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**Emotion Depends on Context, Culture, and Their Interaction:  
Evidence from Effective Connectivity**

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### ABSTRACT

Situated models of emotion hypothesize that emotions are optimized for the context at hand, but most neuroimaging approaches ignore context. For the first time, we applied Granger causality (GC) analysis to determine how an emotion is affected by a person's cultural background and situation. Electroencephalographic (EEG) recordings were taken from mainland Chinese and US participants as they viewed and rated fearful and neutral images displaying either social or non-social contexts. Independent components analysis (ICA) and GC analysis was applied to determine the epoch of peak effect for each condition and to identify sources and sinks among brain regions of interest. We found that source-sink couplings differed across culture, situation, and culture x situation. Mainland Chinese participants alone showed preference for an early-onset source-sink pairing with the supramarginal gyrus as a causal source, suggesting that, relative to US participants, Chinese participants more strongly prioritized a scene's social aspects in their response to fearful scenes. Our findings suggest that the neural representation of fear indeed varies according to both culture, situation, and their interaction in ways that are consistent with norms instilled by cultural background.

*Keywords:* Effective connectivity, Granger causality, EEG, emotion, culture, context

43

**1. INTRODUCTION**

44 Emotion categories such as anger and fear are not monolithic entities but vary widely in their  
45 neural, physiological, and behavioral manifestations (Kreibig, 2010; Wilson-Mendenhall et al.,  
46 2011; Wormwood et al., 2019). This variation occurs by traits of the experiencer, such as gender  
47 (Fischer et al., 2004), personality (Lim et al., 2012), and cultural background (Kwon et al., 2013;  
48 Mesquita et al., 2016), as well as aspects of the emotion's context (Wilson-Mendenhall et al., 2011;  
49 Kreibig, 2010). Such variation is readily explained by psychological constructionist approaches to  
50 emotion, which argue that emotions emerge from situation-specific activity within a set of brain  
51 networks that are themselves involved in supporting basic psychological processes that are not  
52 specific to emotions (Barrett, 2014; Lindquist & Barrett, 2012). This contrasts with a basic emotion  
53 approach, wherein emotions are localized to specific brain regions or anatomically defined  
54 networks (e.g., Panksepp & Watt, 2011; Tracy & Randles, 2011). Past research has examined the  
55 neural basis of emotions (Lindquist & Barrett, 2012; Vytal & Hamann, 2010), the cultural  
56 influence on emotional behaviors, perceptions, and experiences (Kitayama et al., 2006; Markus &  
57 Kitayama, 1991), and the situated nature of emotion (Leshin et al., in revision; Wilson-Mendenhall  
58 et al., 2011). Yet situated emotion has received little examination on the level of effective  
59 connectivity.

60 The purpose of this study was to examine the effects of culture and context on fear by  
61 applying Granger causality (GC) analysis to electroencephalographic (EEG) measures of brain  
62 activity, obtained while participants viewed images evoking different emotions. Fear is one of the  
63 most well-studied emotion categories in both animal and human research (see Leshin & Lindquist,  
64 2020). Its neural correlates, although often associated with the amygdala (see Lindquist et al.,  
65 2012), encompass regions throughout the midbrain, basal ganglia, medial temporal lobe

66 (amygdala, hippocampus), ventral and dorsal anterior cingulate cortex, insula, lateral prefrontal  
67 cortex, medial prefrontal cortex, posterior cingulate cortex, lateral parietal cortex, sensorimotor  
68 cortex, and visual cortex (Lindquist et al., 2012; Vytal & Hamann, 2010). For the first time, the  
69 present work examines the extent to which the brain's effective connectivity may depend on the  
70 context of the fear experience, the cultural background of the experiencer, and their interaction.

### 71 **1.1 Hypothesis 1 (H1): Effect of Context in Emotion Processing**

72 Many models of emotion hypothesize that emotions are situated phenomena that prepare the  
73 organism to manage a given situation by conferring adaptive advantages (Barrett & Finlay, 2018;  
74 Roseman & Smith, 2001). Yet relatively few studies explicitly model the impact of the context on  
75 the neural basis of emotion. In this study, context was operationalized as the presence (social) or  
76 absence (non-social) of people in a scene. Social situations involve representing faces, body  
77 postures, and others' behaviors (Fiske & Taylor, 1991), whereas non-social situations involve  
78 representing spatiotemporal information and non-human animals. These situations might also  
79 invoke different behavioral affordances such as representation of the mental states of others versus  
80 motor actions. Indeed, when Wilson-Mendenhall and colleagues (2011) instructed participants  
81 undergoing fMRI to imagine and embody moments of either social threats (e.g., being censured)  
82 or non-social threats (e.g., a fire), scenarios involving social threats were associated with greater  
83 activation within the vmPFC, a region associated with representing the minds of others (Heberlein  
84 et al., 2008). In contrast, scenarios involving non-social threats were associated with greater  
85 activation within regions involving visuospatial representation and motor actions, such as the  
86 parahippocampal gyrus, superior temporal gyrus and mid-cingulate cortex. Similarly, Vieira and  
87 colleagues (2020) found preferential activation of the mPFC in the context of social threats (i.e.,  
88 facial portrayals of anger) versus non-social threats (i.e., portrayals of arachnids).

89 Consistent with Wilson-Mendenhall et al., (2011), we expected that (H1) the neural basis  
90 of fear would differ when experienced in a social versus non-social context—for instance, by  
91 showing greater effective connectivity amongst regions implicated in socially situated fear  
92 conditions (e.g., vmPFC) or activating regions involved in emotion perception of faces (e.g.,  
93 supramarginal gyrus or superior temporal gyrus; Bechara et al., 1995; Silani et al., 2013). In  
94 contrast, for non-social fear conditions, we predicted greater effective connectivity among regions  
95 involved in motor action and planning (e.g., supplementary motor area or mid-anterior cingulate;  
96 Paus, 2001).

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## 98 **1.2 Hypothesis 2 (H2): Effect of Culture on Emotion Processing**

99 Culture involves one's socioecological context as well as one's values, norms, icons, and lay  
100 theories (Gelfand et al., 2017; Markus & Kitayama, 1991). The impact of culture on emotion  
101 experience is well researched (Kitayama et al., 2006; Markus & Kitayama, 1991; Mesquita &  
102 Frijda, 1992; De Leersnyder et al., 2021). There is evidence that cultural norms may have evolved  
103 via socialization to facilitate the needs of different groups; geographic proximity, which suggests  
104 similar ancestors and/or historical contact, predicts a greater likelihood that two cultures possess  
105 more similar understanding of the meaning of emotion categories than more geographically distant  
106 cultures (Jackson et al., 2019). Similarly, migration history over millennia is associated with the  
107 intensity of affiliative emotions expression; cultures of a relatively heterogeneous migration  
108 history (e.g., the United States) are more likely to strongly and intensely express smiles compared  
109 to cultures of more homogeneous history (Rychlowska et al., 2015).

110 Such culturally instantiated norms serve to predict which emotions a person will experience  
111 in a given context, the features of that emotion, and how individuals are likely to regulate and

112 express their emotions. Regarding experience, emotion-based norms in Western societies  
113 champion the expression and accentuation of emotion, thus encouraging individuals to experience  
114 independent emotions (e.g., anger) and to experience their emotions intensely (De Leersnyder et  
115 al., 2021). In contrast, emotion-based norms of Eastern societies favor emotions that promote  
116 group harmony and collectivist values (e.g., shame) and that do not stand out from the group as  
117 overly intense (Boiger et al., 2020; De Leersnyder et al., 2021).

118 Cultures also vary regarding the features ascribed to an emotion. For instance, individuals  
119 from Belgium and Japan experience shame and anger as consisting of different appraisals and  
120 action tendencies (Boiger et al., 2020). Despite relatively less research on cross-cultural  
121 differences in the neural basis of emotion experience, studies on empathy (Cheon et al., 2013) and  
122 emotion perception (see Han & Ma, 2014) suggest that during the perception of the same social  
123 stimuli, East Asian participants are more likely to show increased activation in brain regions  
124 associated with the representation of others' minds, whereas Western participants are more likely  
125 to show activation in regions associated with the self and the experience and expression of intense  
126 emotions (Han & Ma, 2014). Our own recent fMRI findings reveal that participants from the US  
127 have greater activation in the dorsal anterior insula, a region associated with negativity (Lindquist  
128 et al., 2016) during negative emotions such as fear (Leshin et al., under revision).

129 Finally, cultures proscribe different emotion regulation goals. Individuals from Eastern  
130 societies show greater likelihood of regulating emotional experiences at the onset of perception  
131 since temperance in experience is valued in these cultures; Matsumoto et al. (2008) found that  
132 participants from more collectivist cultures tend to endorse emotion suppression more strongly  
133 than cultures prioritizing individualism. Neural correlates of such cultural variation have also been  
134 found (e.g., Hajcak & Nieuwenhuis, 2006; Moser et al., 2006, 2009, 2010). For instance, Asian

135 American and European American participants showed group differences in the parietal late  
136 positive potential during an emotion regulation task, suggesting culturally instantiated tendency  
137 for emotion down-regulation exclusive to Asian participants (Murata et al., 2013).

138 For this study, culture is operationalized by nationality, with participants having been born  
139 and lived in mainland China or the United States until at least 18 years of age. Consistent with  
140 earlier findings, we expected that (H2) the neural basis of fear would differ by culture, that Chinese  
141 participants would show greater activation and connectivity amongst regions involved in the  
142 representation of social others (e.g., superior temporal gyrus) or emotion regulation (e.g., DLPFC),  
143 while US participants would show greater activation and connectivity among regions involved in  
144 the representation of the self (e.g., vmPFC) or the expression of emotion (e.g., SMA).

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### 146 **1.3 Hypothesis 3 (H3): Context Interaction with Culture in Emotion Processing**

147 Finally, evidence suggests that individuals from collectivist societies are more likely to incorporate  
148 context into mental representations (Nisbett & Miyamoto, 2005), including emotions (Masuda et  
149 al., 2008). Chua et al. (2005a) found that Chinese participants were more likely to visually saccade  
150 to the background context of visual scenes, whereas American participants more quickly and more  
151 frequently fixated on the central image. Similarly, Taiwanese participants focus more on the  
152 emotions induced by the situation, whereas American participants focus more on the agency of the  
153 main character (Chua et al., 2005b). These findings and similar ones (Masuda et al., 2008; Nisbett  
154 & Miyamoto, 2005) are aligned with the collectivist-individualist distinction (Markus & Kitayama,  
155 1991), with individuals from collectivist cultures consistently giving greater priority to context  
156 compared to individualist cultures. We thus predicted that (H3) the neural basis of fear would  
157 differ according to culture, such that Chinese participants would show greater activation and

158 connectivity amongst regions involved in the representation of social others (e.g., superior  
159 temporal gyrus) or emotion regulation (e.g., dlPFC) in social contexts, whereas US participants  
160 would show greater activation and connectivity amongst regions involved in the representation of  
161 the self (e.g., vmPFC) or the expression of emotion (e.g., SMA) regardless of context.

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## 2. METHOD

### 2.1 Participants

165 Participants included 21 United States natives of European-American descent (12 females, mean  
166  $\pm$  SD:  $21.5 \pm 1.9$  years) and 19 Chinese natives who had lived in mainland China for at least 18  
167 years (13 females, mean  $\pm$  SD:  $23.1 \pm 2.8$  years) recruited from local colleges and communities.  
168 Among the Chinese participants, no significant gender difference was found for time living in  
169 China and the US. Both Chinese and US groups included only native or proficient English-  
170 speaking participants. Participants had no history of neurological disorder and normal or corrected-  
171 to-normal vision. All participants were right-handed, as measured by the Edinburgh inventory  
172 (Oldfield, 1971; Toga & Thompson, 2003). Participants gave informed consent before the  
173 experiment and received monetary compensation afterwards.

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### 2.2 Stimuli and Experimental Procedure

176 The study protocol was approved by the University's Institutional Review Board. The image set  
177 comprised 180 colored images (60 sad, 60 fear, 60 neutral), with images obtained from the  
178 International Affective Picture System (Lang et al., 1999), Open Affective Standardized Image Set  
179 (Kurdi et al., 2017) and Nencki Affective Picture System (Marchewka et al., 2014). To establish  
180 normed categorizations, participants ( $N = 444$ ; 54% female,  $M_{age} = 37.13$  years,  $SD = 11.48$ ) were



181 recruited on Amazon's Mechanical Turk to rate each image on the degree of valence, arousal, and  
182 emotion category. Despite differences in mean age between the norming group and the  
183 experiment's participants, the fear-neutral categorization is not expected to be influenced by age;  
184 across the adult age span, people tend to report the same intensity of negative affective states in  
185 daily life (Carstensen et al., 2000), and age-related differences in emotion appear to be a product  
186 of situation selection rather than age (Livingstone & Isaacowitz, 2019). Fear and neutral images  
187 differed significantly in ratings of valence ( $F = 169.51, p < 0.001$ ) and arousal ( $F = 494.42, p <$   
188  $0.001$ ). Images of a given category were rated as higher on that category than on other emotion  
189 categories. To reduce the number of comparisons, this study only examined data obtained for fear  
190 (versus neutral) images. No significant between-culture difference in ratings was found for these  
191 images.

192 Images appeared on a 17" computer monitor 60 cm in front of the participants. Figure 1  
193 depicts the sequence of stimuli. Participants were told to immerse themselves in the images as if  
194 they were experiencing the content of the images themselves. After a practice trial, they completed  
195 five runs of image sets, each run containing 36 randomly ordered images, including six instances  
196 of each combination of context (social and non-social) and emotion (fear, sad, neutral). The set of  
197 five runs took about 30 minutes and was followed by a nine-minute resting state task, in which  
198 participants were told to focus on the screen's fixation cross and keep their mind at rest.

199

200 FIGURE\_1

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### 202 **2.3 EEG Acquisition and Pre-processing**

203 Figure 2 summarizes the steps applied in pre-processing the EEG dataset and conducting a Granger  
204 causality analysis. EEG signals were recorded using an EEG cap (Electro-Cap International, Inc.)  
205 embedded with 62 active electrodes covering frontal, central, parietal and occipital areas, based on  
206 the modified 10–20 system of the International Federation (Sharbrough et al., 1991). Recordings  
207 were referenced to the left ear lobe and grounded to between AFz and Fpz. EEG signals were  
208 amplified with a g.USBamp amplifier (g.tec Medical Engineering). EEG signals were sampled at  
209 256 Hz and band-pass filtered between 0.01 and 75 Hz to take out unwanted frequency bands, and  
210 notch-filtered at 60 Hz to remove US electrical mains hum.

211 EEG data was pre-processed according to the steps in Figure 2a. First, EEG data were  
212 visually inspected to exclude trials that contained electrode drift noise and muscle movement-  
213 related noise. Then the EEG signal was decomposed into independent components (ICs) through  
214 independent component analysis (ICA), and ICs were visually inspected so that components  
215 resembling EOG activity were rejected from further analysis. Signal acquisition and processing  
216 were all conducted using the BCI2000 system (Schalk et al., 2004), MATLAB (The MathWorks,  
217 2004), and EEGLAB (Delorme et al., 2011).

218

### 219 **2.4 Effective Connectivity Analysis**

220 While the use of affective pictures is a commonplace but well-established method of inducing  
221 emotion (e.g., Lench et al., 2011), both GC and effective connectivity analysis are still relatively  
222 novel compared to traditional quantitative EEG methods such as ERD/ERS (e.g., Nam et al.,

223 2011), ERPs (e.g., Lee et al., 2017), and spectral power analysis (e.g., Roche et al., 2019).  
224 Although some studies have used GC to examine EEG patterns associated with the recognition of  
225 emotion (Chen et al., 2013; Keil et al., 2009), GC analysis has not to our knowledge been applied  
226 to examine individual differences in emotion, especially concerning culture and context. We see  
227 the latter to be an especially novel contribution of the presented work.

228 Granger causality (GC) is the causal statistical influence between two simultaneously  
229 measured time series datasets, in this case representing neural activity at specific regions of  
230 interest. It is a metric for effective connectivity, which, unlike structural and functional  
231 connectivity, is concerned with the *directed* causal influence between active brain regions. As a  
232 metric for effective connectivity, GC is regarded as an exploratory alternative to dynamic causal  
233 modeling (DCM) (Bressler & Seth, 2010; Roebroeck et al., 2011). Our implementation of GC  
234 analysis (Figure 2) was the same as that of Kim et al., (2017) and Kim et al., (2019). After artifact  
235 removal, source localization was completed in three steps: ICA, dipole fitting, and node selection  
236 (Figure 2b). Effective connectivity among the selected nodes was evaluated using the EEGLAB  
237 Source Information Flow Toolbox (SIFT; Delorme et al., 2011) Finally, for the epoch of peak  
238 power for each condition, graph theory metrics were obtained to identify nodes as Granger causal  
239 sources and sinks, which indicate effective connectivity from or to a given node, respectively. For  
240 details of this study's implementation of Granger causality analysis, see supplementary material.

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242 FIGURE\_2

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### 3. RESULTS

GC metrics for culture, context, and their interaction were obtained for fear-neutral contrast rather than making explicit comparisons of networks for fear and neutral emotion, similar to other EEG- and fMRI-based analyses of emotion (e.g., Diano et al., 2017; Fusar-Poli et al., 2009; Peelen et al., 2010). The purpose of the analysis was to examine categorical differences in overall patterns of connectivity (e.g., differences in source-sink couplings) rather than quantitative analysis comparing specific GC metrics. For this reason, further quantitative analyses (e.g., determining significant differences in connectivity strength between conditions) were not conducted following extraction of GC metrics (for a similar approach, see Coben & Mohammad-Rezazadeh, 2015). Still, connections themselves are determined statistically significant by ICA.

#### 3.1 Dipole fitting and epoch selection

Dipole fitting resulted in eight cortical regions of interest, listed in Table 1. All extracted brain sources were less than 10% residual variance (RV), a criterion for determining statistically significant brain sources.

EC analysis was based on alpha bands (8-13 Hz). Given the mean frequency band of the alpha power, the most significant time point for each condition was selected in the time-frequency grid map, which shows the Granger causality between brain nodes. At the most significant time point, the AR values of all brain sources were computed to determine the main brain source (highest AR value at that time point) and sink (lowest AR value). Additional graph metrics CF and CM were obtained for these time-specific source-sink pairings. A single pairing was obtained for each condition.

**267 3.2 EC Analysis of Context on Emotion (H1)**

268 Table 2 also shows main GC metrics for the social and non-social conditions (see Figure 3 for a  
269 visualization). The social condition showed a relatively earlier-onset (20 ms) pairing involving the  
270 SMG (source) and mACC (sink). The non-social condition showed a relatively later onset (240  
271 ms) involving the PMC/SMA (source) and dPCC (sink), as well as enhanced bidirectional flow  
272 between the SMG and sensory cortex.

**273 3.3 EC Analysis of Culture on Emotion (H2)**

274 Table 2 shows GC metrics for culture (see Figure 4 for a visualization). US participants showed a  
275 relatively later onset (130 ms) pairing involving the PMC/SMA (source) and dPCC (sink),  
276 accompanied by the primary sensory cortex as a major source of outflow to the angular gyrus and  
277 mACC. Chinese participants showed a relatively earlier onset (20 ms) pairing involving the SMG  
278 (source) and dPCC (sink). In contrast to US participants, Chinese participants show relatively less  
279 coupling with the sensory cortex and show the angular gyrus as a source rather than sink.

280 TABLE\_1

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282 TABLE\_2

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284 FIGURE\_3

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286 FIGURE\_4

### 287 **3.4 EC Analysis of Culture x Context Interaction on Emotion (H3)**

288 Table 3 shows the GC metrics for the four unique combinations of culture and context (see Figure  
289 5 for a visualization). For social images, both US and Chinese participants showed pairings with  
290 relatively later onset (380 and 460 ms, respectively) compared to the corresponding pairings for  
291 the non-social condition (130 and 210 ms, respectively). While the social condition showed the  
292 dPCC as a sink regardless of culture, GC source differed by culture, with US participants favoring  
293 the PMC/SMA and Chinese participants favoring the SMG. For non-social images, the GC source  
294 was the same for both cultures while sink differed by culture, with US participants favoring the  
295 dIPFC and Chinese participants favoring the dPCC.

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297 TABLE\_3

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299 FIGURE\_5

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## 4. DISCUSSION

### 301 **4.1 Effective connectivity during emotion is mediated by context**

302 Consistent with the notion that emotions are highly situated (Wilson-Mendenhall et al., 2011), we  
303 predicted that (H1) social and non-social images would elicit different connectivity patterns  
304 reflecting differences in situated fear. Indeed, the non-social condition showed a pairing of the  
305 PMC/SMA (source) and dPCC (sink), suggesting that non-social instances of fear preferentially  
306 evoked sensorimotor representations—a finding consistent with Wilson-Mendenhall and  
307 colleagues (2011). In contrast, the social condition showed an early latency pairing of the SMG  
308 and mACC, accompanied by outflow from the angular gyrus. While consistent with our prediction,  
309 this pairing is too early to plausibly reflect response to the image but may reflect anticipation of

310 upcoming social information and motor action. The SMG is involved in recognizing emotion in  
311 facial expressions (Adolphs et al., 1996), and the mACC is involved in many processes related to  
312 motor control (Lindquist et al., 2012). The angular gyrus is extensively involved in social  
313 cognition; it is commonly activated in theory of mind tasks that involve inferences regarding  
314 others' beliefs and goals (Schurz et al., 2017), and it is active in instances of action-outcome  
315 evaluation when observed actions are attributed to another person's agency as opposed one's own  
316 (Farrer & Frith, 2002). With regard to the latter, it has been suggested that the angular gyrus is  
317 more generally a supramodal area acting as a mediator between perception and interpretation (van  
318 Kemenade et al., 2017).

319

#### 320 **4.2 Effective connectivity during emotion is mediated by cultural background**

321 Consistent with known cultural differences in emotion (see De Leersnyder et al., 2021), we  
322 predicted (H2) cultural differences in effective connectivity patterns during fear. Indeed, we found  
323 that for US participants the PMC appeared as a source, accompanied by outflow from S1. Positive  
324 and negative images are known to affect motor cortex excitability (Hajcak et al., 2007), and the  
325 SMA is thought to receive projections from the mACC with the function of directing attention and  
326 motor response (Devinsky et al., 1995; Lindquist et al., 2012). This suggests that US participants  
327 were experiencing fear—whether social or non-social—as a state involving heightened sensory  
328 processing and motor preparation.

329 In contrast, Chinese participants showed a source-sink pairing involving the SMG with  
330 outflow from the angular gyrus. As discussed earlier, the angular gyrus is involved in social  
331 cognition (Schurz et al., 2017) and action-outcome awareness (van Kemenade et al., 2017). The  
332 SMG is more specifically associated with visual recognition of emotion in facial expressions



333 (Adolphs et al., 1996). Together, this suggests that Chinese participants might have been engaging  
334 in relatively more social processing, regardless of social v. non-social context. These findings are  
335 consistent with earlier findings that East Asian participants, relative to Western participants, show  
336 greater tendencies to construct emotional meaning based on others' emotional and mental states  
337 (e.g., Masuda et al., 2008). Interestingly, the SMG is also implicated in attenuating egocentricity  
338 bias (Silani et al., 2013), a finding consistent with this interpretation. Notably, the angular gyrus-  
339 SMG pairing was relatively earlier in latency than US participants' activation, and too early to  
340 reflect a response to the presented image. This may suggest that Chinese participants recruited  
341 regions known to support socio-emotional processing in an anticipatory manner, rather than in  
342 response to the given image. In addition, our findings suggest that Chinese participants showed  
343 less preference for the recruitment of sensorimotor regions in response to the images, relative to  
344 US participants.

345       It is further worth noting that these differences were found despite any potential for  
346 acculturation of Chinese participants to the US context. Our recruitment criteria ensured that  
347 Chinese participants had lived at least 18 years in mainland China. Given that the average age of  
348 Chinese participants was  $23.1 \pm 2.8$  years (SD), we do not expect that exposure to US culture  
349 superseded Chinese native's cultural background. However, previous work on emotional  
350 acculturation (De Leersnyder et al., 2011) suggests that this effect is worth examining in future  
351 studies, provided a sample with greater variation in acculturation time.

352

### 353 **4.3 The interaction of context and culture on effective connectivity during emotion**

354 Lastly, we expected (H3) a context x culture interaction involving cultural differences in source-  
355 sink pairing for social images. Indeed, while other combinations of culture and context consistently

356 showed the PMC/SMA as a causal source, the Chinese-social condition alone showed a marked  
357 lack of outflow from the PMC/SMA and instead showed both the angular gyrus and the SMG as  
358 a Granger causal sources. Similarly, while other interactions consistently showed the dPCC as  
359 causal sink, the US-non-social condition alone showed the dlPFC as a causal sink. This is  
360 consistent with our analysis of culture, in that it appears that Chinese participants have more  
361 strongly prioritized regions involved in social emotional processing (SMG, angular gyrus) relative  
362 to other regions involved in representation of sensory information and action planning (dlPFC,  
363 PMC, S1).

364 We also observed that the CH-social connectivity strength was the strongest among all  
365 combinations of culture and situation, although the CH-S and US-S connectivity magnitudes are  
366 comparable. Altogether, differences of source-sink pairing corroborate a view that, relative to US  
367 participants, Chinese participants prioritized social aspects of the scene when experiencing fear.

368

#### 369 **4.4 Implications**

370 Altogether, our results suggest that neural patterns of effective connectivity indeed reflect  
371 situational and cultural differences in instances of fear. This is consistent with an emphasis of  
372 context in social psychology (Asch, 1956; Latane & Darley, 1968), as well as emotion models  
373 wherein emotion is highly situated (Leersnyder et al., 2021; Gendron et al., 2020; Lindquist, 2013).  
374 This contrasts with theoretical approaches (e.g., Ekman & Cordaro, 2011; Izard, 2011) that treat  
375 emotions as having dedicated neural circuitry that activates in a consistent and specific manner  
376 across contexts (Kragel & LaBar, 2016; Saarimäki et al., 2016).

377 Apart from theoretical implications, these findings may also inform future research on  
378 brain-computer-interfaces (Nam et al., 2018) that seek to “read” the emotional experiences of users

379 and predict their behavior or studies that seek to find biomarkers of emotional disorders such as  
380 depression (Cai et al., 2020; Li et al., 2019). Modeling the situated nature of emotions may give  
381 technology greater purchase in these categorization efforts.

382

#### 383 **4.5 Limitations and Future Research**

384         Several limitations bear acknowledgement. First, EEG has relatively impoverished spatial  
385 resolution compared to fMRI or PET, perhaps accounting for why we failed to find a component  
386 representing the amygdala, for instance. However, it should be noted that other components—such  
387 as the mACC—are highly connected to the amygdala (Vogt et al., 1987) and are thought to  
388 subserve responses to salient stimuli (see Lindquist et al., 2012). Furthermore, other studies  
389 examining emotion have similarly found lack of heightened amygdala activity when contrasting  
390 fear with other emotions (Peelen et al., 2010; Winston et al., 2003), and meta-analyses of the fMRI  
391 and PET literature (bearing better spatial resolution than EEG) reveal that the amygdala is less  
392 reliably active in fearful experiences than in other emotional states (Lindquist et al., 2012) and in  
393 some cases is not necessary for fear response (Amsel et al., 2015; Ponnusamy et al., 2007).

394         Second, our manipulation of context and emotion category was restricted to fear in social  
395 and non-social situations, despite the wealth of emotion categories and means of characterizing a  
396 situation (e.g., imminence of threat, ability to escape; Harrison et al., 2015). However, consistent  
397 with previous findings on positive emotion (e.g., Iwata et al., 1995; Iwata & Buka, 2002), we  
398 predict that other emotion categories would show similar variation in culture and context, insofar  
399 as those emotion categories are affected by the instillment of cultural norms. Furthermore,  
400 considering proposed universal functions of fear in threat avoidance, fear might be an emotion  
401 category where cultural differences might be least likely. If true, the present study may be

402 underestimating the range of cultural differences in the neural basis of emotion. Nonetheless,  
403 future research may compare variation both within and between emotion categories.

404 Third, our study was not designed to discriminate among the host of measurable  
405 phenomena underlying a given instance of emotion, such as situation appraisal, accessing  
406 conceptual knowledge, accessing norms of emotion conceptualization, and the initiation of  
407 response in physiology and behavior (Barrett et al., 2007; De Leersnyder et al., 2021). Still,  
408 differences of source-sink pairings may speak to culture's influence on the variety of psychological  
409 processes occurring in an instance of emotion—for instance, suggesting differences in response  
410 (e.g., heightened sensorimotor processing during fear) and appraisal (e.g., heightened emphasis on  
411 social processing). Future research should investigate the extent to which these differences  
412 correlate with differences in appraisals, behavioral intentions, peripheral physiology, or eye  
413 tracking to further disambiguate their meanings.

414 A final limitation is the issue of sample size, which is not uncommon for studies of effective  
415 connectivity. Still, our sample ( $N = 21$  US and 19 Chinese) surpassed that required by a power  
416 analysis using G\*Power (Cohen's  $d = .5$ , power = 0.8; Faul et al., 2007). It is also worth noting  
417 that the sample size was greater than those of previous GC analyses: 10 participants in Protopapa  
418 et al. (2014), 20 in Kim et al. (2017), and 20 in Kim et al. (2019).

419

420

## 5. CONCLUSION

421 The purpose of this study was to determine the effect of context, culture, and their interaction in  
422 how emotional content is represented via effective connectivity amongst brain regions. In a task  
423 involving emotion induction from fearful and neutral images, we found context-, culture- and  
424 context by culture-driven differences in terms of Granger causality metrics. To our knowledge,

425 this is the first study that has applied GC to examine context, culture, and their interaction on the  
426 effective connectivity of brain networks during emotion. Our findings corroborate a constructionist  
427 account of emotion, wherein the experience of emotion is highly situated.

428

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437

#### 438 **Conflict of interest**

439 The authors have no conflicts of interest to declare.

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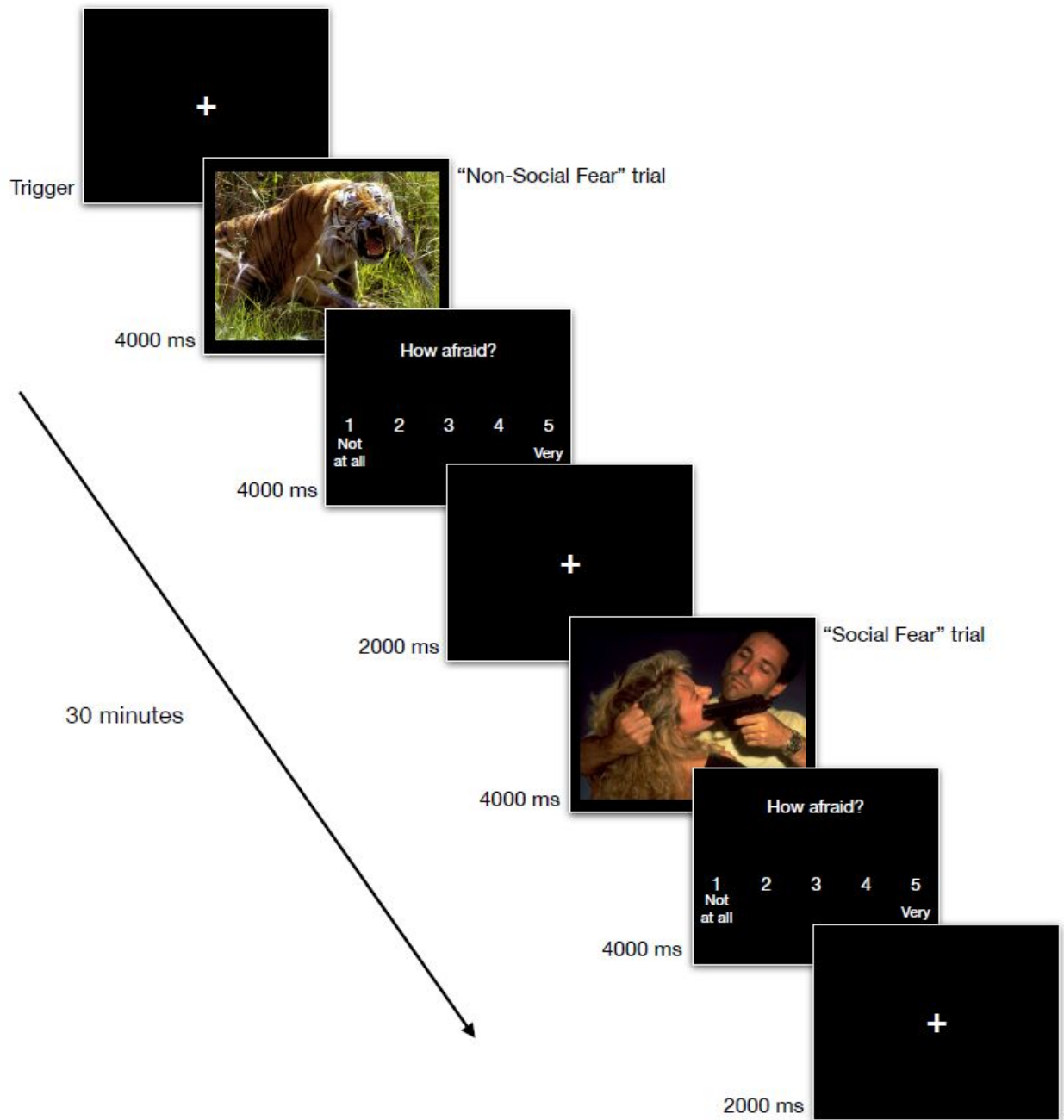
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- 701

702 **Figure legends**

703

704 **Figure 1.** Schematic of stimulus sequence and timing of the task. At the beginning of each trial,

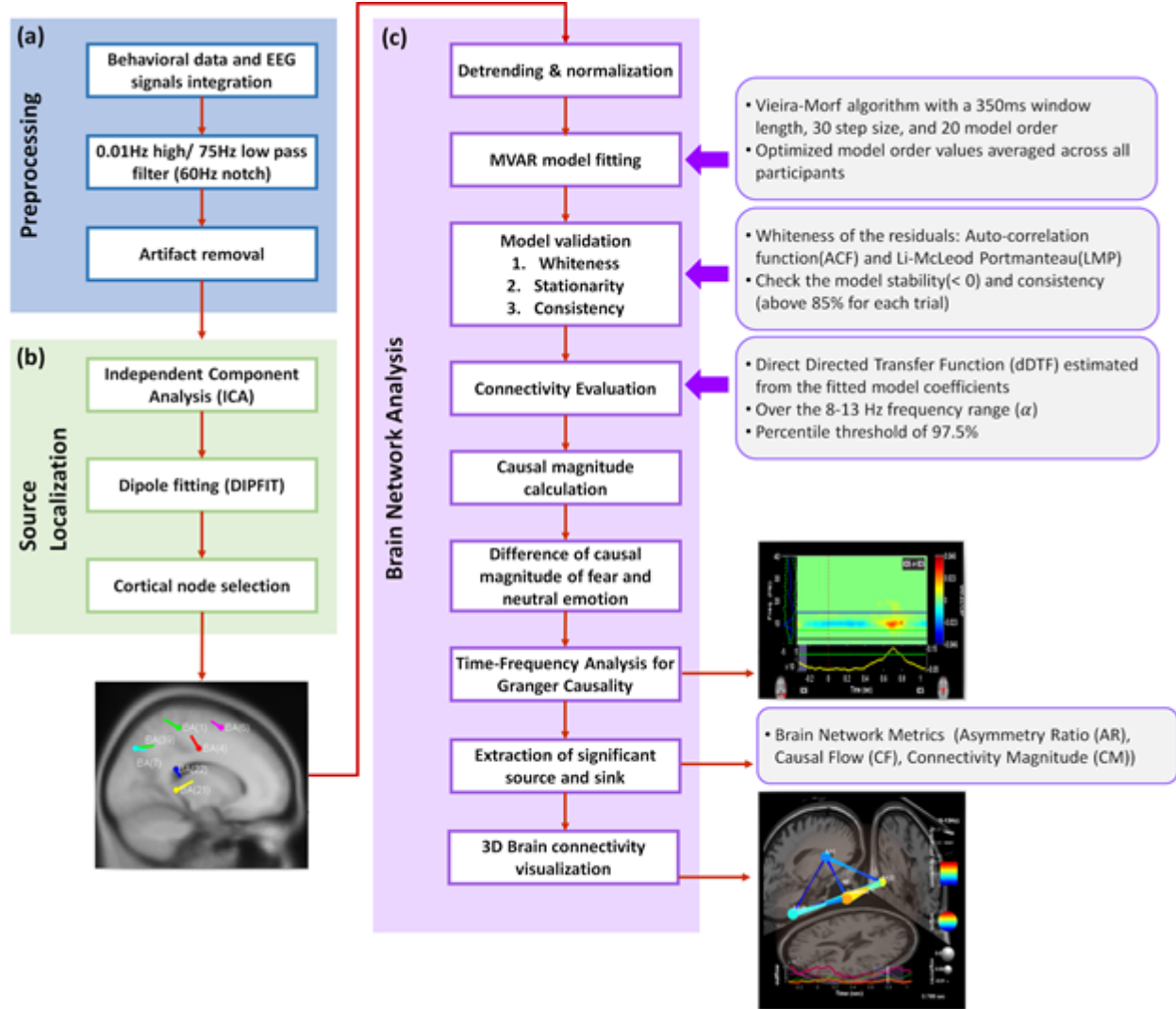
705 cross fixation was displayed for 2 seconds, followed by an affective picture for 4 seconds, and then

706 emotion rating scales were presented for 4 seconds. The total duration of each trial was 12 seconds

707 regardless of conditions.



708



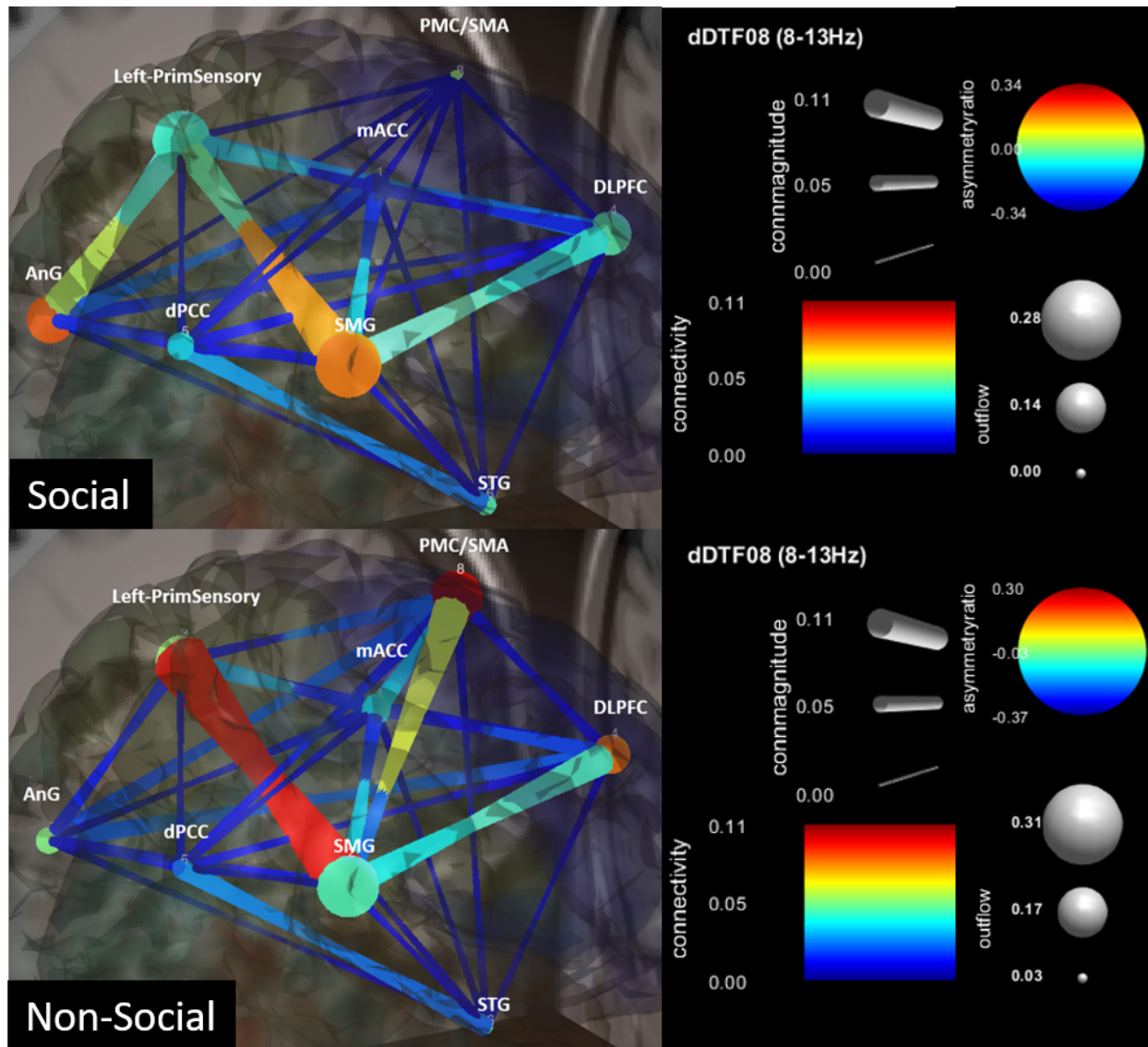
709

710 **Figure 2.** Connectivity analysis procedures. (a) Preprocessing, (b) Source Localization, (c) Brain

711 Network Analysis

712

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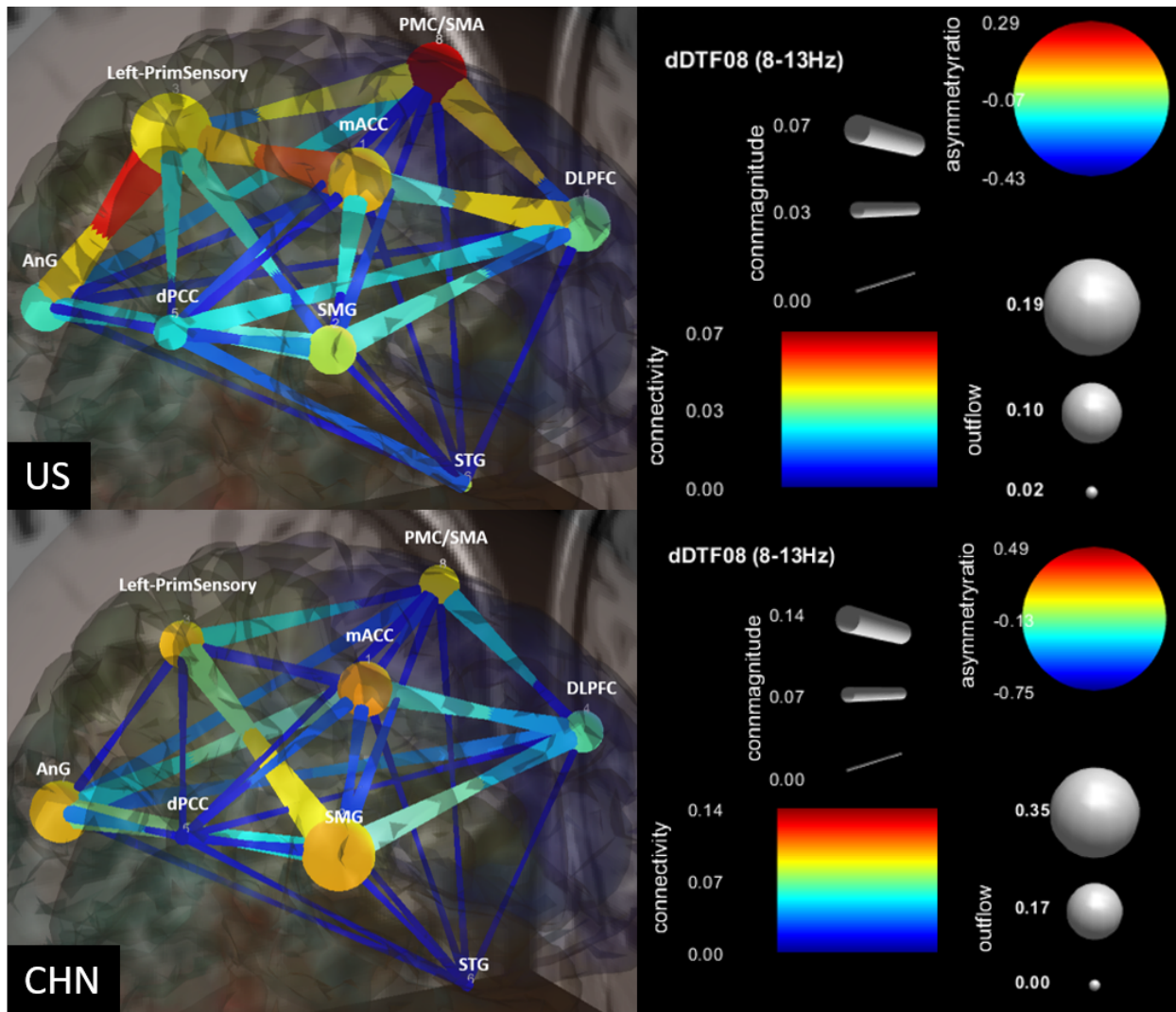


714

715 **Figure 3.** Effective connectivity of social and non-social conditions. For nodes, warmer colors  
 716 indicate causal sources, cooler colors indicate causal sinks, and larger diameters indicate greater  
 717 outflow from the node. For edges, warmer colors indicate greater connectivity strength and  
 718 larger diameters indicate greater connectivity magnitude.

719

720

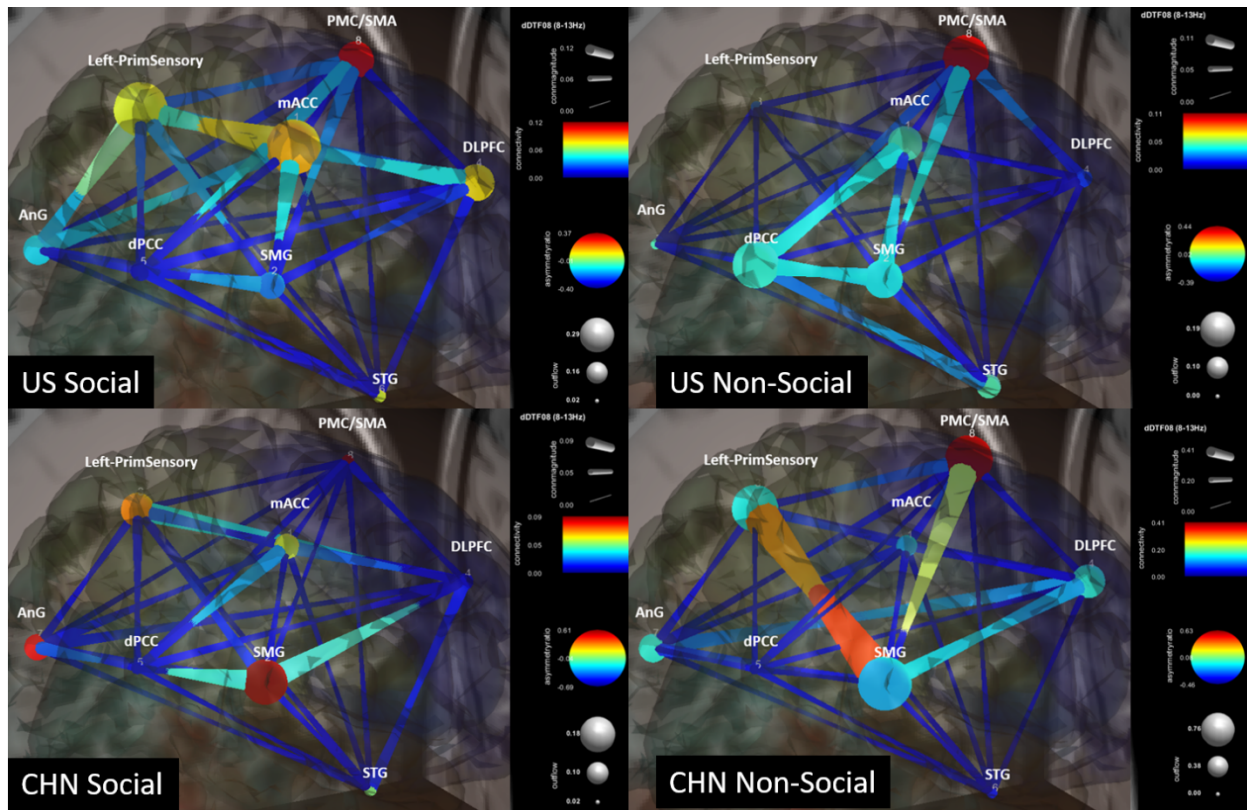


721

722 **Figure 4.** Effective connectivity of US and Chinese (CHN) participants. For nodes, warmer  
 723 colors indicate causal sources, cooler colors indicate causal sinks, and larger diameters indicate  
 724 greater outflow from the node. For edges, warmer colors indicate greater connectivity strength  
 725 and larger diameters indicate greater connectivity magnitude.

726

727



728

729 **Figure 5.** Effective connectivity of culture-context interaction. For nodes, warmer colors indicate

730 causal sources, cooler colors indicate causal sinks, and larger diameters indicate greater outflow

731 from the node. For edges, warmer colors indicate greater connectivity strength and larger

732 diameters indicate greater connectivity magnitude.

733

734 **Table 1**

735 The cortical regions associated with Brodmann's area (BA) localized during affective  
 736 processing.

Comp.	Talairach coord. (x, y, z)	Location	Lobe	Closest BA	RV (%)
1	-2, -3, 41	Mid-anterior cingulate cortex (mACC)	Limbic	24	3.81
2	35, -32, 19	Supramarginal gyrus (SMG)	Parietal	40	6.53
3	-42, -29, 45	Left-PrimSensory (1)	Parietal	1	4
4	13, 46, 24	Dorsolateral prefrontal cortex (DLPFC)	Frontal	9	2.9
5	17, -63, 25	Dorsal posterior cingulate cortex (dPCC)	Limbic	31	3.82
6	27, 5, -20	Superior temporal gyrus; temporal pole (STG/TP)	Temporal	38	4.8
7	-60, -53, 6	Angular gyrus (AnG)	Parietal	39	7.4
8	-21, 28, 52	Premotor cortex and supplementary motor area (PMC/SMA)	Frontal	6	4.76

737 *Note:* Comp refers to component number. BA = Brodmann area. RV = residual variance

738

739 **Table 2**740 *Granger causality metrics for peak epochs for univariate effects of culture and context*

Variable	Culture		Context	
	US	CHN	Social	Non-social
Epoch (ms)	130	20	20	240
Source	PMC/SMA (8)	SMG (2)	SMG (2)	PMC/SMA (8)
Source AR	0.2917	0.1183	0.1742	0.2974
Source CF	0.0577	0.0596	0.0544	0.0767
Sink	dPCC (5)	dPCC(5)	mACC (1)	dPCC (5)
Sink AR	-0.1653	-0.6828	-0.2816	-0.2227
Sink CF	-0.0268	-0.0916	-0.0475	-0.0207
Source-Sink CM	0.008	0.0222	0.0312	0.0151

741 *Note.* Epoch indicates the given condition's most significant time, following stimulus onset,  
742 according to the time-frequency grid map. CHN: China, AR = asymmetric ratio, CF = causal flow,  
743 CM = connectivity magnitude, PMC/SMA = primary motor cortex/supplementary motor area,  
744 SMG = supramarginal gyrus, dPCC = dorsal posterior cingulate cortex, mACC = mid-anterior  
745 cingulate cortex. Values beside regions correspond to components listed in Table 1.

746

747 **Table 3**748 *Granger causality metrics for peak epochs for culture-context interaction*

Variable	Social		Non-social	
	US	CHN	US	CHN
Epoch (ms)	380	460	130	210
Source	PMC/SMA (8)	SMG (2)	PMC/SMA (8)	PMC/SMA (8)
Source AR	0.2953	0.6074	0.3763	0.6267
Source CF	0.0611	0.0831	0.062	0.3513
Sink	dPCC (5)	dPCC (5)	dIPFC (4)	dPCC (5)
Sink AR	-0.3572	-0.6427	-0.2816	-0.4408
Sink CF	-0.0699	-0.0811	-0.0205	-0.0048
Source-Sink CM	0.0382	0.0391	0.0264	0.0031

749 *Note.* Epoch indicates the given condition's most significant time, following stimulus onset,  
750 according to the time-frequency grid map. CHN: China, AR = asymmetric ratio, CF = causal flow,  
751 CM = connectivity magnitude, PMC/SMA = primary motor cortex/supplementary motor area,  
752 SMG = supramarginal gyrus, dPCC = dorsal posterior cingulate cortex, dIPFC = dorsolateral  
753 prefrontal cortex, mACC = mid-anterior cingulate cortex. Values beside regions correspond to  
754 components listed in Table 1.

755

**756 Supplementary Material**

757 *MVAR Model Fitting:* To fit a multivariate autoregressive model (MVAR) to the ICs, a  
758 Vieira-Morf algorithm was applied with 500 ms window length, 30 step size, and 20 model order.  
759 Model order was optimized from 1 to 40, thereby minimizing the Hannan-Quinn model selection  
760 criterion for each participant. An average across all participants was obtained for the optimized  
761 model order. The model was then validated according to whiteness of the residuals (auto-  
762 correlation and Li-McLeod Portmanteau, or LMP), model stability, and consistency (>85% for  
763 each trial). In particular, the LMP test was selected for its conservativeness.

764 After validation, connectivity was evaluated using a direct Directed Transfer Function  
765 (dDTF; Korzeniewska et al., 2003), which measures directed information transfer between sources  
766 at each frequency for the duration of the trial. Causal magnitude of connections was calculated  
767 depending on each condition (Culture, Context, Culture x Context). The differences of the causal  
768 magnitudes of fear and neutral emotion were extracted depending on the conditions, followed by  
769 the GC time-frequency analysis, which allowed us to provide causal source/sink and generate a  
770 visualization of brain region connectivity.

771 *Time-Frequency Analysis for GC:* In the GC time-frequency analysis, we extracted the  
772 maximal activation time points within the averaged alpha frequency bands across all paired brain  
773 nodes. From the results of the time-frequency analysis, graph theoretic measures were used to  
774 determine the causal source and causal sink for each condition (Bollobás & Thomason, 1985;  
775 Mullen et al., 2011; Vecchio et al., 2016). Sources and sinks are nodes bearing the lowest and  
776 highest asymmetry ratios (AR), respectively. AR is:

$$777 \quad AR = \frac{Outflow - Inflow}{Inflow + Outflow}, -1 \leq AR \leq 1$$



778           Where inflow is the summed connectivity strengths of all incoming connections for a given  
779 node, and outflow is the sum of connectivity strengths of all outgoing connections for a given  
780 node. Outflow thus characterizes the causal influence of a node on the rest of the system, while  
781 inflow characterizes the causal influence *on* a given node by the rest of the system. AR values near  
782 1 indicate causal sources, values near -1 indicate sinks, and intermediate values indicate either a  
783 balanced flow or a flow that is nonsignificant (Mullen, 2010). For the sources and sinks, other  
784 graph metrics such as causal flow ( $CF = Outflow - Inflow$ ; Sridharan et al., 2008) and  
785 connectivity magnitude (CM, the absolute value of connectivity strength) were also determined  
786 for further analysis. Finally, dDTF was applied to the 8-13 Hz frequency range with a percentile  
787 threshold of 97.5% that would determine which connections to visualize.

788

789 **References to Supplementary Material**

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