Suppression of Sensorimotor Alpha Power Associated With Pain Expressed by an Avatar: A Preliminary EEG Study

Christian C. Joyal1,2*, Sarah-Michelle Neveu1, Tarik Boukhalfi1, Philip L. Jackson3 and Patrice Renaud1,4

1Laboratory of Virtual Reality Applications in Psychiatry (ARVIPL), Research Center, Philippe-Pinel Institute of Montreal, Montreal, QC, Canada, 2Cognition, Neuroscience, Affect and Behavior Research Group (CogNAC), Psychology Department, University of Quebec at Trois-Rivières, Trois-Rivières, QC, Canada, 3Psychology Department, University Mental Health Institute of Quebec (CRIUSMQ) and Laval University, Quebec, QC, Canada, 4Psychology Department, University of Quebec in Outaouais, Gatineau, QC, Canada

Several studies using functional magnetic resonance imaging (fMRI) showed that empathic capabilities are associated with the activation (and deactivation) of relatively specific neural circuits. A growing number of electroencephalography studies also suggest that it might be useful to assess empathy. The main goal of this study was to use quantitative electroencephalography (qEEG) to test whether observation of pain expressed by an avatar (virtual reality) induces a suppression of alpha waves over sensorimotor cortical areas, as it is observed with human stimuli. Not only was it the case, but also the magnitude of alpha suppression was correlated with perspective-taking capacity of participants. Both empathy levels and magnitude of sensorimotor alpha suppression (SAS) were significantly higher in women than men. Interestingly, a significant interaction emerged between levels of individual empathy and specificity of experimental instructions, where SAS in participants with good perspective-taking was higher during passive observation of the distressed avatar, while the opposite was true during an active (trying to understand) condition. These results suggest that: (1) synthetic characters are able to elicit SAS; (2) SAS is indeed associated with perspective-taking capacities; (3) Persons with poorer perspective-taking capacities can show significant SAS when proper instructions are provided. Therefore, qEEG represents a low-cost objective approach to measure perspective-taking abilities.

Keywords: empathy, assessment, electroencephalography, qEEG, perspective taking, alpha suppression, avatar

INTRODUCTION

Currently, in clinical settings, empathy is usually assessed through self-report questionnaires (i.e., the Interpersonal Reactivity Index, Davis, 1983), which are highly susceptible to bias due to false responses, social desirability, and other factors (e.g., Van de Mortel, 2008). Identifying a neurobiological correlate of empathy would make it possible to develop an objective assessment. Several experimental studies have demonstrated that functional magnetic resonance imaging (fMRI) allows the visualization and quantification of key cortical and subcortical brain activation...
associated with empathy (e.g., Jackson et al., 2005; see Bernhardt and Singer, 2012; for a review). fMRI, however, is costly and not accessible in most clinical or forensic settings. The main goal of the present study was to confirm the capacity of a low-cost, available, portable neuroimaging technique—quantitative electroencephalography (qEEG)—to evaluate empathy levels. EEG records local electric potentials generated by the cerebral cortex and qEEG mathematically breaks down the frequency spectrum of electrical waves. This approach allows measurement of regional (different cortical areas) power (or amplitude) of particular oscillatory bands with high precision for both frequency (e.g., 1-Hz gradient) and time (1-s gradient). Given that empathic traits and states are associated with regional cortical modulation, qEEG might be useful to evaluate an individual’s empathy levels.

One of the most exciting discoveries in neuroscience over the past half-century is that of mirror neurons, i.e., frontoparietal cortical cells that are activated (mirroring) in human and non-human primates during observation of a congener performing an act or behavior (Rizzolatti and Craighero, 2004). Mirror neuron responses activate the primary motor cortex (Hari et al., 1998; Muthukumaraswamy et al., 2004), forming a neural system that is hypothesized to promote prosocial behaviors through linking perception (seeing and understanding someone in distress) to action (providing assistance; Preston and de Waal, 2002; Pineda, 2005). Given that similar reactive activations are also observed in the somatosensory cortex (the other side of the central fissure) when a person observes painful stimuli or another person in pain (e.g., Avenanti et al., 2005; see Keysers and Gazzola, 2010; for a review), both primary motor and somatosensory cortices represent an important part of the cortical areas involved in the neural foundations of social interactions (Perry et al., 2011; Vanderwert et al., 2013) and empathy (Bernhardt and Singer, 2012).

qEEG is perfectly suited to measure sensorimotor cortical activation. First, sensorimotor cortex correspond to middle electrodes (T7-C3-Cz-C4-T8), which are less sensitive to eye blinks than anterior electrodes. Second, regional cortical asynchrony induces a power reduction in alpha wave frequencies (8–13 Hz), especially those surrounding 8–10 Hz (Pfurtscheller and Lopes da Silva, 1999; Goldman et al., 2002), which is easily measured with Fast Fourier Transformation (FFT) of the EEG signal. The sensorimotor alpha suppression (SAS) is thought to reflect a downstream cortical activation generated by the mirror neurons (Pineda, 2005). Interestingly, a growing number of qEEG studies suggest that empathic capacities are also associated with the magnitude of SAS (Cheng et al., 2008a; Yang et al., 2009; Perry et al., 2010; Woodruff et al., 2011; Moore et al., 2012; Hoenen et al., 2013, 2015; see also Babiloni et al., 2012; for more anterior regions of interest; Ono et al., 2009; for using the corollary enhancement of beta power in central locations).

Both qEEG source localization (Yang et al., 2009; Moore et al., 2012), and magnetoencephalography source modeling (Whitmarsh et al., 2011) have confirmed that SAS associated with empathic response is highest above the sensorimotor cortical cortex, more particularly on the posterior bank of the central sulcus (Cheng et al., 2008b). Interestingly, SAS may be significantly stronger in women than in men (Cheng et al., 2006, 2008a; Yang et al., 2009; see also Han et al., 2008; Schulte-Rüther et al., 2008), which would be compatible with the well-established fact that women, in general, possess higher empathy capacities and social sensitivity than men (e.g., Baron-Cohen et al., 2005; Toussaint and Webb, 2005). Gender difference in SAS is not systematically reported, however (Perry et al., 2011), and deserves further investigation.

SAS induced by a painful expression exhibited by another person is viewed as a gating mechanism that disinhibits sensory cortices, helping to understand the pain of others (Whitmarsh et al., 2011; Moore et al., 2012). Peng et al. (2015) suggest that central (or sensorimotor) alpha oscillatory modulation associated with pain perception is determined by sensori-discriminative, affective motivational and cognitive-modulative aspects of pain experience. Therefore, qEEG represents a promising, accessible, and affordable technique for evaluating empathy and its sub-components that avoids any self-report bias.

qEEG might also help enhance empathy through neurofeedback. Neurofeedback is an operant learning technique based on brain-computer interfaces. Although evidence-based data with qEEG neurofeedback generally concerns attention deficits and impulsivity (Arns et al., 2014), it has been used successfully to train other capacities, both for clinical (Simkin et al., 2014) and non-clinical (Grzuželj, 2014) purposes. Among these trainable capacities is empathy (Cavazza et al., 2014; Moll et al., 2014; Yao et al., 2016).

However, many questions need to be addressed before SAS can be used as a correlate of empathy, let alone a neurofeedback target. First, some studies (but not all, e.g., Perry et al., 2011; Woodruff et al., 2011; Hoenen et al., 2013) do not demonstrate its specificity as they fail to provide comparisons with alpha suppression that occurs simultaneously in other (non-central) cortical regions. The occipital cortices, most notably, should be considered because it is well known that alpha power is suppressed posteriorly by visual stimulation or increased attention load (Thut et al., 2006).

Second, the majority of existing studies elicited SAS through presentation of simple motor stimuli (e.g., observing or performing movements; Perry et al., 2011; Woodruff et al., 2011). Only a handful of qEEG investigations used presentation of stimuli related to empathy (e.g., signs of distress or pain), and these stimuli were typically limited to body parts, usually the hands (e.g., hands being pricked, cut, or crushed; Yang et al., 2009; Perry et al., 2010). One exception used video clips of human actors in painful (sad) situations (Hoenen et al., 2013), although the mode of expression was verbal (story telling), which is not well suited for neurofeedback training. Past studies also used brief stimulus presentations, commonly ranging from 1.7 s to 5 s for pictures (e.g., Yang et al., 2009; Perry et al., 2010; Moore et al., 2012; Hoenen et al., 2015), up to 80 s for video clips (Cheng et al., 2008a; Woodruff et al., 2011; Hoenen et al., 2013). It remains to be seen whether SAS can also be detected with longer (and noisier) stimulus presentations (e.g., 120 s), which is mandatory for neurofeedback training (Budzynski et al., 2009).

Third, although visual stimulation and virtual reality represent the best options for conducting neurofeedback studies,
very few EEG studies used virtual agents expressing pain to generate brain response associated with empathy (Cavazza et al., 2014). While it is known that avatars can elicit empathic responses in humans (e.g., Paiva et al., 2005; Cheetham et al., 2009; Joyal et al., 2014), their capacity to elicit SAS associated with empathy remains to be demonstrated (de Borst and de Gelder, 2015). This point is crucial to the eventual development of neurofeedback training, which could involve, for instance, presenting avatars expressing different types and intensities of emotions in response to brain wave characteristics of the participant.

Finally, empathy is a multifaceted construct and its sub-components should be considered separately in EEG studies. The four-factor model of empathy proposed by Davis (1983) is still the best validated model to date (Chrysikou and Thompson, 2016). According to that model, empathy encompasses four different capacities: (1) perspective taking, or the tendency to spontaneously adopt the psychological point of view of others; (2) cognitive fantasizing, or the tendency to transpose ourselves imaginatively into fictional situations; (3) empathic concern, or the tendency to have feelings of sympathy or compassion oriented toward others; and (4) personal distress, or the tendency to have self-oriented feelings of personal anxiety or fear in response to seeing others in distress (Davis, 1983; Chrysikou and Thompson, 2016). To be clinically relevant, a biological correlate of empathy should be sensitive to perspective taking, as a defect in this capacity is a classic predictor of low communication skills, antisocial behaviors, and interpersonal violence (Chandler, 1973). To date, two studies have reported that perspective-taking capacities have a modulating effect on SAS (Perry et al., 2010; Hoenen et al., 2013), and a third reported a specific and significant correlation between SAS and perspective-taking capacities, although the study was based on motor (moving fingers) stimuli (Woodruff et al., 2011). It remains to be seen if the same association would be observed within an empathic context, especially if the character presented is synthetic.

The main goal of this preliminary investigation was to assess the capacity of avatars to elicit empathy-related SAS, while considering extraneous factors such as non-central alpha suppression and presentation of equivalent stimuli not expressing pain. Another objective of this study was to measure the strength of association between SAS and individual levels of empathy and its sub-components. We attempted to confirm the superiority of women vs. men in empathy-related SAS.

Results

All participants were right-handed, and all were included in the analysis (3 right, 1 left, 12 dominant). The sample consisted equally of men and women (n = 12), all screened for histories of neurological or psychiatric conditions through phone pre-screening and an on-site questionnaire. Participants had to refrain from drinking alcohol for 24 h prior to testing, and from drinking coffee (or any beverage containing caffeine) and smoking tobacco for 12 h prior to testing.

The EEG cap was designed to record electrical cortical activity (Figure 1). Participants were seated in a CAVE-like, 4-wall immersive environment (iCube, Viz-Tek Inc.) wearing 3D active shutter glasses (EdgeVR, Volfoni, Inc.) and headphones fitted with the wireless Acticap (Figure 1). This EEG system was chosen because it is particularly robust against electromagnetic fields (active electrodes with a co-integrated amplifier and noise subtraction; Metting Van Rijn et al., 1996; Usakli, 2010).

A 2-min period of habituation was first allowed, in which participants could freely explore the content of a neutral animation presented in 3D. Because simple observation of movement is known to suppress central alpha wave (e.g., Muthukumaraswamy et al., 2004), experimental conditions involved a non-moving avatar, a moving avatar, and the same moving avatar expressing pain. Stereoscopic stimuli were presented for 2 min each and consisted of the four following items (see Boukhalfi et al., 2015 for technical details): (1) change of the environment background from black to lighter gray (baseline condition, eye-open, luminosity modification); (2) presentation of a whole-body, adult Caucasian male avatar, seated in front of the same gray background, dressed in black and gray, audibly and regularly breathing (neutral condition);

**Materials and Methods**

**Participants**

Based on effect sizes obtained in previous studies (e.g., Hoenen et al., 2013), 24 right-handed adults were recruited from the general population through online classified advertising to participate in this study (mean age: 26.7 ± 4.6, 20–40). The sample consisted equally of men and women (n = 12), all screened for histories of neurological or psychiatric conditions through phone pre-screening and an on-site questionnaire. Participants had to refrain from drinking alcohol for 24 h prior to testing, and from drinking coffee (or any beverage containing caffeine) and smoking tobacco for 12 h prior to testing.

**Questionnaires**

Levels of empathy were assessed individually with a validated French version (Gilet et al., 2013) of the International Reactivity Index (IRI), a self-report questionnaire that assesses four components of empathy: perspective taking (the tendency to spontaneously adopt the psychological point of view of others), fantasizing (the tendency to transpose ourselves imaginatively into fictional situations), empathic concern (having feelings of sympathy or compassion toward others), and personal distress (self-oriented feelings of personal anxiety or fear in response to seeing others in distress; Davis, 1983; Chrysikou and Thompson, 2016). In the French version, items are rated on a 7-point scale ranging from 1 (does not describe me well) to 7 (describes me very well), generating higher mean scores than the original 5-point scale (1983).

**Neurophysiological Material and Virtual Reality Environment**

A 32-electrode EEG cap (Acticap, extended 10–20 system, Brain Products, LLD) equipped with active wireless electrodes (ActiChamp amplifier paired with a MOVE system, Brain Products) was used to record electrical cortical activity (Figure 1). Participants were seated in a CAVE-like, 4-wall immersive environment (iCube, Viz-Tek Inc.) wearing 3D active shutter glasses (EdgeVR, Volfoni, Inc.) and headphones fitted with the wireless Acticap (Figure 1). This EEG system was chosen because it is particularly robust against electromagnetic fields (active electrodes with a co-integrated amplifier and noise subtraction; Metting Van Rijn et al., 1996; Usakli, 2010).

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(3) presentation of the same seated avatar with the same audible breathing but moving forward and backward with hands on knees (movement condition); and (4) presentation of the same seated and moving avatar expressing pain facially and orally (pain condition). Facial expressions of emotions by these stimuli had been previously validated with another non-clinical sample of participants (Joyal et al., 2014).

Participants were asked either to simply observe the virtual character as an external object, without trying to understand or feel his emotions (Observation) or to try to understand and feel the emotion expressed by the virtual character (Empathy). Stimuli were presented six times in total—two different instructions (observe or empathize) across four different conditions (baseline, neutral, movement and expressed pain)—with the order of presentation counterbalanced for instruction (observation or empathy) and conditions (Neutral → Movement → Pain, or Pain → Movement → Neutral). Each presentation was followed by a 2-min rest period.

Data Acquisition

This study is based on continuous qEEG signals recorded at bilateral sensorimotor (T7-C3-Cz-C2-T8) and occipital (O3-Oz-O2) sites (Recorder software, Brain Products). The more lateral T7 and T8 electrodes were added to the classical central electrodes (C3-Cz-C4) to include lateral parts of the sensorimotor cortex (Fabbri-Destro and Rizzolatti, 2008), usually overlooked by previous EEG studies. Data were referenced at FPz and re-referenced offline with bilateral mastoids to reduce eye-blink contamination. Electrical impedance was held below 25 kΩ, as required with active EEG electrodes. Data were sampled at 500 Hz and filtered with bandpass set at 0.01 Hz (high-pass) and 70 Hz (low-pass), and a notch filter for the 60 Hz frequency (North American electrical noise). Signals exceeding ±100 µV (muscle artifacts) were automatically rejected.

Data Analyses

Data processing followed the procedure of previous studies that used SAS to evaluate social cognition and empathy (Perry et al., 2011; Woodruff et al., 2011). First, both sensorimotor and occipital sites were recorded to make it possible to distinguish between alpha modulation generated by observation of expressed pain (sensorimotor) vs. alpha wave reaction to more general modifications of the visual environment (occipital) or attentional processes (widespread). Second, individual EEG outputs were inspected for artifacts by two independent raters (including a certified medical EEG technician) until a 100% inter-rater agreement was reached. At least 60 s of artifact-free EEG data was required (and obtained in all cases) to achieve minimal stability for spectral decomposition (qEEG). Third, records were divided into 1 s segments (minimum of 60 segments), and for each segment the integrated power in the 8–13 Hz range was computed using a Fast Fourier Transform (FFT) obtained at 1 Hz intervals with a Hanning window. Fourth, segments were averaged for each condition (baseline, neutral, movement and pain). Given that the absolute signal power is sensitive to individual differences (e.g., skull density, scalp thickness, baldness, electrode impedance), ratios were computed for each condition based on the baseline data (i.e., neutral/baseline; movement/baseline; pain/baseline). Finally, ratios were log transformed because they are not normally distributed (Pineda and Oberman, 2006). A negative log ratio under indicates a suppression of power compared to the baseline. Therefore, the
statistical significance, the simple observation of the avatar tended to induce greater SAS (all types of presentations still taken together), than trying to empathize with it (observe: $M = -0.219 \pm 0.23$ vs. empathize: $M = -0.166 \pm 0.22$; $F_{(1,47)} = 2.69, p = 0.10, r = 0.22$). No interaction was statistically significant.

Limiting the analyses to the pain condition revealed that the magnitude of SAS in both men ($M = -0.377 \pm 0.23$) and women ($M = -0.404 \pm 0.24$) with high empathy levels was significantly higher than that for both men ($M = -0.206 \pm 0.18$) and women ($M = -0.212 \pm 0.21$) with low empathy levels ($F_{(1,23)} = 4.34, p = 0.05, r = 0.42$). However, the interaction between the instruction condition (simply observing distress vs. attempting to empathize with the distressed avatar) and the level of empathy (low vs. high) approached significance ($F_{(1,47)} = 2.96, p = 0.09, r = 0.27$), indicating that simple observation tended to be sufficient to elicit significant central alpha suppression in persons with high levels of empathy, whereas attempting empathize with the avatar was necessary (and successful) to elicit alpha suppression in persons with low levels of empathy.

Finally, bivariate two-way Pearson correlations showed that the magnitude of SAS provoked by the distressed avatar was associated (nearly significant) with the perspective-taking capacities of the participants under the observing ($r = 0.398, p = 0.054$) but not the empathizing conditions. No other correlations approached significance.

### DISCUSSION

The main goal of this study was to determine whether an avatar expressing pain can induce a significant SAS in humans. In accord with fMRI investigations (e.g., Gobbini et al., 2011), this study found that a synthetic agent can activate brain regions associated with empathy. It was found that SAS was evoked by observation of an avatar expressing pain and was significantly stronger than that evoked by the same avatar executing the same movement without expressing pain. Therefore, SAS was not simply due to viewing movements (e.g., Muthukumaraswamy et al., 2004). In addition, SAS did not simply reflect a posterior (occipital) alpha modulation associated with attentional processing (e.g., Thut et al., 2006), because the latter was entered as a co-variable in the analyses. These results represent a partial answer to the questions raised by de Borst and de Gelder (2015), who correctly wondered if using avatars for the neurobiological assessment of empathy is appropriate.

Another goal of this study was to confirm that SAS is associated with individual trait empathy or its sub-components. In accordance with Woodruff et al. (2011), it was found that the magnitude of SAS evoked by the observation of pain correlated with perspective-taking capacities, but not with the three other components. Therefore, the usefulness of SAS to assess empathy seems to concern perspective-taking capacities in particular.

As expected (Cheng et al., 2006, 2008a; Yang et al., 2009), a higher magnitude of SAS was found in women, on average, than
in men. Also in accord with previous investigation (Moore et al., 2012), instructing participants to simply observe vs. to attempt to understand what the avatar was feeling had no effect, on average, on the magnitude of SAS. Interestingly, however, participants with higher empathy only needed to observe the distressed avatar to show significant SAS, whereas participants with lower empathy capacities needed to consciously try to understand the feelings of the avatar to show a significant SAS. These results suggest not only the presence of an automatic brain mechanism in empathic persons but also that the mechanism can be elicited through conscious effort. This possibility should be tested with clinical populations that lack empathy.

This study should not serve as a blueprint for neurofeedback paradigms, however. Although empathy-related SAS was higher, on average, at T7, it was not necessarily the case for all participants. As shown in the results, standard deviations (inter-individual variation) were elevated (much more than variations of empathy levels). Therefore, neurofeedback paradigms aiming at modulating empathy-related SAS will have to target cortical sites determined individually, as they might differ from one person to another.

In conclusion, this study confirms suggestions that qEEG and sensorimotor alpha waves can serve to assess empathy (Yang et al., 2009; Perry et al., 2010; Woodruff et al., 2011; Hoenen et al., 2013), and, more specifically, perspective-taking and sensorimotor alpha waves can serve to assess empathy at modulating empathy-related SAS will have to target cortical sites determined individually, as they might differ from one person to another.

In conclusion, this study confirms suggestions that qEEG and sensorimotor alpha waves can serve to assess empathy (Yang et al., 2009; Perry et al., 2010; Woodruff et al., 2011; Hoenen et al., 2013), and, more specifically, perspective-taking capacities. The effectiveness of using avatars to evaluate and, eventually, to train cerebral response associated with empathy was also demonstrated. The search for a single brain site to use in such training proved to be futile, however, as inter-subject variability was too high. While evaluative qEEG studies for empathy can make use of the average signals of all central electrodes, future neurofeedback protocols will have to determine individually which region is most effective for each participant. Finally, the usefulness of the present results should be confirmed in future qEEG studies that use participants with known empathy deficits recruited from clinical and forensic settings.

**AUTHOR CONTRIBUTIONS**

CJ initiated and contributed to experimental design, conducted the literature review, analyzed and interpreted the data and wrote the manuscript. S-MN collected the data and contributed to experimental design and data interpretation. TB created the stimuli, programed the presentation scripts and coordinated the multiplatform interface. PJ contributed to experimental design, data interpretation and revision of the manuscript. PR initiated and contributed to experimental design, revision of the manuscript and data interpretation.

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**REFERENCES**

Arns, M., Heinrich, H., and Strehl, U. (2014). Evaluation of neurofeedback in ADHD: the long and winding road. *Biol. Psychol.* 95, 108–115. doi: 10.1016/j.biopsycho.2013.11.013

Avenanti, A., Bueti, D., Galati, G., and Aglioti, S. M. (2005). Transcranial magnetic stimulation highlights the sensorimotor side of empathy for pain. *Nat. Neurosci.* 8, 955–960. doi: 10.1038/nn1481

Babiloni, C., BUFFO, P., Vecchio, F., Marzano, N., Del Percio, C., Spada, D., et al. (2012). Brains “in concert”: frontal oscillatory α rhythms and empathy in professional musicians. *Neuroimage* 60, 105–116. doi: 10.1016/j.neuroimage.2011.12.008

Baron-Cohen, S., Knickmeyer, R. C., and Belmonte, M. K. (2005). Sex differences in the brain: implications for explaining autism. *Science* 310, 819–823. doi: 10.1126/science.1115455

Bernhardt, B. C., and Singer, T. (2012). The neural basis of empathy. *Annu. Rev. Neurosci.* 35, 1–23. doi: 10.1146/annurev-neuro-062111-150536

Boukhalfi, T., Joyal, C., Bouchard, S., Neveu, S. M., and Renaud, P. (2015). Tools and techniques for real-time data acquisition and analysis in brain computer interface studies using qEEG and eye tracking in virtual reality environment. IFAC-PapersOnLine 48, 46–51. doi: 10.1016/j.ifacol.2015.06.056

Budzynski, T. H., Budzynski, H. K., Evans, J. R., and Abarbanel, A. (Eds.) (2009). *Introduction to Quantitative EEG and Neurofeedback: Advanced Theory and Applications*. 2nd Edn. New York, NY: Academic Press.

Cavazza, M., Aranyi, G., Charles, F., Porteous, J., Gilroy, S., Klovatich, I., et al. (2014). “Towards empathic neurofeedback for interactive storytelling.” in 2014 Workshop on Computational Models of Narrative OpenAccess Series in Informatics (OASiS), 5th Edn. (Vol. 41) eds M. A. Finlayson, J. C. Meister and E. G. Bruneau (Dagstuhl, Germany: Schloss Dagstuhl-Leibniz-Zentrum fuer Informatik), 42–60.

Chandler, M. J. (1973). Egocentrism and antisocial behavior: the assessment and training of social perspective-taking skills. *Dev. Psychol.* 9, 326–332. doi: 10.1037/h0034974

Cheetham, M., Pedroni, A., Antley, A., Slater, M., and Jäncke, L. (2009). Virtual milgram: empathic concern or personal distress? Evidence from functional MRI and dispositional measures. *Front. Hum. Neurosci.* 3:29. doi: 10.3389/neuro.09.029.2009

Cheng, Y.-W., Lee, P. L., Yang, C. Y., Lin, C. P., Hung, D., and Decety, J. (2008a). Gender differences in the mu rhythm of the human mirror-neuron system. *PLoS One* 3:e2113. doi: 10.1371/journal.pone.0002113

Cheng, Y.-W., Yang, C. Y., Lin, C. P., Lee, P. L., and Decety, J. (2008b). The perception of pain in others suppresses somatosensory oscillations: a magnetoencephalography study. *Neuroimage* 40, 1833–1840. doi: 10.1016/j.neuroimage.2008.01.064

Cheng, Y.-W., Tzeng, O. J., Decety, J., Imada, T., and Hsieh, J. C. (2006). Gender differences in the human mirror system: a magnetoencephalography study. *Neuroreport* 17, 1115–1119. doi: 10.1097/01.wnr.0000223393.59328.21

Chrysalou, E. G., and Thompson, W. J. (2016). Assessing cognitive and affective empathy through the interpersonal reactivity index: an argument against a two-factor model. *Assessment* 23, 769–777. doi: 10.1177/1073191115599055

Cochin, S., Barthelemy, C., Lejeune, B., Roux, S., and Martineau, J. (1998). Perception of motion and qEEG activity in human adults. *Electroencephalogr. Clin. Neurophysiol.* 107, 287–295. doi: 10.1016/s0013-4694(98)00071-6

Cochin, S., Barthelemy, C., Roux, S., and Martineau, J. (1999). Observation and execution of movement: similarities demonstrated by quantified electroencephalography. *Eur. J. Neurosci.* 11, 1839–1842. doi: 10.1046/j.1460-9586.1999.00598.x

Davis, M. H. (1983). Measuring individual differences in empathy: evidence for a multidimensional approach. *J. Pers. Soc. Psychol.* 44, 113–126. doi: 10.1037/0022-3514.44.1.113
de Borst, A. W., and de Gelder, B. (2015). Is it the real deal? Perception of virtual characters versus humans: an affective cognitive neuroscience perspective. Front. Psychol. 6:376. doi: 10.3389/fpsyg.2015.00376

Fabbri-Destro, M., and Rizzolatti, G. (2008). Mirror neurons and mirror systems in monkeys and humans. Physiology 23, 171–179. doi: 10.1152/physiol.00044.2008

Gilet, A. L., Mella, N., Studer, J., Grünh, D., and Labouve-Vief, G. (2013). Assessing dispositional empathy in adults: a french validation of the interpersonal reactivity index (IRI). Can. J. Behav. Sci. 45, 42–48. doi: 10.1037/a0030425

Gobbini, M. I., Gentili, C., Ricciardi, E., Bellucci, C., Salvini, P., Laschi, C., et al. (2011). Distinct neural systems involved in agency and animacy detection. J. Cogn. Neurosci. 23, 1911–1920. doi: 10.1162/jocn.2011.21574

Goldman, R. I., Stern, J. M., Engel, J. Jr., and Cohen, M. S. (2002). Simultaneous EEG and EMG of the α rhythm. Neuroreport 13, 2487–2492. doi: 10.1097/01.wnr.0000047685.05940.80

Gruzelier, J. H. (2014). EEG-neurofeedback for optimising performance. I: a review of cognitive and affective outcome in healthy participants. Neurosci. Biobehav. Rev. 44, 124–141. doi: 10.1016/j.neubiorev.2013.09.015

Han, S., Fan, Y., and Mao, L. (2008). Gender difference in empathy for pain: an electrophysiological investigation. Brain Res. 1196, 85–93. doi: 10.1016/j.brainres.2007.12.062

Hari, R., Forss, N., Arvikainen, S., Kirveskari, E., Salenius, S., and Rizzolatti, G. (1998). Activation of human primary motor cortex during action observation: a neuromagnetic study. Proc. Natl. Acad. Sci. U S A 95, 15061–15065. doi: 10.1073/pnas.95.25.15061

Hoenen, M., Lübbe, K. T., and Pause, B. M. (2015). Somatosensory μ activity reflects imagined pain intensity of others. Psychophysiology 52, 1551–1558. doi: 10.1111/psyp.12522

Hoenen, M., Schain, C., and Pause, B. M. (2013). Down-modulation of μ-activity through empathic top-down processes. Soc. Neurosci. 8, 515–524. doi: 10.1080/17470919.2013.833550

Jackson, P. L., Meltzoff, A. N., and Decety, J. (2005). How do we perceive the pain of those who are different from us: modulation of EEG in the μ/α range. Cogn. Affect. Behav. Neurosci. 10, 493–504. doi: 10.3758/CABN.10.4.493

Perry, A., Stein, L., and Bentin, S. (2011). Motor and attentional mechanisms involved in social interaction—evidence from mu and a EEG suppression. Neuroimage 58, 895–904. doi: 10.1016/j.neuroimage.2011.06.060

Schulthe-Rüther, M., Markowitsch, H. J., Shah, N. J., Fink, G. R., and Piecke, M. (2008). Gender differences in brain networks supporting empathy. Neuroimage 42, 393–403. doi: 10.1016/j.neuroimage.2008.04.180

Usakli, A. B. (2010). Improvement of EEG signal acquisition: an electrical aspect and filtering. Appl. Artif. Intell. 8, 515–524.

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