were present in the peripheral nervous system activations of fathers in when listening to typical infant cry. To improve our understanding of how fathers respond to and process infant communicative signals, fathers'

central nervous system activations in response to infant cry need to be studied. Here we aimed to investigate early temporal dynamics of fathers' and non-fathers' brain activation in response to infant communicative signals, specifically ASD infant cry, typically developing infant cry, and infant laughter. We hypothesized different brain activations in the two groups, fathers and non-fathers, related to signal interpretation, attention and action in response to ASD compared to typical infant cry. Specifically, we expected (i) to find differential brain activations in response to distinct infant vocalizations in language processing related areas and in motor areas, consistently with previous findings (Venuti et al., 2012), and (ii) to find that these activations differ between fathers and non-fathers because of their different exposure and experience with infants' vocalizations.

2. Materials and Method

2.1 Participants

A total of 22 adult males recruited from a database of people who had previously given consent to be enrolled in psychological human studies participated in the research. Exclusion criteria were neurological or psychiatric disorders, including substance abuse/dependence and psychotropic medication. In research involving autonomic measures, care is taken to control participants' use of prescription medications/illicit drugs and alcohol consumption. Participants were not drinkers, nor had they consumed alcohol or taken medication in the 24 hours preceding the study. Participants signed informed consents and no incentives were given to the participants. All participants' education levels were matched between father and non-father groups. Participants were all highly educated (all had at least a University degree), and their socioeconomic status, measured with the Four-Factor Index of Social Status (Hollingshead, 1975) did not differ for the two groups (medium-high level). Of the 22 participants recruited, data were analyzed for 20; this enabled us to detect large effects (effect

size $>.8$) employing t -test family statistics on independent groups with a p -value set at 0.003 to account for the number of comparisons. One participant (a non-father) was excluded because he was being treated for a psychiatric condition, and data from another participant (a father) were excluded because of technical problems during the experiment. Fathers of typically developing (TD) children under 3 years of age ($n = 10$), mean age of 33 years ($SD = 3.2$) did not statistically differ from non-fathers ($n = 10$), mean age of 32 ($SD = 4.5$), $t(19) = .95$, ns . Finally, for the father group, the amount of time spent with their children was assessed. All the fathers were living with their spouse and children full-time and spent the majority of their free time with their children (between 3 and 5 years old). All fathers declared that they were involved daily in some caregiving activities (i.e., milk bottle preparation, changing diapers, and bedtime routines).

2.2. Stimuli

Target stimuli were distress vocalizations (infant cries). Typically developing infants' cries [TD] were compared with two other infant vocalizations and a control sound: atypically developing infants' cries (cries of children with ASD [ASD]), positive vocalizations (infant laughter [LAU]), and white noise [WN]. Infant vocalizations were extracted from home videos (details for the specific groups are provided below). A research assistant, who was unaware of the purposes of the study and blind to children's typical versus atypical group membership, reviewed video records of the children for appropriate stimuli. An exclusion criterion was that the audio recording of infant vocalization contained background noise that would interfere with acoustic analysis (e.g., adult talk, sounds from toys, or other environmental noise). To optimize and equate for sound quality and volume, and ensure that the stimuli were representative of the typical range of infant vocalizations, the first 5 sec of

infant vocalizations were used as experimental stimuli. A total of 8 stimuli per class were selected (TD, ASD, LAU and WN).

Typical cry stimuli [TD]—Infant distress vocalizations (cries) were extracted from home videos of unedited cry bouts of 10 TD (5 girls/5 boys) firstborn 13-month-olds. TD children were part of a longitudinal research project and did not present any cognitive concerns as confirmed by their Wechsler Preschool and Primary Scale of Intelligence-II (WPPSI-II; the reliability coefficients for the WPPSI-II U.S. composite scales range from .89 to .95; Wechsler, 1989) scores at age 4 years.

Atypical crying stimuli [ASD]—Infant distress vocalizations (cries) were extracted from home videos of unedited cry bouts of 10 (5 girls/5 boys) firstborn 13-month-olds later diagnosed with Autism Spectrum Disorder (ASD). The home videos belonged to a database collected during a longitudinal study of early markers of autism. Children with ASD received a clinical diagnosis between 36 and 40 months of age (1) from a child psychiatrist according to DSM-IV-TR criteria (American Psychiatric Association, 2000), and (2) they met the Clinical diagnosis of ASD for the DSM-5 (American Psychiatric Association, 2013), confirmed by (2a) the Autism Diagnostic Interview- Revised (ADI-R; a semi-structured, investigator-based interview for caregivers of individuals who may be ASD; ADI-R psychometric characteristics were excellent: both specificity and sensitivity are higher than 90%; Lord et al., 2000) and (2b) the Autism Diagnostic Observation Schedule-Generic (ADOS-G; a semi-structured assessment of social interaction, communication, play, and imaginative use of materials for individuals who may have ASD (ADOS specificity = 97% and sensitivity = 96.7%; Lord et al., 2000). To eliminate cases of secondary autism, children with ASD were free from other medical conditions (e.g., seizures, Fragile X syndrome) and had no visual or hearing impairments. Their cognitive level was evaluated as average at the

age of 4 years using the Griffiths Mental Development Scales (reliability of the administration is 90%; Griffiths, 1996; Hanson, 2982; Luiz et al., 2006).

Acoustic details of crying stimuli—To be sure that TD and ASD stimuli were acoustically different and representative of the typical range of cry sounds for TD and ASD groups, respectively, cry sounds were digitized and analyzed using Praat acoustic analysis software (Boersma & Weenink, 2005). Episodes of crying of the two types differed in the duration of pauses (a silence longer than 250 ms within the episode of crying) in sec (TD: $M = 1.25$, $SD = 0.29$ and ASD: $M = 0.62$, $SD = 0.91$), $F(1,19) = 2.59$, $p < .05$), and in the number of utterances (expressed vocalization of distress between two pauses; TD: $M = 3.15$, $SD = 1.33$ and AD: $M = 2.06$, $SD = 1.91$), $F(1,19) = 3.88$, $p < .05$, within episodes of crying. Next, long-term average spectrum (LTAS) was employed to provide spectral information for each cry episode. LTAS is helpful in discriminating cry characteristics of different categories of children (Scheiner et al., 2002). For all cries, the First Spectral Peak (FSP) of the LTAS was obtained. FSP is the frequency value (in Hz) of the first amplitude peak across the LTAS. It is an estimate of the average f_0 of an episode of crying (Lin & Green, 2007). FSPs (in Hz) of cries were lower for TD children ($M = 469.89$, $SD = 29.97$) than for ASD children ($M = 519.67$, $SD = 27.21$), $F(1,19) = 3.35$, $p < .05$. These results are consistent with previous findings that have indicated that cries of children with ASD usually have different waveform modulations in terms of shorter pauses, fewer utterances, and higher fundamental frequency and are perceived as more unexpected (Esposito & Venuti, 2009; Esposito & Venuti, 2010; Esposito et al., 2012; Esposito et al., 2013; Sheinkopf et al., 2012; Venuti et al., 2012).

Laughter stimuli [LAU]—Infant positive vocalizations (laughter) were extracted from home videos of unedited laughter bouts of the same infants used for extracting the TD stimuli. The duration of pauses (a silence longer than 250 ms within the episode of laughter) in sec was $M = 1.38$ ($SD = 0.50$), and the number of utterances (expressed positive vocalization between

two pauses) was $M = 3.63$, $SD = 0.91$. FSPs (in Hz) of laughter were $M = 371.51$, $SD = 18.07$. These results accord with previous research (Lin & Green, 2007).

White Noise [WN]—Noise sounds were built to generate a control condition for infant vocalization taking into consideration morphological features of the temporal pattern expressed by infant cries. Using Cool Edit Pro Version 1.2 Syntrillium Software (<http://www.syntrillium.com>), we generated white noise streams of 15 sec, the same duration as the infant sounds. To ensure the same temporal modulation as present in infant crying, white noise was perfectly matched for intensity and range of frequencies to the TD infant cries.

2.3. Stimulus presentation and response measurements

After stimulus preparation, 64 audio files (8*4*2) were presented randomly to participants (recorded at 44,100 Hz with a stereo resolution of 32 bit) interspaced with 10 sec of silence, using a personal computer in a sound shielded room. Each stimulus was presented twice. Participants were asked to listen to the stimulus while focusing on a “+” sign on a light-green neutral background, shown on a large LCD display (101 cm) placed at 100 cm from the participants. Central Nervous System (CNS) responses were recorded using a 32-channel EEG at 1024 Hz. EEG was chosen because of its high temporal resolution which allowed us to test fast and prompt CNS responses to infant vocalizations.

2.4 Preprocessing and Preliminary Analysis

The signal was time-locked to the stimuli onset and epochs were selected from 50 ms before stimuli onset to 1 sec after stimuli onset. For each participant, each condition, and each channel, the average signal was computed and the signal was filtered. A highpass 0.01 Hz filter was applied to the EEG signal to exclude slow drifts and a lowpass 25 Hz filter was

applied to exclude the noise. The signal was then normalized to mean = 0 and standard deviation = 1. Channels FC2, F4, and O1 were discarded due to technical issues. Electrodes were clustered and one average value for each cluster and each participant in response to each stimulus type was calculated. Electrodes were clustered as follows: orbitofrontal left (Fp1, AF3), dorsolateral left (F7, F3, FC5, FC1, C3), temporal left (T7, CP5), parietal left (CP1, P7, P3, PO3), orbitofrontal right (Fp2, AF4), dorsolateral right (F8, FC6, C4), temporal right (T8, CP6), parietal right (CP2, P8, P4, PO4), occipital (Oz, O2), and central (Fz, Cz, Pz). Analyses were conducted on the cluster-averaged values.

2.5 Analysis

To analyze Event-Related Potentials for each condition (TD, ASD, LAU, WN) and each group (fathers, non-fathers) the responses in the first second after stimulus onset were subdivided into four time-windows centered on well-known ERP waves: P200 (150-250ms), P300 (250-350ms), N400 (350-450ms) and Late Positivity (450ms-1000ms). For each time-window one average value was calculated. To assess the effects of group and stimulus type on brain responses, an ANOVA was conducted with the group (father, non-father) as between-subjects factor and stimulus type as within-subject factor (TD, ASD, LAU, WN). Students' *t*-tests were run as post-hoc analysis. The analysis were conducted separately for each time-window and each cluster. Bonferroni corrections were applied on ANOVA results to account for the large number of comparisons ($\alpha = .001$).

3. Results

A significant interaction between group and stimulus type on the left dorsolateral frontal cluster of electrodes was found for the time window corresponding to the P200 wave ($F(3,54) = 6.46, p < .001$). Specifically, P200 was stronger in response to WN compared to LAU only in fathers ($t(9) = -3.17, p < .05$) [Fig1a]. Also, even if not statistically significant different, it is worth reporting that fathers and non-fathers showed opposite dynamics in response to ASD cry and LAU. Non-fathers responded to ASD cry and LAU with a larger P200 and smaller Late Positivity compared to fathers [Fig2a-b].

4. Discussion

Cry is the earliest and, for quite a long period of time, the most significant communication tool infants can use to communicate to parents their need for nurture and care. The importance of adults' responses to this infant communicative signal is also underlined by the presence of a set of infant cry-specific responses, found especially in mothers and adult females, which highlight how infant cry attracts women's attention favoring at the same time their promptness to action (De Pisapia et al., 2013; Messina et al., 2015). On the other hand non-adaptive parental responses to infant cries undermine early parent-infant interaction and attunement, causing long term effects on infants' social, emotional and cognitive development. An extreme example is the case of Autism Spectrum Disorders, where the atypical characteristics of the cry contribute in hindering parent-infant relationships by failing to elicit infant-cry specific responses both in the central and in the peripheral nervous system in mothers and in non-parent adults (Esposito et al., 2015; Messina et al., 2015). However, despite their increasing societal role in children caring and nurture, little is known about paternal brain mechanisms underlying responses to infant cry. Here we aimed to investigate

fathers' and non-fathers' brain activations in response to infant typical and atypical cry. Brain responses were assessed through EEG recording while participants were listening to audio stimuli of typically developing infant cry (TD), ASD infant cry (ASD), infant laughter (LAU) and white noise (WN). Focusing on the fast and immediate central nervous system responses to infant vocalization and noise, brain activations within the first second after stimuli onset were analyzed. Specifically we focused our attention on four well-known ERP waves: the P200, linked to input stimuli initial processing attentional levels and affective information (Carretié et al., 2001; Dennis et al., 2007; Singhal et al., 2002), the P300, elicited after habituation in response to an unexpected stimuli (Polich & Margala, 1997), the N400, related to semantic processing (Lau et al., 2008; Kiefer, 2002) and the Late Positivity related to stimuli familiarity and affective content (Rugg, 1990; Schupp et al., 2000). Analysis revealed a differential P200 dynamics over the left dorsofrontal area in response to the different audio stimuli within the two groups, fathers vs non-fathers. Specifically, fathers showed a stronger P200 in response to white noise compared to infant laughter. Also over the same area, fathers and non-fathers showed opposite wave dynamics overall the first second from stimuli onset in response to ASD cry and infant laughter. For instance, fathers showed a larger P200 and a smaller Late Positivity compared to non-fathers. Findings highlighted a differential early processing and distinct stimuli-elicited attentional levels and emotional arousal in fathers compared with non-fathers. Indeed, fathers' attention seems to be caught more efficiently by white noise rather than infant laughter. This attitude may be due to the evolutionary importance of prompt motor reactions to and fast comprehension of unexpected and possibly threatening sounds in the environment, whereas infant laughter being a non-threatening or possibly dangerous sound would elicit a weaker reaction. On the other hand infant laughter as well as ASD cry elicits a stronger P200 in non-fathers compared to fathers. These two sounds, infant laughter and ASD cry are likely to be not familiar and therefore

more arousing to non-fathers. The status of these stimuli is supported also by the dynamics of the Late Positivity wave, which is weaker in non-fathers underlying less familiarity with them. We would have expected typical infant cry also to be less familiar to the group of non-fathers. However, typical infant cry bear some resemblance with adult cry and non-fathers may also have experienced some of it with younger relatives, whereas ASD cry has very different acoustical characteristics. Fathers, thanks to their experience with infants, may readily interpret ASD cry as some kind of cry despite its atypicalities, while non-fathers may not have the same prompt adjustment. Consistent with findings from Venuti and colleagues (2012) (Venuti et al., 2012) we found differential activations in brain areas involved in language processing and action programming in fathers in response to infant laughter and noise. Also, brain responses dynamics appear to be opposite in fathers and non-fathers in response to ASD cry and infant laughter. The differential responses found in the motor programming and language processing brain areas point to a difference between fathers and non-fathers in very early stages of the audio stimuli processing, which may underlie a differential preparation of motor output in fathers and non-fathers. Further studies will need to apply Messina and colleagues experimental protocol (2016) assessing muscular activation in response to cry also in fathers. Other factors may also be involved and need to be further investigated. Responses to infant cry are complex and the decision upon the adequate output behavior may take longer processing-time and the external context is also likely to play an important role on infant vocalizations' processing, since the presence or not of the baby may weight strongly on fathers expectations and, in turn, perceptions. Moreover the sample size of the present research, which was small due to recruitment difficulties, is a limitation which will need to be address in the future. Following researches will than need to increase the sample size addressing the role of contextual cues on infant-cry perception and investigating the brain activations upon longer time-windows by applying different adequate techniques,

such as the functional Near Infrared Spectroscopy (fNIRS) and the functional Magnetic Resonance Imaging (fMRI).

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Conflict of Interests

The authors declare no conflict of interest.

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Figure 1. Within-groups ERPs. Brain responses in the left dorsolateral frontal cluster of electrodes in the first second after stimuli onset within groups. Black lines represent grand average response to typical development infant cry (TD). The 75% gray lines represent the grand average response to ASD cry (ASD). The 50% gray lines represent the grand average response to infant laughter (LAU). The 25% gray lines represent the grand average response to white noise (WN). a) Fathers' responses. Dashed lines represent significantly different P200 waves. Specifically the P200 elicited in response to infant laughter significantly differs from the P200 elicited by white noise. b) Non-fathers' responses. * $p < .05$

Figure 2. Between-groups ERPs. Brain responses in the left dorsolateral frontal cluster of electrodes in the first second after stimuli onset between groups. Full black lines represent fathers' responses, while dashed black lines represent non-fathers' responses. a) ERPs elicited by ASD cry. a) ERPs elicited by infant laughter. a) ERPs elicited by typical cry. a) ERPs elicited by white noise.