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Research Report

Theta and alpha oscillations linked to risk identifications

Jungang Qin[a], *Tatia M.C. Lee*[c,d], *Shihui Han*[a,b,*]

[a]*Department of Psychology, Beijing 100871, PR China*
[b]*Key Laboratory of Machine Perception (Ministry of Education), Peking University, Beijing 100871, PR China*
[c]*Laboratory of Neuropsychology, The University of Hong Kong, Hong Kong, PR China*
[d]*Laboratory of Cognitive Affective Neuroscience, The University of Hong Kong, Hong Kong, PR China*

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ABSTRACT

Our recent functional MRI and event-related potential studies suggest that neural mechanisms underlying identifications of environmental and personal risks are characterized by distinct neural structures and time courses. The current work further investigated the role of non-phase locked activity in dissociation of the neural processes of environmental and personal risks. We recorded electroencephalogram (EEG) from healthy adults when they identified risky and safe environmental or personal events depicted in words or phrases. Event-related synchronization (ERS) and desynchronization (ERD) in association with risky and safe environmental and personal events were calculated using Morlet's wavelet analysis. We found that, relative to the identification of safe environmental events, the identification of risky environmental events induced increased theta band power at 260–380 ms over the frontal cortex and increased alpha band power after 700 ms with a wide scalp distribution. Moreover, theta band powers associated with the identification of risky environmental events correlated positively with subjective ratings of the risk degree of environmental events. In contrast, the identification of risky personal events was linked to decreased alpha band power at 740–900 ms with a wide scalp distribution compared with the identification of safe personal events. Our findings indicate that theta and alpha band neural oscillations are involved in differentiation between environmental and personal risks.

1. Introduction

Risk perception is extremely important for regulation of human behaviors under risk contexts and hence has been studied extensively by both social scientists and neuroscientists. Psychometric approach to risk perception examines attitudes and intuitive judgments about risks using psychophysical scaling and multivariate analysis (Slovic, 1992). Researchers in this field have identified 'dread' factor (the severity and dreadfulness, such as lack of controllability, involuntariness) and 'unknown' factor (knowledge-related characteristics, such as whether the risk is observable, known) that can account for most variance of the rating scores of risks (Slovic, 1987). Moreover, psychometric studies suggest that risk perception is highly domain specific. Risks can be decomposed into sub-categories in terms of health/safety, recreational, social, and ethics decisions (Weber et al., 2002).

Recent brain imaging studies have tried to disentangle neural substrates underlying the processing of risks in different domains (Vorhold et al., 2007; Qin and Han, 2009a,b). For

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[*] *Corresponding author*. Department of Psychology, Peking University, 5 Yiheyuan Road, Beijing 100871, PR China. Fax: +86 10 6276 1081.
E-mail address: shan@pku.edu.cn (S. Han).

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example, we recently recorded neural activities using event-related potential (ERP) and functional magnetic resonance imaging (fMRI) from human adults when they assigned valence (risky or safe) to environmental and personal events (Qin and Han, 2009a). We found that the identification of environmental risks is associated with increased amplitudes of the P200 over the frontal area and increased amplitudes of a late positive potential (LPP) over the central–parietal area. In parallel with the ERP results, our fMRI research found that the identification of environmental risks was associated with increased activations in the ventral anterior cingulate (vACC) and posterior cingulate cortex (PCC). The brain imaging findings suggest that the identification of environmental risks is underpinned by an early process of emotional conflict and a late retrieval process of emotional experiences. More interestingly, the neural activities mentioned above were observed for the identification of environmental risks but not for the identification of personal risks (Qin and Han, 2009a). These neuroimaging findings are consistent with the proposition that environmental risks are more dreadful than personal risks (Slovic, 1987) and risk perception is different between environmental and personal risk domains (Schütz et al. 2000; Hendrickx and Nicolaij, 2004).

The current work further investigated whether the processes of environmental and personal risks are mediated by different neural oscillations that are non-phase locked to stimulus onset. Previous studies have shown that non-phase locked neural oscillations are involved in a variety of cognitive and emotional processes (Basar et al., 1999a,b; Krause, 2003). Event-related oscillatory electroencephalogram (EEG) activities associated with specific processes are characterized with either relative increase in the power of a given frequency band during either external or internal stimulus processing (event-related synchronization, ERS) or relative decrease in the EEG power (event-related desynchronization, ERD) (Pfurtscheller and Klimesch, 1991; Pfurtscheller and Lopes da Silva, 1999). For example, it has been shown that the processing of affective pictures that may induce positive or negative emotions is associated with early (200–500 ms poststimulus) theta ERS (Aftanas et al., 2001a,b; Mu et al., 2008). The emotion related ERS is greater over the right hemisphere for negative stimuli but greater over the left hemisphere for positive stimuli (Aftanas et al., 2001a,b). Perception of sequentially presented threatening and pleasant pictures also induces theta band ERS (Aftanas et al., 2003a). In addition, the theta band neural oscillations are modulated by trait anxiety constructs (low vs. high trait-anxious) and alexithymia construct (non-alexithymic vs. alexithymic) of the subjects (Aftanas et al., 2003a,b). Alpha band oscillations are also involved in the processing of emotional stimuli (Crawford et al., 1996; Tsang et al., 2001; Sarlo et al., 2005). Specifically, long-latency alpha ERS is linked to the processing of pictures with emotional contents (Aftanas et al., 2001a, 2002).

The aforementioned studies indicate that theta and alpha oscillations are related to threatening and emotional stimuli. As the emotional processing engages in risk identifications (Qin and Han, 2009a), it is likely that theta and alpha band activities also contribute to risk identifications. To assess this, we record EEG from healthy adults when they performed tasks to identify risky or safe environmental and personal events conveyed via words or phrases. The stimuli and procedure in the current experiment are illustrated in Fig. 1. The neural substrates underlying identification of risks were measured by contrasting neural oscillations associated with risky events with those associated with safe ones. Such contrasts rule out confounds such as semantic processing and motor responses. We also measured subjective ratings of risk degrees so as to examine whether theta and alpha activities can predict subjective feeling of risks.

2. Results

2.1. Behavioral results

Response accuracies to the identification of both environmental and personal risks were over 88%. Responses were faster to risky than safe items in the environmental risk identification task (819 vs. 892 ms, t (13) = 5.691, $p < 0.001$) but not in the personal risk identification task (892 vs. 864 ms, $p > 0.1$). Paired t-test showed that risk rating scores were significantly higher for environmental than personal items (risky events: 3.73 ± 0.39 vs. 2.87 ± 0.49, t (13) = 8.26, $p < 0.001$; safe events: 0.49 ± 0.32 vs. 0.30 ± 0.30, t (13) = 3.36, $p < 0.01$). Rating scores of emotional salience obtained after the EEG recording procedure were significantly higher for environmental than personal risky items (2.98 ± 0.94 vs. 2.42 ± 0.78, t (13) = 4.27, $p < 0.001$) whereas there was no significant difference in rating scores of emotional salience between environmental and personal safe items (0.82 ± 0.74 vs. 0.77 ± 0.70, t (13) = 0.90, $p > 0.05$).

2.2. EEG results

2.2.1. ERD/ERS associated with environmental events

Oscillatory activities associated with environmental events were quantified by calculating theta and alpha band activities

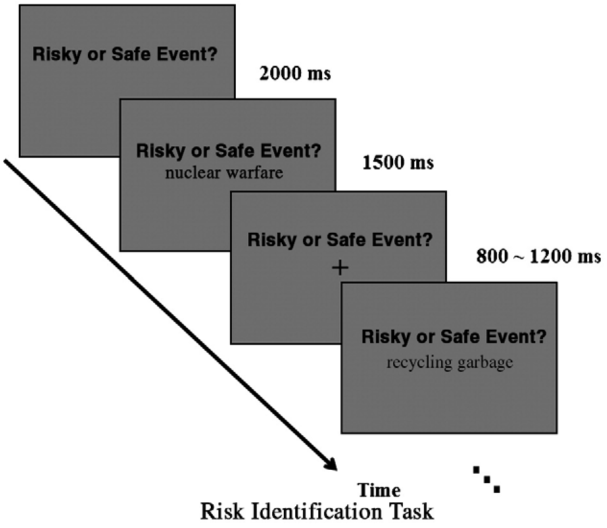

Fig. 1 – Illustration of the risk identification task and the experimental design. Each blocks of trials started with the presentation of instructions to define the task. Each trial consisted of the presentation of the events and a randomized inter-stimulus interval. Events were presented in a random order in each block.

in five consecutive time windows (T1: 0–220 ms; T2: 220–440 ms; T3: 440–660 ms; T4:660–880 ms; T5: 880–1100 ms after stimulus onset), as illustrated in Figs. 2a and b. Both risky and safe environmental items induced theta band ERS at 220–1100 ms. The maximum ERS was observed at 660–880 ms over frontal–central areas (risky items: Cz: 56.3%; FC1: 71.1%; safe items: Cz: 58.1%; FCz: 66.8%). However, risky and safe environmental items induced lower alpha band ERD between 220 and 1100 ms with maximum power at 440–660 ms over the posterior parietal areas (risky items: PO6: 43.6%; P4: 39.3%; safe items: P7: 38.2%; P5: 36.2%). Risky and safe environmental items also induced upper alpha band ERD at 220–1100 ms with maximum change at 440–660 ms at the posterior parietal electrodes (risky items: PO6: 50.6%; P7: 49.8%; safe items: PO6: 47.8%; P3: 46.0%).

2.2.2. *ERD/ERS associated with personal events*

Theta and alpha band activities associated with personal events are shown in Figs. 2c and d. Both risky and safe personal items induced theta band ERS over the frontal area with maximum changes at 880–1100 ms (risky items: AF3: 66.7%; AF7: 59.9%; safe items: FP: 185.5%; AF3: 146.8%) but lower alpha band ERD with maximum changes at 440–660 ms (risky items: PO4: 39.6%; P6: 39.3%; safe items: P6: 30.7%; PO6: 30.5%) and upper alpha band ERD over the parietal area with maximum changes at 440–660 ms (risky items: PO6: 48.8%; PO4: 48.2%; safe items: PO6: 47.3%; P6: 45.4%).

2.2.3. *EEG activity associated with identification of environmental risks*

To investigate oscillatory activities specifically involved in the identification of risky events, we compared the magnitudes of theta and alpha band ERS/ERD induced by risky and safe items by conducting a repeated measure analysis of variances (ANOVA) with Valence (Risky vs. Safe) and Hemisphere (Left vs. Right) as within-subjects independent variables.

The effects of stimulus valence on oscillatory activities linked to the identification of environmental risks were illustrated in Fig. 3a. A significant main effect of Valence was observed at 260–380 ms over the frontal area (F1–F2: $F(1,13)=4.75$, $p<0.05$; F3–F4: $F(1,13)=6.14$, $p<0.05$) and at 740–980 ms over the parietal-temporal areas (P3–P4: $F(1,13)=10.00$, $p<0.01$; PO3–PO4: $F(1,13)=8.12$, $p<0.05$; TP7–TP8: $F(1,13)=11.31$, $p<0.01$; T7–T8: $F(1,13)=10.12$, $p<0.01$), the identification of risky environmental items induced greater theta band ERS relative to the identification of safe environmental items. Lower alpha band power was also greater in association with the identification of risky than safe environmental items at 660–860 ms (F3–F4:$F(1,13)=6.45$, $p<0.05$; FC3–FC4: $F(1,13)=6.79$, $p<0.05$; C5–C6: $F(1,13)=10.37$, $p<0.01$; PO5–PO6: $F(1,13)=6.19$, $p<0.05$; CP5–CP6: $F(1,13)=12.42$, $p<0.01$; TP7–TP8: $F(1,13)=12.13$, $p<0.01$; T7–T8: $F(1,13)=12.85$, $p<0.01$). Similar effect was evident for upper alpha band power at 700–940 ms (PO5–PO6: $F(1,13)=5.19$, $p<0.05$; T7–T8: $F(1,13)=10.71$, $p<0.01$; F3–F4:

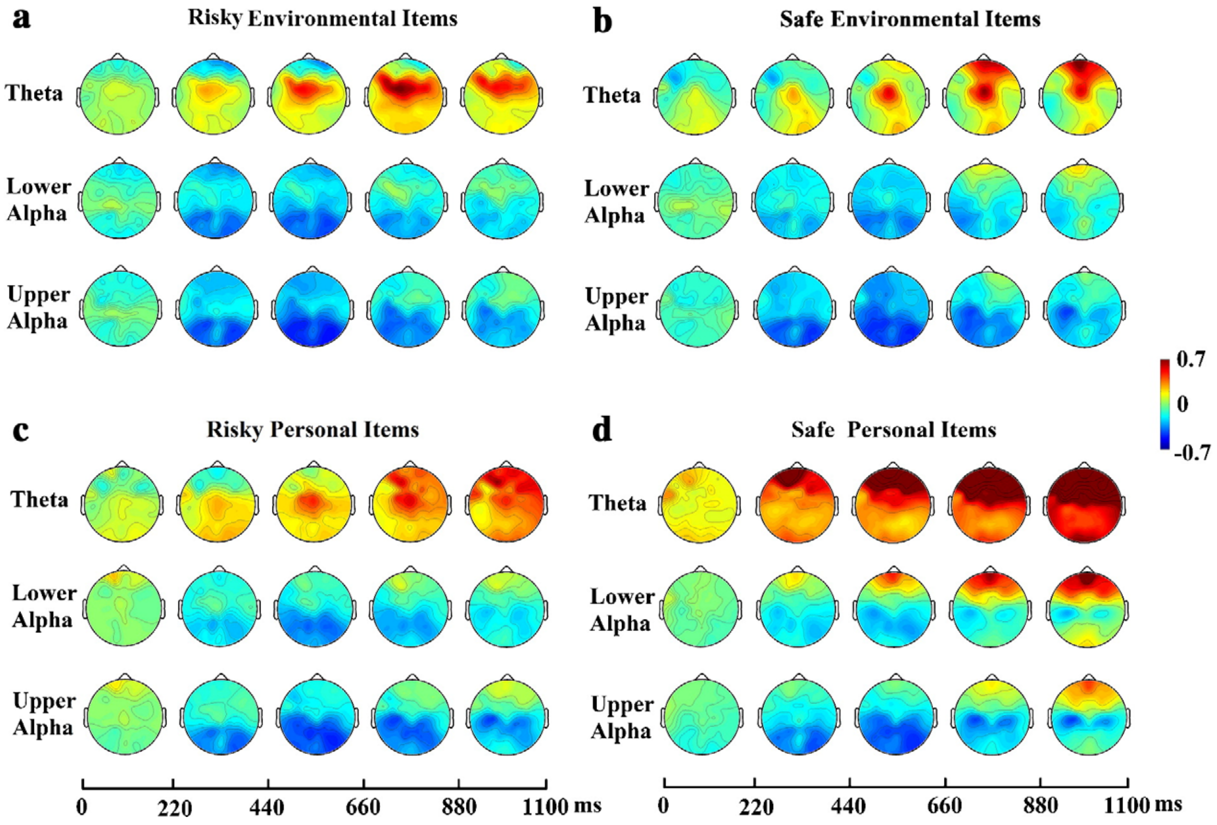

Fig. 2 – Topographies of theta and alpha band ERD/ERS in each stimulus condition. (a) The topographies of ERD/ERS associated with risky environmental items; (b) The topographies of ERD/ERS associated with safe environmental items; (c) The topographies of ERD/ERS associated with risky personal items; (d) The topographies of ERD/ERS associated with safe personal items.

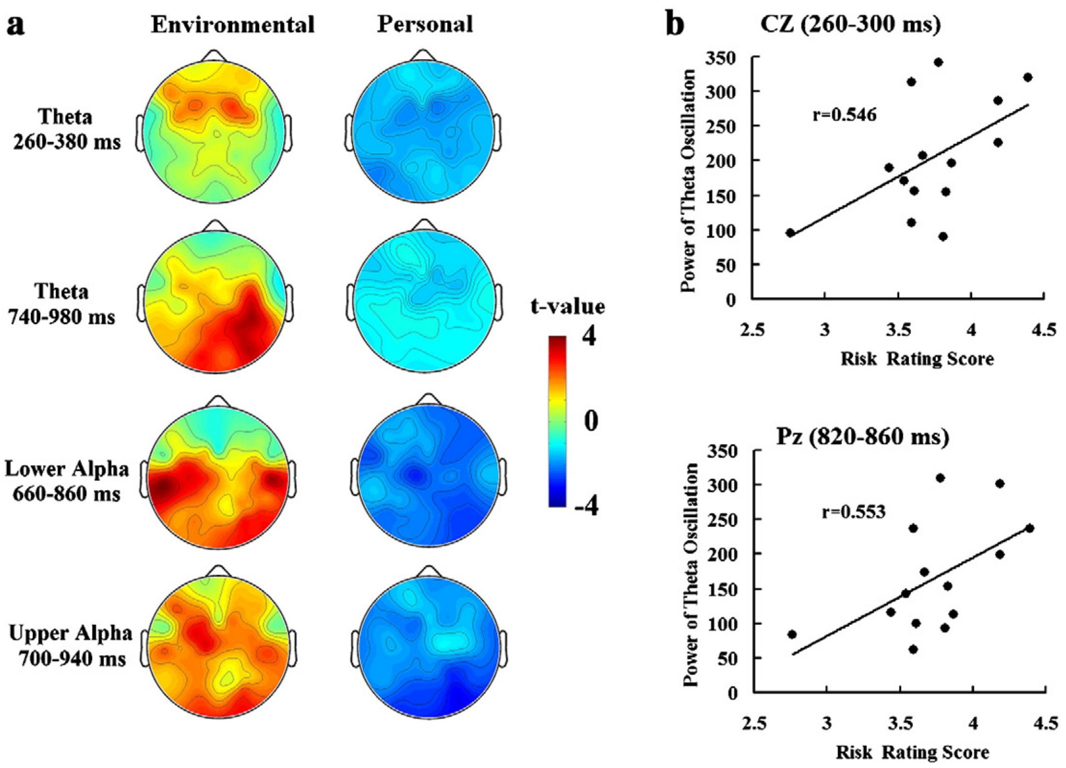

Fig. 3 – (a) Topographies of the *t*-values differentiating risky and safe items; (b) The correlation between theta band power associated with risky environmental items and subjective rating scores of risk degree of risky environmental items.

$F(1,13)=10.91$, $p<0.01$; FC3–FC4: $F(1,13)=10.13$, $p<0.01$; C3–C4: $F(1,13)=6.52$, $p<0.05$).

More interestingly, we found that theta band powers associated with the identification of risky environmental events over the frontal/central/parietal areas correlated with the rating scores of risk degree of risky environmental items (260–300 ms, Cz: $r=0.546$, $p<0.05$; 820–860 ms, Pz: $r=0.553$, $p<0.05$; Fig. 3b). The greater the theta band power, the more risky the environmental items were rated.

2.2.4. *EEG activity associated with identification of personal risks*

The identification of risky personal items failed to invoke increased theta or alpha band power relative to the identification of safe personal items (ps>0.05, Fig. 3a). However, alpha band power decreased significantly to the identification of risky than safe personal items, as indicated by the significant main effect of Valence on the lower band alpha at 740–900 ms (PO5–PO6: $F(1,13)=6.68$, $p<0.05$; P3–P4: $F(1,13)=5.68$, $p<0.05$; P7–P8: $F(1,13)=6.15$, $p<0.05$; T7–T8: $F(1,13)=12.85$, $p<0.01$; FC3–FC4: $F(1,13)=5.24$, $p<0.05$; C3–C4: $F(1,13)=5.49$, $p<0.05$) and on the upper alpha band at 740–940 ms (PO5–PO6: $F(1,13)=9.30$, $p<0.01$; P3–P4: $F(1,13)=6.86$, $p<0.05$; P7–P8: $F(1,13)=5.61$, $p<0.05$; CP3–CP4: $F(1,13)=4.88$, $p<0.05$; T7–T8: $F(1,13)=12.85$, $p<0.01$; F3–F4: $F(1,13)=6.02$, $p<0.05$; FC3–FC4: $F(1,13)=4.91$, $p<0.05$).

2.2.5. *Distinct neural oscillations associated with environmental and personal risk identifications*

Neural oscillations were subjected to ANOVAs with Risk (Environmental vs. Personal) and Valence (Risky vs. Safe) as within-subjects independent variables to confirm the distinct oscillatory activities in association with the identification of environmental and personal risks. ANOVAs of theta band power showed a reliable interaction of Risk × Valence at 260–380 ms over the frontal–central areas (F3–F4: $F(1,13)=7.01$, $p<0.05$; FC3–FC4: $F(1,13)=6.43$, $p<0.05$; C3–C4: $F(1,13)=5.16$, $p<0.05$, Fig. 4a) and over the parietal area (PO3–PO4: $F(1,13)=5.65$, $p<0.05$; P3–P4: $F(1,13)=5.07$, $p<0.05$; CP3–CP4: $F(1,13)=4.74$, $p<0.05$, Fig. 4d), suggesting that risky environmental events induced greater theta band activity relative to safe environmental events whereas a reverse pattern was observed for personal events. ANOVAs of alpha band power also showed a significant interaction of Risk × Valence at 580–860 ms (lower alpha: PO3–PO4: $F(1,13)=11.58$, $p<0.01$; PO7–PO8: $F(1,13)=12.33$, $p<0.01$; P3–P4: $F(1,13)=11.91$, $p<0.01$; P7–P8: $F(1,13)=10.99$, $p<0.01$; CP3–CP4: $F(1,13)=11.35$, $p<0.01$; TP7–TP8: $F(1,13)=9.41$, $p<0.01$; T7–T8: $F(1,13)=7.21$, $p<0.05$; C3–C4: $F(1,13)=9.74$, $p<0.01$; FC3–FC4: $F(1,13)=6.31$, $p<0.05$, Figs. 4b and e) and at 780–940 ms (upper alpha: PO3–PO4: $F(1,13)=7.89$, $p<0.05$; PO7–PO8: $F(1,13)=8.40$, $p<0.05$; P3–P4: $F(1,13)=6.05$, $p<0.05$; P7–P8: $F(1,13)=4.77$, $p<0.05$; CP3–CP4; $F(1,13)=6.64$, $p<0.05$; TP7–TP8: $F(1,13)=8.02$, $p<0.05$; T7–T8: $F(1,13)=7.30$, $p<0.05$; Fig. 4c), indicating a reverse pattern of alpha band power linked to the identification of environmental and personal risks.

2.2.6. *Hemispheric asymmetry in neural oscillations related to environmental risk identifications*

ANOVAs of theta band power related to environmental items showed a significant interaction of Valence × Hemisphere at

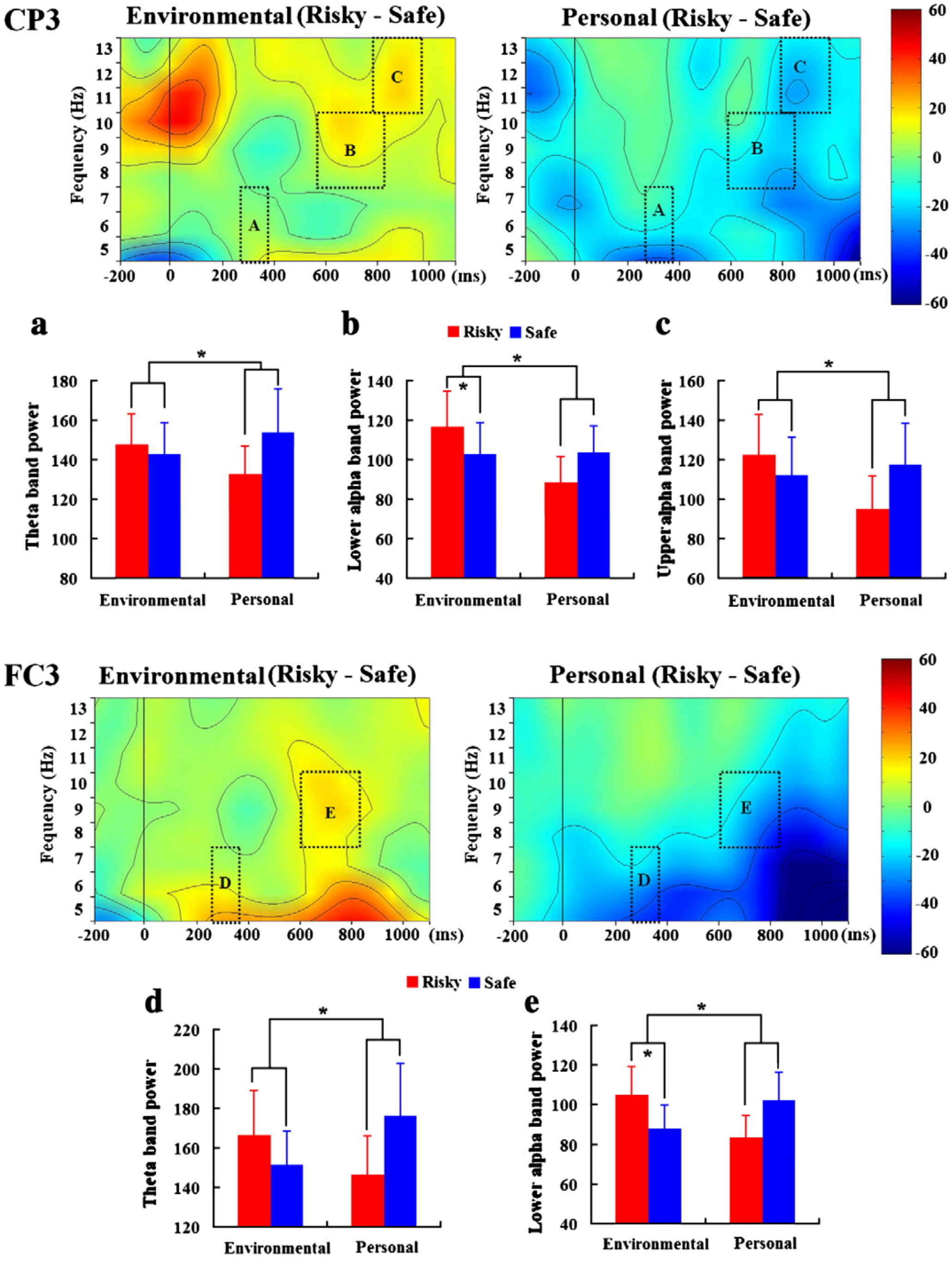

Fig. 4 – Illustration of the time–frequency representations of the differential theta and alpha band power between risky and safe items at CP3 and FC3. The histograms show the power values associated with each stimulus condition within specific time windows and frequency bands.

780–980 ms over parietal–central–temporal areas (CP3–CP4: $F(1,13)=5.03$, $p<0.05$; C5–C6: $F(1,13)=8.01$, $p<0.05$; T7–T8: $F(1,13)=6.09$, $p<0.05$), theta band power associated with the identification of environmental risks was greater over the right than left hemispheres. A reliable interaction of Valence × Hemisphere was also observed at 540–620 ms over parietal areas for lower alpha band (PO5–PO6: $F(1,13)=5.52$, $p<0.05$; P3–P4: $F(1,13)=4.99$, $p<0.05$), due to that alpha band power elicited by the identification of environmental risks was larger over the left than right hemispheres. Upper alpha band linked to the identification of environmental risks, however, was greater over the right than left hemispheres at 860–940 ms (AF3–AF4: $F(1,13)=6.82$, $p<0.05$, AF7–AF8: $F(1,13)=5.72$, $p<0.05$; FP1–FP2: $F(1,13)=14.55$, $p<0.01$).

2.2.7. *Hemispheric asymmetry in neural oscillations related to personal risk identifications*

Alpha band power linked to personal risk identifications was greater over the right than left hemispheres, resulting in significant interaction of Valence × Hemisphere at 820–

900 ms (lower alpha: PO7–PO8: $F(1,13)=5.25$, $p<0.05$; P5–P6: $F(1,13)=5.70$, $p<0.05$; TP7–TP8: $F(1,13)=9.22$, $p<0.05$; CP5–CP6: $F(1,13)=11.71$, $p<0.01$; T7–T8: $F(1,13)=8.21$, $p<0.05$; F5–F6: $F(1,13)=6.91$, $p<0.05$; AF3–AF4: $F(1,13)=7.13$, $p<0.05$) and at 860–940 ms (upper alpha: PO3–PO4: $F(1,13)=5.87$, $p<0.05$; PO7–PO8: $F(1,13)=12.26$, $p<0.01$; P3–P4: $F(1,13)=9.46$, $p<0.01$; P7–P8: $F(1,13)=8.92$, $p<0.05$).

3. Discussion

Following our previous fMRI and ERP studies (Qin and Han, 2009a), the current work further investigated whether the identification of environmental and personal risks is mediated by distinct non-phase locked neural oscillations. EEG was recorded from subjects who were required to identify risky and safe environmental and personal events. Behavioral responses were faster to the items depicting risky than safe environmental events but did not differ between risky and safe personal events, suggesting greater salience or dread of risk perception of environmental than personal events.

3.1. *ERS and ERD related to environmental and personal events*

The EEG data showed first that, relative to the neural rhythms during the pre-stimuli interval, items describing environmental and personal events induced theta band ERS over the frontal–central area and alpha band ERD over the parietal–occipital areas. Theta and alpha band oscillations have been observed in association with different cognitive tasks (Basar et al., 1999b; Klimesch, 1999). Theta band ERS are elicited by tasks requiring episodic memory retrieval (Doppelmayr et al., 1998), identifications of semantic violations in online sentence processing (Hald et al., 2006), and affective valence discrimination of visual displays (Aftanas et al., 2001a; Mu et al., 2008). Alpha ERD are linked to attentional control and memory retrieval (Klimesch, 1999), inhibitory motor control (Hummel et al., 2002), and recognition of emotional face expression (Güntekin and Başar, 2007). To identify environmental and personal risks depicted in words or phrases requires the processing of semantic meaning of each item, retrieval of emotional experiences or knowledge from memory, and manipulation of motor responses. Thus it is not surprising that the stimuli used in the risk identification tasks elicited theta band ERS and alpha band ERD.

3.2. *Neural oscillations associated with identifications of environmental risks*

More importantly, we found evidence that both theta and alpha band activities were modulated by stimulus valence that differentiates risky and safe items. The identification of risky environmental events was associated with increased theta band activity relative to the identification of safe environmental events. In addition, the theta band ERS related to the identification of environmental risks was more salient at central and parietal electrodes over the right than left hemispheres. Prior research has shown that the right lateralized theta ERS is associated with the processing of pictures with emotional contents (Aftanas et al., 2001a,b, 2003a,b). Similarly, risky environmental events may evoke enhanced emotional responses such as dread compared to safe environmental events. Such emotional responses may take place even when subjects identify environmental risks that are depicted in words or phrases. In agreement with this, the amplitude of early theta oscillation positively correlated with subjective ratings of risk degree of environmental events, suggesting a link between theta oscillations and subjective feelings of risks.

Theta band oscillations have been recorded from neurons in the limbic structures such as the cingulate cortex (Leung and Borst, 1987). The rostral part of the cingulate cortex (Brodmann areas 24/32) is the largest cluster that shows positive correlations between theta band activity and glucose metabolism (Pizzagalli et al., 2003). As our previous ERP and fMRI results revealed that the identification of environmental risks engages the anterior and posterior cingulate cortex (Qin and Han, 2009a), it may be proposed that the theta band ERS linked to the identification of environmental risks observed here may arise from the cingulate cortex. Previous research has shown that theta band oscillations contribution to the P300 response (Basar, 1998, 1999) and the P300 amplitudes positively correlate with subjective ratings of environmental risks (Qin and Han, 2009a). Thus the long-latency posterior theta ERS observed in the current work possibly functioned similarly to the P300 to mediate retrieval of emotional experiences during environmental risk identifications (Qin and Han, 2009a). Taken together, our findings indicate that both phase-locked and non-phase locked neural activities are involved in the identification of environmental risks.

Similar to the theta band activity, both lower and upper alpha band power also increased during the perception of the risky than safe environmental events, suggesting that the alpha band activity also engages in differentiation between risky and safe environmental events. In addition, the upper alpha band effect at 860–940 ms was stronger over the right than left frontal areas. Alpha band ERS was observed during the process of emotional pictures (Aftanas et al., 2001a, 2002; Mu et al., 2008). In the current study, the increased alpha band power linked to the identification of environmental risks may subserve emotional responses during risk perception such as dread to environmental risks. Previous studies also found that the right and left frontal areas dominate the processing of negative and positive information, respectively (Davidson, 1998, 2004; Cunningham et al., 2005). This is consistent with the dominance of the right frontal alpha band oscillations observed here since risky environmental events may induce negative emotions and withdrawal behaviors.

3.3. *Distinct neural substrates of environmental and personal risk identifications*

Both the theta and alpha band oscillations in association with personal risk identification showed a pattern distinct from that linked to environmental risk identification. First, the early theta band power was not involved in the identification of personal risks. Second, risky personal events reduced alpha band power relative to safe personal events. In line with our prior fMRI and ERP studies (Qin and Han, 2009a), the current

EEG results support the idea that the identification of risks in different domains such as social/physical risks and environmental/personal risks defined in the previous psychometric studies (Slovic 1992; Weber et al., 2002) are mediated by distinct neural mechanisms (Qin and Han, 2009a,b). Moreover, both the current EEG findings and our previous ERP results support the view that environmental risks are identified earlier than personal risks during the neural processing. Environmental risks such as earthquake and chemical pollution usually result in serious damages to a large population. Thus early detection of environmental risks is necessary for human beings to avoid catastrophic consequences of environmental risks to human society. Although alpha band power is involved in the identification of personal risks, the underlying neural mechanisms may be different from that of environmental risks as alpha band power reduced rather than increased to the personal risks. However, modulation of the lower alpha band power by personal risk identification was more salient over the right than left hemispheres, similar to that linked to environmental risk identification. This reflects the fact that both personal and environmental risks generate negative emotional responses and withdrawal behaviors that are mediated mainly by the right hemisphere (Davidson, 1998, 2004).

4. Conclusion

While our previous work showed that ERP (e.g., P200 and LPP) and fMRI (e.g., vACC and PCC) signals are involved in differentiation between environmental and personal risks (Qin and Han, 2009a), the current EEG study showed further evidence for distinct neural mechanisms underlying risk perception in the environmental and personal domains. Theta band neural oscillations engaged in the identification of environmental but not personal risks. Alpha band activities were involved in the identification of both environmental and personal risks but possibly reflected different neural mechanisms. The distinct oscillatory brain dynamics in association with the identification of environmental and personal risks provide neuroscience evidence for the view that perception of environmental risks is distinct from that of personal risks (Schütz et al. 2000; Hendrickx and Nicolaij, 2004). As previous studies suggest that personal variables such as profession affect the risk perception (Slovic, 1987), our EEG findings may be limited to a specific population (e.g., college students).

As most evaluative judgments are referenced to the self (Zysset et al., 2002), the risk identification task used in our studies may also be implicitly referenced to the self. Consistent with this, the MPFC/vACC and PCC involved in the risk identification tasks (Qin and Han, 2009a,b) overlapped with the cortical midline structures that have been identified to be engaged in self-referential processing (Kelley et al., 2002; Zhu et al., 2007; Han et al., 2008; also see Northoff et al., 2006 for review). While the current EEG study showed that theta and alpha neural oscillations were associated with risk identification, our recent work also found evidence that theta and alpha neural oscillations are involved in differentiation between trait judgments of self and others (Mu and Han, in preparation). These results of non-phased locked activity are consistent with the fMRI findings and suggest that it is likely that judgments of personal and environment risks are referenced to the self.

5. Experimental procedures

5.1. *Subjects*

Seventeen undergraduate and graduate students (7 males and 10 females) from Peking University participated in the study as paid volunteers. Three of the female subjects were excluded from data analysis because of excessive artifacts during EEG recording. The behavioral and EEG data were reported from fourteen subjects (7 males and 7 females, aged between 20 and 29 years, mean age ± SD = 24.64 ± 2.68, values are given as mean ± SD throughout). All subjects were right-handed, had normal or corrected-to-normal vision, and had no neurological or psychiatric history. Subjects gave informed consent prior to the study. This study was approved by a local ethics committee at the Department of Psychology, Peking University.

5.2. *Stimuli and procedure*

The stimuli were Chinese words or phrases (each consisting of 2 to 4 Chinese characters), which described either a potentially risky or a safe event that may occur in everyday life. There are 40 phrases describing the risky environmental events and 40 phrases describing the safe environmental events. Environmental risky events refer to those that may produce catastrophic consequences to the health and living conditions of human beings and animals in a local area or around the world, such as “tsunami”, “earthquake”, “nuclear warfare”, “volcanic eruption”, or “air pollution”. Safe environmental events refer to those that would not induce damage to the health and living conditions of people, such as “appropriate rainfall”, “virescence”, “railway construction”, “using solar energy”, or “recycling garbage”. There were also 40 words or phrases describing potentially risky personal events and 40 words or phrases describing safe personal events. Risky personal events refer to those that would bring harmful consequences (e.g., physical injury or health problems) to an individual, such as “smoking”, “taking in heroin”, “bungee jumping”, “surfing”, or “swimming in the ocean”. Safe personal events refer to those that would not induce potential physical injury or health problems, such as “playing piano”, “reading”, “jogging”, “watching cinema”, or “wearing sunglasses”. The stimuli were identical to those used in our previous study (Qin and Han, 2009a). Each stimulus subtended a visual angle of 1.28° × 0.51°–2.61° × 0.51° (2.0 × 0.8 cm–4.1 × 0.8 cm, width × height) at a viewing distance of 90 cm.

Each subject participated in eight blocks of trials, in which the stimuli and tasks varied. In each two blocks of trials, subjects either (1) were presented with words/phrases depicting environmental events (half safe and half risky) and judged risky vs. safe environmental events (environmental risk identification task); (2) were presented with half words/phrases depicting environmental events and half pseudo words/phrases, and judged real vs. pseudo words/phrases (semantic control task); (3) were presented with words/phrases depicting personal events (half safe and half risky) and judged risky vs. safe personal events (personal risk identification task); or (4) were presented with half words/phrases depicting personal events and half pseudo words/phrases, and judged real vs. pseudo words/phrases (semantic control task). Subject pressed one of the two buttons to indicate risky/safe in the risk identification task or real/pseudo words/phrases in the control task using the index or middle finger. The responding hand was counterbalanced across subjects. Each block of trials began with the presentation of instructions for 2000 ms, which defined the task (i.e., risk identification or semantic control tasks) for each block. There were 80 trials in each block. On each trial a word/phrase was presented for 1500 ms at the centre of the screen, which was followed by a fixation cross with a duration varying randomly between 800 ms and 1200 ms. The stimuli in each block of trials were presented in a random order and the order of risk identification or semantic control tasks was counterbalanced using the Latin-square design for each subject. After the EEG recording session, subjects were asked to evaluate the risk degree (0=safe, 6=extremely risky) and emotional salience (0=no, 6=extremely high) for each stimulus item using a 7-point Likert scale.

5.3. *Data recording and analysis*

The electroencephalogram (EEG) was continuously recorded from 60 scalp electrodes that were mounted on an elastic cap according to the extended 10–20 system, with the addition of two mastoid electrodes. The electrode at the right mastoid was used as reference. Eye blinks and vertical eye movement were monitored with electrodes located above and below the left eye. The horizontal electro-oculogram was recorded from electrodes placed 1.5 cm lateral to the left and right external canthi. The electrode impedance was kept less than 5 kΩ. The EEG was amplified (band pass 0.01–100 Hz) and digitized at a sampling rate of 250 Hz.

Both behavioral performance and EEG data analysis focused on the responses to risky and safe stimuli presented in the environmental and personal risk identification task. Reaction times (RTs) were subjected to a repeated measure analysis of variances (ANOVA) with Risk (environmental vs. personal) and Valence (risky vs. safe) as within-subject independent variables. Two-tailed paired *t*-tests were conducted to compare the risk rating scores of the environmental and personal events.

We first calculated ERPs for each stimulus condition (risky environmental items, safe environmental items, risky personal items, safe personal items). The ERPs were averaged separately off-line with averaging epochs beginning 400 ms before stimulus onset and continuing for 1300 ms for eliminating boundary effect of results, and then focused on the time window from 200 ms before stimulus onset and continuing for 1100 ms. Trials contaminated by eye blinks, eye movements, or muscle potentials exceeding ±50 μv at any electrode were excluded from the average. In order to obtain non-phase-locked event-related EEG activity in each stimulus condition, ERPs in each stimulus condition were subtracted from each corresponding EEG epoch (e.g., ERPs elicited by risky environmental items were subtracted from each EEG epoch associated with risky environmental items), which helped to remove the phase-locked EEG activity from the EEG data.

The time–frequency (TF) wavelet decomposition of the EEG activity was used to quantify change of the oscillatory activity. The EEG is convoluted by complex Morlet's wavelet $w(t, f_0)$ (Kronland-Martinet et al., 1987) that has a Gaussian shape both in the time domain (SD σ_t) and in the frequency domain (SD σ_f) around its central frequency f_0:

$$w(t, f_0) = A\ \exp\left(-t^2/2\sigma_t^2\right)\ \exp\ (2i\pi f_0 t)$$

with $\sigma_f = 1/2\pi\sigma_t$. Wavelets are normalized so that their total energy is 1, the normalization factor A being equal to:

$$\left(\sigma_t\sqrt{\pi}\right)^{-1/2}.$$

A wavelet family is characterized by a constant ratio (f_0/σ_f), which should be chosen in practice greater than ~5 (Grossman et al., 1989). The wavelet family we used is defined by $f_0/\sigma_f = 5$ (wavelet duration $2\sigma_t$ of about 1.6 periods of oscillatory activity at f_0), with f_0 ranging from 6 to 14 Hz in 1 Hz steps. At 8 Hz, this leads to a wavelet duration ($2\sigma_t$) of 199 ms and to a spectral bandwidth ($2\sigma_t$) of 3.2 Hz, and at 30 Hz to a duration of 40 ms and a bandwidth of 16 Hz. The time resolution of this method thus increases with frequency, whereas the frequency resolution decreases.

The time-varying energy $E(t, f_0)$ of the signal in a frequency band is the square norm of the result of the convolution of a complex wavelet $w(t, f_0)$ with the signal s(t):

$$E(t, f_0) = |w(t, f_0) \times s(t)|^2.$$

Convolution of the signal by a family of wavelets provides a TF representation of the signal. It generates a in each frequency band, leading to a TF representation of the signal. By averaging the TF energy of each single trial, both non-phase-locked activities and noise will be added up; only activities the amplitude of which is high enough compared with background EEG will emerge. Then we got the non-phase-locked components (TF energy averaged across single trials) with a high signal-to-noise ratio.

To illustrate the change of oscillatory activities linked to different stimulus conditions, we computed the event-related desynchronization and synchronization (ERD/ERS) of spectrum power for each stimulus condition using the following formula (Pfurtscheller and Aranibar, 1979):

$$\mathrm{ERD/ERS} = [(A - R)/R] \times 100\%.$$

The formula defined the ERD/ERS as a percentage decrease/increase of spectrum power density for specific event compared to a reference (the average power from 200 ms before the stimuli onset to the stimuli present).

To investigate oscillatory activities associated with identification of environmental risks, the power values associated with risky and safe items were compared directly without baseline subtraction, according to Kaiser et al. (2004), "effects may be detected only when conditions are compared directly, without baseline correction." Specifically, repeated measure ANOVAs were conducted on the power of each of the three frequency bands (theta: 5–7 Hz; lower alpha: 8–10 Hz; upper alpha: 11–13 Hz) with within-subject independent variables being Stimulus Valence (Risky Vs. Safe) and Hemisphere (Left Vs. Right Hemisphere) to examine the effects of Stimulus Valence and Hemisphere on the EEG power. To confirm the specificity of oscillatory activities associated with identification of environmental risks, we calculated repeated measure ANOVAs with Risk

(Environmental vs. Personal risks) and Stimulus Valence as within-subject independent variables. Correlation was calculated between the rating scores of risky events and the induced theta/alpha band power.

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