Clarifying the Relationship Between Trait Empathy and Action-Based Resonance indexed by EEG mu-rhythm suppression

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Abstract

Sensorimotor resonance, the vicarious activation of the sensory motor system during observation of another's actions, is thought to contribute to important social functions including empathy. Previous research has shown that sensorimotor resonance, as measured by suppression of the electrophysiological (EEG) mu rhythm, is predicted by trait empathy, but findings are inconsistent. Here we report data from a high-powered study (*N*=252) to clarify the relationship between sensorimotor resonance as indexed by mu suppression during action observation and trait empathy as measured by the well-established Interpersonal Reactivity Index (IRI). Our initial pre-registered analyses at central electrode locations indicate that sensorimotor resonance is unrelated to general trait empathy or its sub-facets, however, these effects could not be isolated from attention-related occipital alpha. An additional non-registered analysis using Independent Component Analysis (ICA) to look at the isolated central mu-component clarified the relationship. Results confirmed the lack of a relationship between the mu-component and the perspective taking, personal distress, or fantasy facets of the IRI, but suggest a possible association with empathic concern such that greater resonance is associated with greater empathic concern. These results question the previously assumed relationship between trait empathy and sensorimotor resonance and highlight the need to investigate experience sharing tendencies in the context of simulation-based resonance.

Keywords: Trait Empathy, Neural Resonance, Mu suppression, EEG

Introduction

People say that in order to gain a true understanding of another, one must attempt to see the world through their eyes, suggesting that empathy relies on using one's own references and body to simulate the experiences of the other. Neuroscience supports these folk psychology notions of how we understand each other; the mere perception of other's actions (Oberman, Ramachandran, & Pineda, 2008), facial expressions (Carr, Iacoboni, Dubeau, Mazziotta, & Lenzi, 2003), or pain (Singer et al., 2004) and the actual experience of these states produce similar patterns of neural activity. A number of studies suggest neural resonance to be a mechanism underlying empathy (e.g. Carr, Iacoboni, Dubeau, Mazziotta, & Lenzi, 2003; de Waal & Preston, 2017; Iacoboni, 2009), as it predicts performance in tasks that require empathy (Pineda & Hecht, 2009), leads to greater subjective experience of empathy (Claus Lamm, Decety, & Singer, 2011), and seems to facilitate pro-social behavior (Endedijk, Meyer, Bekkering, Cillessen, & Hunnius, 2017). A frequently used index of neural resonance in the somatosensory motor system is suppression of the electrophysiological (EEG) mu rhythm. Various studies associate mu suppression with trait empathy (Cheng, Lee, et al., 2008; Woodruff & Klein, 2013; Woodruff, Martin, & Bilyk, 2011), but findings are contradictory and based on studies with relatively small sample sizes. In the present study, we report findings from a large combined dataset of mu suppression studies run in our laboratory to elucidate the relationship between sensorimotor resonance as indexed by mu suppression and different facets of trait empathy.

Neural Correlates of Empathy

The interaction of distinct neural networks gives rise to the integrated and complex experience of empathy (Lamm, Bukowski, Silani, & Bukowski, 2015; Zaki, 2014). The simulation network comprised of the anterior insula and middle anterior cingulate cortex is primarily implicated in experience sharing, the embodied simulation of other people's experiences including actions, somatosensory experiences, pain, and affective states (Lamm et al., 2015; Zaki, 2014). Simulation theory and the perception action model of empathy (Preston & de Waal, 2002) theorize that action based resonance in particular is an important underlying mechanism to experience sharing - the automatic activation of neural representations when viewing the actions and emotions of others results in autonomic and somatic responses in the individual that correspond to the exact state of the individual that is being observed (Decety & Jackson, 2004; Gallese, 2003; Preston & de Waal, 2002; Silk, 2012). These theoretical accounts are supported by empirical evidence showing that the motor system can be regarded as the foundation for higher order social processes, such as imitation, perspective taking, and emotional sensitivity and recognition (Adolphs, Damasio, Tranel, Cooper, & Damasio, 2000; Buccino et al., 2004; Clark, Tremblay, & Ste-Marie, 2004; Decety & Chaminade, 2003; Hoenen, Lübke, & Pause, 2017; Keysers et al., 2004; Kaplan & Iacoboni, 2006; Claus Lamm, Batson, & Decety, 2007; Ruby & Decety, 2004; Saarela et al., 2007; Van Baaren, Holland, Kawakami, & Van Knippenberg, 2004; see Blakemore & Decety, 2001 for a review).

The mentalizing network—comprised of the temporoparietal junction (TPJ), temporal poles, medial prefrontal cortex, and precuneus (Bzdok et al., 2012; Saxe & Kanwisher, 2003)—is primarily implicated in perspective taking or cognitive empathy, the ability to draw explicit inferences about another's mental and emotional states (Baker, Saxe & Tannenbaum, 2009; Frith & Rith, 2012). Both simulation and mentalizing, although neurologically and behaviorally discernable, predict similar empathic outcomes such as accurate inferences about others' inner states (Zaki, Weber, Bolger, & Ochsner, 2009) and motivations to help (Batson, 1991, 2011;

Cialdini et al., 1987; Eisenberg & Miller, 1987). When it comes to experience sharing, however, the exact nature of such empathic outcomes depends on top-down regulatory processes that regulate the shared experience and foster self-other distinction, the ability to keep self and other perspectives separate (Decety & Meyer, 2008; Eisenberg, 2000; Goldman, 2013; Hoffman, 1975; Jackson, Rainville, & Decety, 2006). Proper emotion regulation and self-other distinction facilitate empathic concern, also referred to as compassion or sympathy, while insufficient regulation and distinction lead to personal distress, a strong aversive and egocentric affective response (Eisenberg, Valiente, & Champion, 2004). Personal distress is often accompanied by heightened physiological arousal (Eisenberg & Eggum, 2009; Eisenberg & Okun, 1996; Eisenberg et al., 2004; Spinrad et al., 2006) and the desire to withdraw from the situation for self-protection, thereby hampering the motivation and ability to help (Batson & Shaw, 1991; Singer & Klimecki, 2014).

Trait empathy measures

The most widely used measure of trait empathy and its sub-components is the Interpersonal Reactivity Index (IRI; Davis, 1983), a self-report measure that assesses perspective taking, empathic concern, and personal distress, in addition to the facet of fantasy, the tendency to identify with fictional characters and their experiences. Although it is important to consider the limitation of self-report measures, the IRI has been linked to performance based measures of empathic accuracy (Brook & Kosson, 2013; Gleason, Jensen-Campbell, & Ickes, 2009; Laurent & Hodges, 2009; Mackes et al., 2018). Scores on the sub-scales of the IRI have been linked to structural differences in neural gray matter (Banissy, Kanai, Walsh, & Rees, 2012) and activation in distinct neural regions associated with empathic processing - specifically, perspective taking has been associated with activation in traditional mentalizing areas (Moriguchi et al., 2006), while personal distress has been associated with activity in regions involved in experience sharing (Cheetham, 2009; Cheng, Lee, et al., 2008; Hadjikhani et al., 2014).

Although there is a connection between the personal distress facet and activation of experience sharing areas of the brain (Cheetham, 2009; Cheng, Lee, et al., 2008; Hadjikhani et al., 2014), the IRI arguably lacks a sub-scale that measures experience sharing of both affect and behavior (Jordan, Jordan, Amir, & Bloom, 2017), such as the sharing of specific emotional states or the extent to which an individual might mimic the behavior of those around them. Based on the simulation theory of empathy, subscales of this nature would specifically tap into the role of sensorimotor resonance as a mechanism for creating shared representations of other's experiences and subsequently a greater understanding of another's emotional state (Gallese, 2007), while still maintaining an appropriate amount of self-other distinction (Decety & Lamm, 2006). Instead, the IRI includes personal distress, which focuses on experience sharing without proper self-other distinction (the sharing of overwhelmingly negative arousal, specifically during emergency situations) and empathic concern, which requires experience sharing, but, unlike personal distress, is also associated with activation in regions involved in costly altruistic behaviors like social attachment and caregiving (Feldmanhall, Dalgleish, Evans, & Mobbs, 2015). This difference suggests that empathic concern requires an other-focused orientation and concern for the welfare of others and thus is distinct from pure experience sharing of emotions and behaviors – a distinction confirmed in previous research evaluating differences in empathic concern and experience sharing subscales (Jordan et al., 2017).

Because the IRI is missing a simulation-based experience sharing scale, previous research has used the personal distress subscale as a replacement for evaluating experience sharing, suggesting that personal distress is specifically associated with the process of emotional contagion (Decety & Yoder, 2016). For the current study, we chose to follow this approach and focus on the personal distress subscale as a proxy for the experience sharing ostensibly facilitated by neural resonance. We also pinpoint the perspective taking subscale as a measure of a cognitive, top-down mechanism that would facilitate empathic outcomes from resonance-based experience sharing.

Trait empathy has been linked to neural simulation in somatosensory areas indexed by suppression of the EEG mu rhythm (e.g. Yang, Decety, Lee, Chen, & Cheng, 2009; Cheng et al., 2008). The mu rhythm is caused by oscillatory activation between 8-13Hz recorded over sensory motor regions (Fox et al., 2016; Kuhlman, 1978; Pfurtscheller, 1979), which originate primarily from brain areas clustered around the central sulcus in sensorimotor areas and parietal areas (Salmelin & Hari, 1994). Its suppression has long been used as an index of neural activity in the sensory motor cortex (Kuhlman, 1978; Pfurtscheller, 1979).

Further, mu suppression during the mere observation of actions, touch, and pain (Decety, Lewis, & Cowell, 2015; Moore, Gorodnitsky, & Pineda, 2012; Mu, Fan, Mao, & Han, 2008), is considered a reliable measure of neural simulation (see Fox et al., 2016 for a meta analysis, and Hobson & Bishop, 2016 for a critical perspective).

Mu Suppression and Trait Empathy

Mu suppression has been associated with better performance in tasks that require emotional empathy (Pineda & Hecht, 2009), but results regarding trait empathy are mixed. Overall trait empathy, as indexed by the IRI average across sub-scales, was not found to be associated with increased mu suppression or more neural simulation (Perry, Troje, & Bentin, 2010). However, the sub-components of perspective taking and personal distress have been found to be related to mu suppression, with personal distress predicting more mu suppression during the perception of static images of pain (Yang et al. 2009) as well as during the observation of videos depicting hand actions (Cheng et al., 2008) at the average of the C3, Cz, and C4 electrodes. This relationship is consistent with previous findings associating personal distress with the activation of experience sharing areas of the brain (Cheetham, 2009; Cheng, Lee, et al., 2008; Hadjikhani et al., 2014), so we predicted that greater personal distress would be linked to greater mu suppression.

For perspective taking, the subscale was shown to predict a greater difference between self and other induced mu suppression for hand actions (Woodruff et al., 2011a) and less suppression during observation of videos of hand actions (Woodruff & Klein, 2013), both measured at electrode Cz. Functional MRI research has shown that activity in sensori-motor areas does positively correlate with perspective taking (Gazzola et al. 2006), thus, we predicted that greater perspective taking would be associated with greater suppression of the mu rhythm during observation of an action, despite inconsistent findings with perspective taking and mu suppression (Woodruff & Klein, 2013; Woodruff et al., 2011a, Woodruff, Daut, Brower, & Bragg, 2011).

Issues of Sufficient Power

Many studies in neuroscience face the problem of being underpowered, decreasing the probability of detecting an effect and overestimating the effects that are detected (Boudewyn, Luck, Farrens, & Kappenman, 2018). Although the previous literature used tasks designed to increase reliability of the measurement of mu suppression (e.g. having a large number trials, with action images or videos repeating from 128-240 times), the studies use a small sample (total *Ns* ranging from 29-40; Woodruff et al., 2011a; Woodruff & Klein, 2013; Cheng, Lee, et al., 2008) that would be inadequate even under the assumption of no measurement error. Increasing the number of trials included in the averages reduces the signal-to-noise ratio (Luck, 2014) and thus, is closely tied to the reliability of the measure. However, at a certain level, when reliability is high (evaluated by testing the internal reliability of the averages (e.g., Olvet & Hajcak, 2009)), *N* is the only other variable that can increase power, since the size of the effect is fixed.

A recent meta-analysis shows that the average effect size of mu suppression during action observation compared to baseline is Cohen's *d* of .31, requiring a minimum sample of 66 to detect the basic mu suppression effect in a one-tailed test (84 would be needed for a two-tailed test; Fox et al. 2016). Moreover, for detecting a medium correlation ($R^2 = .09$) with a power of 80%, a sample size of 82 is required assuming no measurement error. Given these concerns with previous work, our goal in the present study is to further investigate and clarify the relationship between trait empathy, measured by the IRI, and mu suppression in a sufficiently powered study.

Current Research

To this end, we re-analyzed EEG and IRI data from six previously completed studies, all of which measured mu suppression during the same motor perception task. We indexed mu suppression as the ratio in mu power during action perception trials to mu power during baseline. Since data were not normally distributed, values were log transformed and then correlated with average ratings on the overall IRI and its sub-scales. We have a pre-registration associated with this study (please see https://osf.io/smqb6/), however, not all analyses from the pre-registration will be reported. Given that the main goal of this paper is to sufficiently clarify the IRI and action-based sensorimotor resonance relationship, we deemed it necessary to include additional non-registered analyses in order to more effectively meet this goal and exclude those analyses that did not address our main research question. Our pre-registered hypotheses predicted a positive association between sensorimotor resonance and the personal distress and perspective taking subscales of the IRI (negative correlation between these IRI subscales and mu suppression), such that participants who score higher on the personal distress or perspective taking subscale would exhibit more sensorimotor resonance to target individuals.

2. Methods

2.1 Participants

Our final sample size after all exclusions consisted of 252 participants. Sensitivity analysis revealed that our study was adequately powered to detect as small an effect as $R^2 = 0.024$ with a power of 80% and $R^2 = 0.038$ with a power of 95%, after adjusting the effect size to account for the reliability of the individual measures of the IRI (α = .79) and mu suppression (α = .97) using the following formula: $r_{\text{adjusted}} = r \times$ SQ root ($\alpha_{\text{IRI}} \times \alpha_{\text{mu suppression}}$).

All participants were fluent in English and right-handed. The sample consisted of 149 females, 102 men, and 1 gender nonconformed individual between the ages of 18-31 years (*M*=20.23, *SD*=2.39) and was relatively diverse with 51.6% White, 28.2% East Asian, 5.6% Hispanic, 4.8% Bi-racial, 4.8% South Asian, 3.6% Black, .8% Other, and .8% no response participants. Participants were recruited from the university undergraduate and graduate population for course credit or cash payment of $10 per hour. The study was approved by the university's Institutional Review Board.

2.1.1 Exclusion Criteria. Our initial sample consisted of 314 participants. Consistent with the pre-registration, participants were excluded for missing EEG data (*N*=10), missing IRI behavioral data (*N*=18), or unusable data as identified by visual inspection or missing task markers (*N*=24). In addition, those with a baseline average mu power at the C3 electrode that was two standard deviations above or below the mean were excluded (*N*=9) in concordance with the pre-registration, and these exclusions were kept consistent across all analyses. Examination of case-wise diagnostics such as Cook's distance and centered leverage values suggested one case that had an undue influence on the model, therefore this participant was also removed from the final analyses for a final sample size of 252.[1]

2.2 Procedure

EEG and behavioral data were combined from six previous studies done in our laboratory. All six studies shared the common components of neural electrophysiological recording during the same motor perception task and administration of the Interpersonal Reactivity Index (IRI) following the task. This motor perception task, a simple action observation video, is typically used in the field to elicit suppression of the mu rhythm and quantify an individual's sensorimotor resonance (Coll, Bird, Catmur, & Press, 2015; Fox et al., 2016; Gutsell & Inzlicht, 2010; Hager, Yang, & Gutsell, 2018; Oberman et al., 2005; Puzzo, Cooper, Cantarella, & Russo, 2011, Simon & Gutsell, 2019).

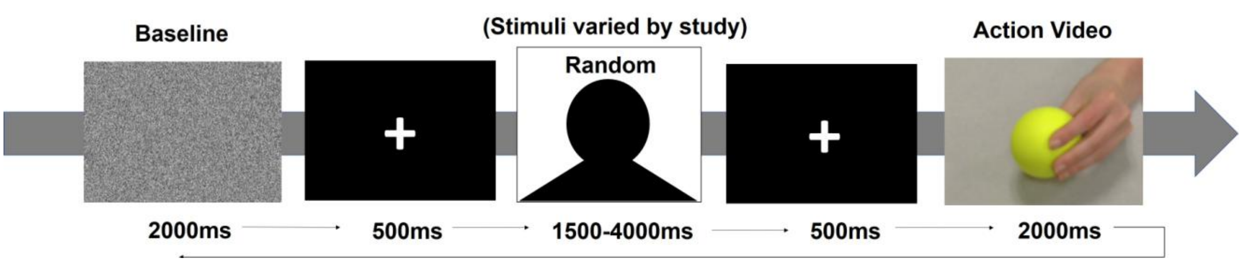
All participants gave informed consent and were fitted with an EEG cap in an isolated testing room. During neural electrophysiological recordings, participants viewed action videos of a right hand squeezing a ball as well as various stimuli before and after each action video. The additional stimuli were different for each of the six studies. For example, some included human faces of varying attractiveness and dominance, or a human silhouette with descriptions of traits relating to levels of warmth and competence (see supplementary materials for detailed descriptions of the individual studies). None of these variations were relevant to our hypotheses, thus, analysis was limited to neural activity during the motor perception task administered in all six studies, selecting exclusively the action video and baseline segments for mu suppression

[1] Results including the outlier are reported here when they differ to the extent that they change the interpretation of results.

calculation. Lastly, participants completed other self-report questionnaires that were relevant to each particular study (see supplementary material).

2.2.1 Motor Perception Task. In the motor perception task, a typical trial consisted of participants viewing a full screen of moving white noise followed by a black screen with a fixation cross, the additional stimuli of interest for particular studies, another fixation cross, and then the action observation video of a right hand squeezing a ball. Some studies contained white noise followed by a fixation cross, and then immediately after, the action observation videos. Within the six studies, the moving white noise presentation length ranged from 500–3500ms, the following black screen with a fixation cross from 300–500ms, and the total length of the hand video clips from 2000ms–30s, depending on the particular study (see Figure 1 for a graphical depiction of a typical trial, and specific trial design per study can be found in supplementary materials).

Figure 1. Depiction of a typical trial for the action observation task.



In order to remain consistent across all six studies, the first 1000ms of the white noise was used as the baseline[2] while the action observation segments were analyzed from 200ms after the onset of the action video for a duration of 1000ms.

[2] One study did not contain a long enough segment of white noise, so 500ms of white noise followed by 500ms of a fixation cross was used for the baseline. Additionally, another study did not contain white

The action videos depicted a right hand squeezing a yellow stress ball at a rate of 1 Hz so that approximately one squeeze was shown for the 1000ms analyzed from each video trial. This presentation was repeated anywhere from 1–30 times across 2–30 targets, resulting in an average of 98 trials for both baseline and action observation (see supplementary materials for the specific number of trials for each study). The hands presented in the video clips were most often male and White, but some of the six studies included hands that were female, East Asian, South Asian, African American, and Hispanic (please see supplementary materials). The hands were depicted in the center of the screen from the wrist down with no jewelry or identifying marks.

2.3 Measures

2.3.1 Interpersonal Reactivity Index. Empathic traits were assessed using four seven-item subscales from the Interpersonal Reactivity Index (IRI) that focus on different aspects of empathy – perspective taking (PT), fantasy (FS), empathic concern (EC) and personal distress (PD) (Davis, 2015, 1980, 1983). Participants responded to phrases on a five-point scale running from 0 (“does not describe me well”) to 4 (“describes me very well”). The internal consistency (standardized alpha coefficients) for all four sub scales are substantial, (r = .75, .78, .72 and .78 for males, .78, .75, .70, .78 for females; Davis, 1980).

2.3.2 Electrophysiological recording and Analysis. Electrophysiological (EEG) data was recorded from 33 active electrodes embedded in a stretch-lycra cap (ActiCap, BrainProducts, GmbH, Munich Germany) using BrainAmp amplifiers and the BrainVision recorder software (BrainProducts, GmbH, Munich Germany), digitized at 500 Hz. Electrodes were arranged according to the 10-20 system with impedances kept below 20 KΩ with an initial reference at FCz. Another pair of bipolar electrodes were placed above and below the right eye

noise at all prior to the videos, thus, 500ms of a black screen followed by 500ms of a fixation cross was used instead, both still having a total of 1000ms of baseline.

to record vertical eye movements and create a separate ocular channel (vertical electrooculogram, VEOG).

Offline EEG data was analyzed using Brain Vision Analyzer (BrainProducts, GmbH, Munich Germany). Recorded EEG was re-referenced to the common average. We applied a .1 Hz high pass filter and corrected for line noise using the Cleanline EEG lab extension (https://bitbucket.org/tmullen/cleanline) in MATLAB (MathWorks, Natick, MA, USA) which adaptively estimates and removes sinusoidal artifacts using a frequency-domain (multi-taper) regression technique with a Thompson F-statistic for identifying significant sinusoidal artifacts. Ocular artifacts were detected through the VEOG or Fp1 channels, depending upon which electrode data was cleanest, and blink markers were placed. An independent component analysis (ocular correction ICA) was used to isolate ocular components based on specific VEOG or Fp1 activity, and automatically remove the effects of eye movement from the EEG (Croft & Barry, 2000). Remaining artifacts exceeding ± 85 μV[3] in amplitude, with a voltage step larger than 50 μV between sample points, or a maximum voltage difference of less than 0.5 μV within a 100 ms interval were rejected automatically for individual channels in each trial.

Fast Fourier Transformation (FFT) was performed on artifact-free, 75% overlapping epochs of 400ms derived from a 1000ms segment (200-1200ms after stimulus onset) from each action video presentation to calculate power in the 8-13 Hz band and were extracted through a 25% Hamming window to minimize data loss. Segments were zero padded to a length of 512ms with 256 data points for a frequency resolution of 1.95 Hz. Based on our experience with previous datasets we chose and pre-registered to segment 200ms after stimulus onset since this is usually when mu suppression first occurs during action observation. We averaged the spectral

[3] The artifact threshold of ± 85 μV mentioned here deviates from the pre-registration, which gave a ± 300 μV artifact threshold. We decided to use a more stringent criterium in order to ensure clean data.

data for the action video and the white noise baseline across all of the trials, which included a sufficiently large average of 98 trials across the six studies, and then calculated mu suppression log ratio scores taking the log of mu power during the action observation over mu power during the baseline. More negative ratio scores indicate a stronger suppression of the mu rhythm and, hence, more cortical activity and greater resonance with the target. The primary region of interest was the sensorimotor cortex, therefore change in mu frequency was calculated at electrodes C3, Cz, and C4 over the sensorimotor cortex as an index of motor system activity (Woodruff et al., 2011a, Pfurtscheller & Lopes Da Silva, 1999; Jaime A Pineda, 2005). We expected the effects to be strongest at C3, the electrode over the contralateral hemisphere from the right hands depicted in the videos. To establish that mu suppression effects were specific to central sensorimotor cortical areas, mu suppression was also calculated for frontal (F3 and F4) as well as occipital (O1 and O2) regions and compared to central electrodes.

In order to verify the robustness of any potential effects across analytic methods and to ensure that suppression in the 8-13 Hz frequency band was indeed resulting from sensorimotor areas, we also performed an ICA-based analysis that attempted to identify mu wave components in full-brain activity (results reported below).

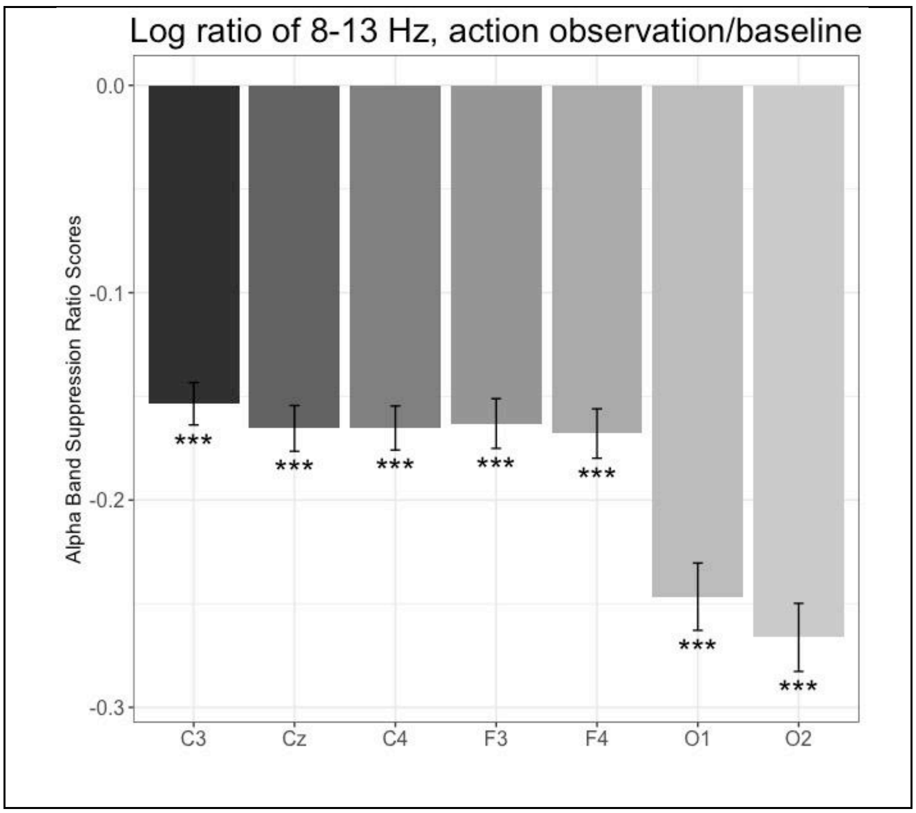
3. Results

3.1 Sensorimotor Resonance

To test the reliability of mu suppression we split trials of action observation in half and calculated mu power across each half separately. The analysis revealed that for C3, Cz, and C4, the log mu power values calculated in the first half of the session were all highly correlated with those calculated for the second half (all p's < .001; all Cronbach's αs = .97), indicating high reliability.

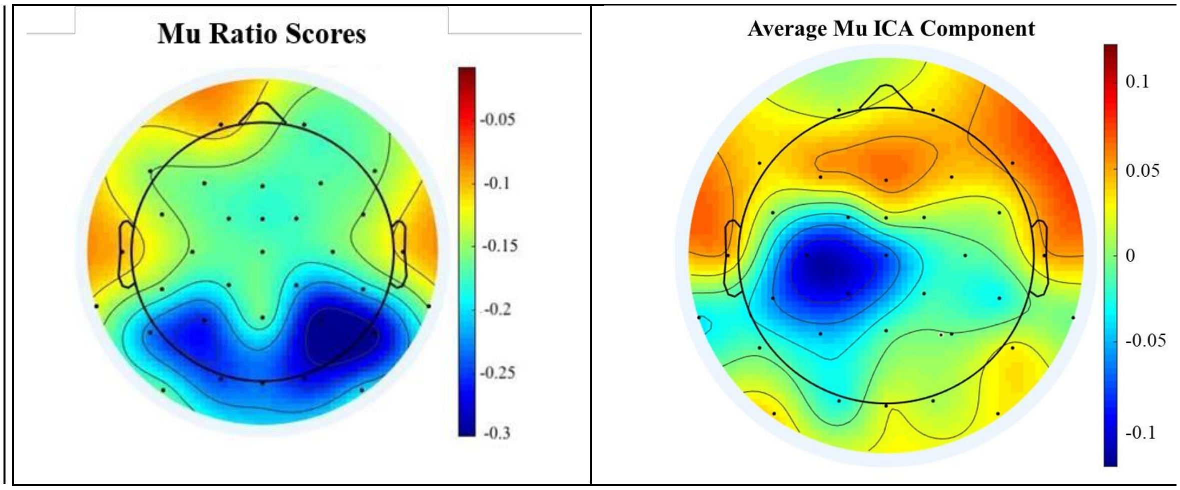
As expected, one-sample *t*-tests showed that log ratio scores at C3 (*M*=-.154, *SD*=.162), C4 (*M*=-.165, *SD*=.169) and Cz (*M*=-.165, *SD*=.175) were significantly different from zero (*t* (251) =-15.00, *p* < .001, *d*=.90, 95% CI [-.17, -.13], *t* (251) =-15.56, *p* < .001, *d*=.92, 95% CI [-.19, -.14] and *t* (251) =-14.99, *p* < .001, *d*=.92, 95% CI [-.19, -.14] respectively), indicating that participants showed mu suppression and suggesting an increase in neural activity in the sensorimotor system during the observation of motor action compared to baseline (see Figure 2).

Figure 2. Log ratio mu suppression scores across Central, Frontal and Occipital electrodes.



However, all control electrode sites also showed significant suppression in power within the 8-13Hz alpha/mu frequency band during action observation (all *p*-values < .001). To test localization of the mu suppression effects for potential differences, we ran a 2 (lateralization: left vs. right) x 3 (centrality: Frontal, Central, Occipital) within-subject repeated measure ANOVA on mu suppression ratio scores using Greenhouse–Geisser corrections when the assumption of sphericity was violated. Mu suppression was significantly greater in the right hemisphere compared to the left ($F(1, 241) = 13.77$, $p < .001$) and greater in occipital electrodes compared to central ($F(1.82, 437.86) = 52.76$, $p < .001$). The expected interaction between lateralization and centrality was not significant ($F(2, 482) = 1.43$, $p = .24$), indicating that lateralization effects were not unique to our Region of Interest. Planned comparisons revealed that mu suppression observed in the central electrodes was significantly different between left (*M*=-.148, *SD*=.160) and right (*M*=-.162, *SD*=.170) hemispheres, $p = .046$, and left central suppression (*M*=-.148, *SD*=.160) was significantly different from left occipital suppression (*M*=-.247, *SD*=.255), $p < .001$, but not left frontal (*M*=-.163, *SD*=.192) electrodes, $p = .140$. Together, these findings suggest that suppression occurs at frontal, central, and occipital electrode sites and that mu suppression measured over the contralateral left somatosensory motor areas is accompanied by similar suppression in frontal and occipital control regions (see Figure 3).

Figure 3. Topographic plots of mu suppression indexed through log mu ratio scores (left) and ICA (right), showing that ICA was successful at isolating the mu to the left sensorimotor region. ~~Left values are uV^2 while~~ Right values are ICA inverse projection weights from EEG.icawinv in EEGLAB.



For this reason, further analyses were needed in order to separate sensorimotor-related mu suppression from attention-related alpha suppression. One technique that has been used to solve this issue of co-occurring alpha and to specifically extract the mu component is Independent Component Analysis (ICA).

3.1.1 Independent Component Analysis. Independent Component Analysis has long been used to separate EEG data into its constituent parts (Jolla et al., 1997; Makeig, Ca, Bell, & Sejnowski, 1996; see Onton, Westerfield, Townsend, & Makeig, 2006 for a review). Blind source separation allows underlying rhythms to be identified independent of other activity in nearby regions, including the component belonging to sensorimotor mu (Bowers, Saltuklaroglu, Harkrider, & Cuellar, 2013; Moore et al., 2012; Onton et al., 2006). This allows better differentiation of sensorimotor mu from occipital alpha, rather than relying on electrode location (Hobson & Bishop, 2017).

To find the mu component, we took our segmented, non-decomposed preprocessed data (preprocessing is described in 2.3.2) from baseline and action observation trials, bandpass filtered it between 1 and 30 Hz to remove high frequency noise, and ran the second-order blind identification (SOBI) ICA algorithm implemented in EEGLAB (Delorme & Makeig, 2004) across all baseline and action observation trials for each participant. The SOBI algorithm has been shown to be an effective way to extract the mu component (Ng & Raveendran, 2009). We then used the "iclabel()" function (Pion-Tonachini, Kreutz-Delgado, & Makeig, under review) to classify the components in our data. IClabel() is a classification algorithm trained on crowdsourced labeling of over 6,000 EEG recordings (https://labeling.ucsd.edu/tutorial). The algorithm provides estimates of each component's likelihood of originating as signal from eight sources: brain, muscle, eye, heart, line noise, channel noise, or other. We used custom MATLAB scripts to identify all components to which iclabel() assigned a plurality or majority likelihood of being brain signal. From these, we algorithmically identified all components with a topographic maximum or minimum at C3, Cz, or C4. All of these components were visually inspected to ensure their localization over the sensorimotor cortex and power peaks around 10 Hz, removing those that did not look like mu (see Figure 2). We then decomposed the ICA activations with the EEGLAB function spectopo(), and exported power values (RMS μV) averaged across 8-13 Hz. For participants with multiple mu components, we averaged them to get one value per segment (see Figure 3). We performed the congruent export for occipital alpha, using components with maxima or minima at O1, Oz, or O2 instead of C3, Cz, or C4.

3.2 IRI behavioral data

The IRI subscale mean values and standard deviations were close to published norms (Brown, 2003; see Table 1). For the entire scale, Cronbach's alpha was .79 based on the 28 items, indicating a high degree of reliability. Cronbach's alpha coefficients for the individual Perspective Taking, Fantasy Scale, Empathic Concern and Personal Distress subscales were .75, .70, .77, and .70.

Table 1. *Scores on each IRI subscale for all subjects (mean ± standard deviation).*

IRI Subscale	All participants	Male participants	Female participants
Perspective Taking	3.64±.68	3.67±.71	3.62±.66
Personal Distress	2.78±.69	2.49±.68*	2.92±.66*
Fantasy Scale	3.53±.74	3.35±.70*	3.63±.75*
Empathic Concern	3.58±.79	3.49±.69	3.45±.44

* $p < .05$ for an independent samples t-test between males and females

3.4 Association between Sensorimotor Resonance and IRI

Using a series of pre-registered Pearson correlations, we correlated IRI subscale scores with mu suppression ratio scores. The mu suppression ratio score at C3 was not correlated with the personal distress subscale score, but it was just outside the threshold of significance, $r(250) = .12$, $p = .069$,[4] suggesting that greater sensorimotor resonance or suppression of the mu rhythm might be associated with fewer reports of trait personal distress, but the effect size of $R^2 = 0.013$ was too small to be detected in our design (see above sensitivity analysis). Counter to our predictions, this correlation is positive, suggesting that people who tend to experience personal distress might also resonate less when observing an action. Also contrary to our predictions, mu suppression at C3 was not correlated with the perspective taking subscale ($r(250) = .014$, $p = .83$, see Table 2).

Table 2. *Correlations and Bayesian statistics for mu suppression ratio score at C3 and Mu Component with IRI subscales (adjusted p values reported for non-registered comparisons).*

		Mu ratio score (C3)	Mu component	Personal Distress	Perspective Taking	Fantasy Seeking	Empathic Concern
Mu ratio score (C3)	Pearson's r	—					
	p	—					
	BF_{10}	—					

[4] The pattern of results for the relationship between personal distress and mu suppression changed when we did not exclude the one outlier who had an undue influence on the model ($r(251) = .075$, $p = .23$).

Mu component	Pearson's r	0.085	—				
	p	0.205	—				
	BF_{10}	0.185	—				
Personal Distress	Pearson's r	0.115	-0.103	—			
	p	0.069	0.122	—			
	BF_{10}	0.407	0.274	—			
Perspective Taking	Pearson's r	0.014	-0.002	-0.013	—		
	p	0.825	0.977	0.835	—		
	BF_{10}	0.081	0.083	0.081	—		
Fantasy Seeking	Pearson's r	0.018	-0.061	0.249***	0.096	—	
	p	0.780	0.487	0	0.13	—	
	BF_{10}	0.082	0.125	220.64	0.247	—	
Empathic Concern	Pearson's r	0.019	-0.172*	0.257***	0.105	0.429***	—
	p	0.760	0.04	0	0.095	0	—
	BF_{10}	0.083	2.303	383.011	0.316	6.895e +9	—

* p < .05, **p < .01, ***p < .001

Given that previous research found a positive association between mu suppression and personal distress at the average of C3, C4 and Cz electrodes (Cheng, Lee, et al., 2008; Yang, Decety, Lee, Chen, & Cheng, 2009b), we performed an additional non-registered exploratory analysis on the average of these electrodes and found that mu suppression was not significantly correlated with the personal distress subscale, $r(250) = .12$, $p = .059$, but it was again just outside the threshold of significance, potentially indicating a pattern consistent with our current findings, but opposite to that found in the previous research. Given additional research showing a relationship at Cz (Woodruff & Klein, 2013; Woodruff et al., 2011a), we performed an additional non-registered exploratory analysis on the Cz electrode and the perspective taking subscale, however we did not confirm this association as mu suppression at the Cz electrode was not associated with the perspective taking subscale $r(250) = .038$, $p = .547$.

Once we found this lack of conclusive evidence of a relationship between mu suppression and the IRI sub-scales, we ran a Bayesian analysis to quantify the evidence for a null correlation using a uniform prior between correlations of -1 and 1 (Wagenmakers, Verhagen, & Ly, 2016). We used JASP to perform Bayesian correlations using Bayes Factor (BF) thresholds of 3.0 as moderate evidence of a correlation and .33 as moderate evidence for the null and 10 and .10 as thresholds for strong evidence (Lee & Wagenmakers, 2013). Unfortunately, the relationship between personal distress and C3 mu suppression fell into the gray area between thresholds, with a Bayes Factor of .41 indicating only suggestive (anecdotal) evidence for the null. There was strong evidence against associations between C3 mu suppression and any of the other subscales ($.080 < BF < .083$) (see Table 2).

The results reported above should be interpreted with caution for several reasons. A critical issue with this analysis is an inability to confirm that mu suppression effects are localized to the sensorimotor cortex, especially given the lack of differentiation observed between mu suppression at C3 and frontal and occipital alpha. We conducted an additional non-registered set of correlations and found that less personal distress was also associated with more suppression at the frontal and occipital control electrode sites (all *p*-values < .032). Specifically, there was a significant relationship between personal distress and occipital suppression at O1 (r (243) = .17, p= .008) (see Table 3).

Table 3. *Correlations and Bayesian statistics for suppression ratio score at left occipital electrode (O1) and occipital Component and IRI subscales (adjusted p values reported for non-registered comparisons)*

		Occipital Component	Ratio Score (O1)	Personal Distress	Perspective Taking	Fantasy Seeking	Empathic Concern
Occipital Component	Pearson's r	—					
	p	—					
	BF_{10}	—					
Ratio Score (O1)	Pearson's r	-0.126	—				
	p	0.295	—				
	BF_{10}	0.484	—				
Personal Distress	Pearson's r	-0.036	0.168*	—			
	p	0.682	0.016	—			
	BF_{10}	0.097	2.542	—			
Perspective	Pearson's r	-0.066	0.037	-0.013	—		

Taking	*p*	0.682	0.555	0.835	—		
	BF_{10}	0.134	0.095	0.081	—		
Fantasy Seeking	Pearson's r	-0.033	0.073	0.248**	0.095	—	
	p	0.682	0.344	0	0.13	—	
	BF_{10}	0.095	0.153	211.33	0.245	—	
Empathic Concern	Pearson's r	-0.028	0.209**	0.257**	0.105	0.429**	—
	p	0.682	0.004	0	0.095	0	—
	BF_{10}	0.091	17.558	377.486	0.312	6.682e +9	—

*p < .05, **p < .01, ***p < .001

Hence, the personal distress subscale predicted alpha/mu suppression across the brain generally, rather than primarily mu suppression at C3.

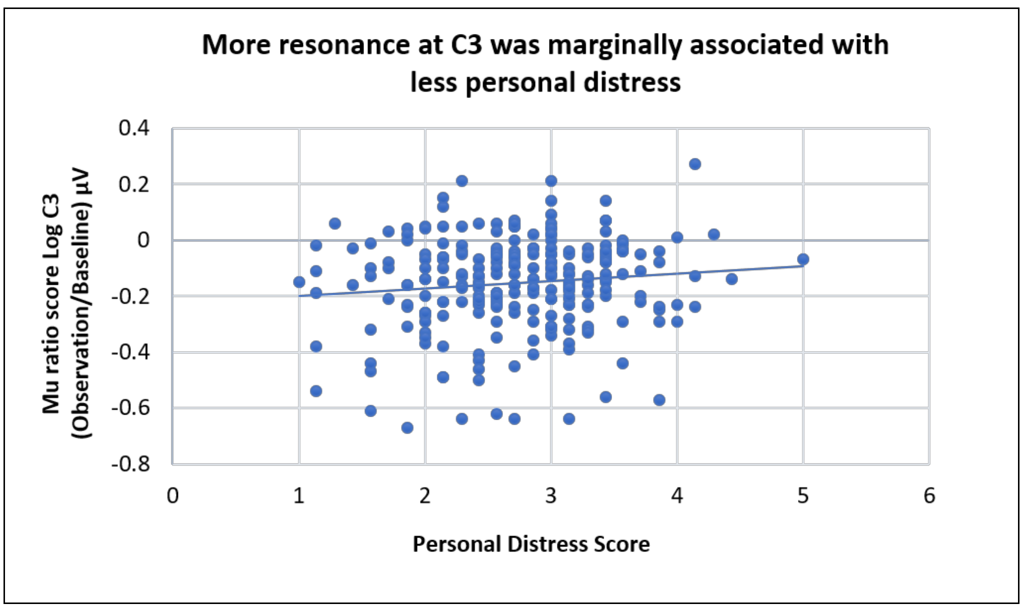
In sum, the current analysis suggests that there is no relationship between EEG mu suppression over left sensorimotor regions and IRI subscales. Although we did find a marginally significant relationship with the personal distress facet, this association was in the opposite direction of our predictions, seemed to be primarily driven by the removal of an outlier, and seemed to be stronger at electrode sites outside of our region of interest and, thus, attributable to occipital and frontal alpha. However, because suppression in the alpha/mu band was not unique to sensorimotor areas, and we could not differentiate mu suppression based on unique patterns of association with the IRI, further information is needed to clarify the relationship between mu suppression and trait empathy. To this end, we conducted an additional set of unregistered analysis at the EEG component level**.**

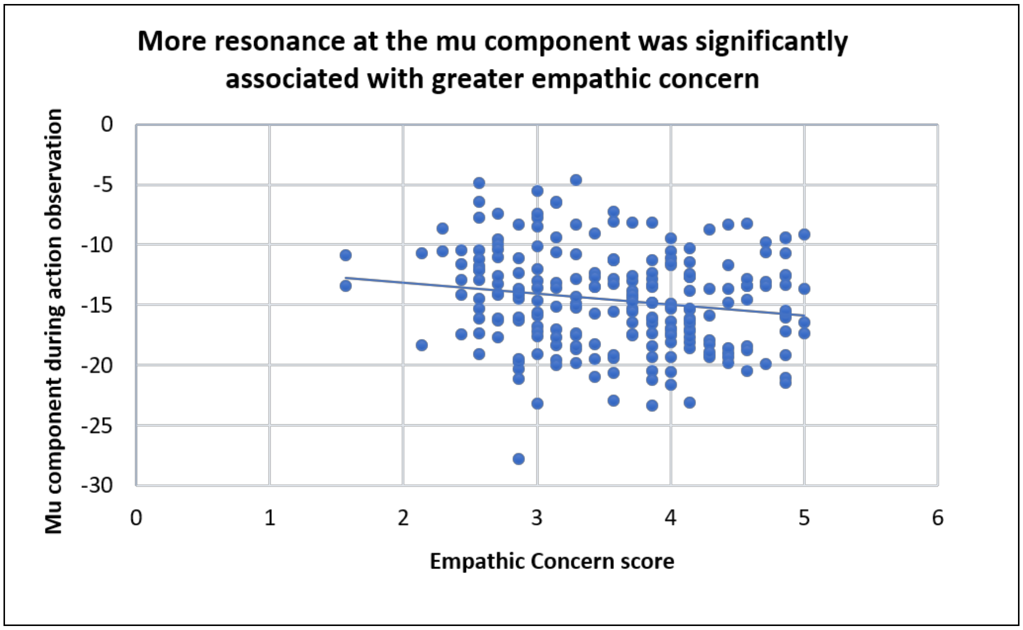
3.4.1 ICA based mu component findings

After identifying a potential better indicator of mu suppression through ICA, we ran additional correlations to assess the relationship between the ICA-based mu component and each of the subscales of the IRI. We specifically looked at the mu component as opposed to mu component ratio scores since creating ratio scores would result in a substantial loss of participants (N=18) as the algorithm could not identify a mu component for both baseline and action observation in every participant. 225 of 252 participants had a useable mu component during action observation, but only 207 had both components needed to compute a ratio. The absence of a correlation between the mu component and the mu suppression ratio score, $r(223) = .085$, $p = .205$ (see Table 2), can be explained by a lack of differentiation in the ratio score between the suppression seen in sensorimotor areas and the attentional effects from frontal and occipital alpha (see Figure 3). Possibly the absence of a correlation could also be due to differences in baseline, since baseline is only used in the mu ratio score but not in the mu component score. However, after factoring in the baseline to create a mu component difference score, there was still no correlation with mu ratio score $r(205) = -.09$, $p = .18$.

After adjusting alpha values to correct for multiple comparisons (Hochberg, 1995) the mu component did correlate with empathic concern, $r(223) = -.17$, $p = .04$, such that those participants who reported feeling more empathically concerned also resonated more (see Figure 4).

Figure 4. Relationship between mu suppression ratio score at C3 and personal distress (top) and mu component during action observation and empathic concern (bottom).





The mu component did not correlate with any of the other subscales (all *r*s < -.002, all *p*s > .12). It is important to note, however, that in unregistered analyses *p*-values greater than .005 should be treated cautiously (Lakens et al., 2018). Moreover, Bayesian analysis showed no more than suggestive (anecdotal) evidence for the empathic concern relationship, *BF* = 2.30 but did confirm strong evidence against the perspective taking relationship, *BF* = .083, and moderate evidence against the personal distress (*BF*=.274) and fantasy subscales *(BF*=.125; see Table 2).

Importantly, occipital components during action observation were not associated with any of the IRI subscales (all *r*s < -.028, all *p*s > .327), and Bayesian analysis confirmed strong evidence against the personal distress, fantasy, and empathic concern subscales (all *BF* < .10), and suggestive (anecdotal) evidence against the perspective taking subscale (*BF* = .134; see Table 3).

Since there were large differences in the sample sizes and stimuli used in each of the six studies (*N*s: 28–68), we took a multi-level modeling approach to assess whether there were variations in the strength of the relationship between mu suppression and IRI subscales across the studies (see supplementary materials for modeling details). This exploratory analysis revealed that the relationship between personal distress and mu suppression score at the C3 electrode did not vary significantly from study to study, as shown by a likelihood ratio test comparing a model that does not allow the slope of the personal distress—mu suppression relationship to vary by study to one that does, $\chi^2(1) = .15$, $p = .70$ (see supplementary materials for model details). The relationship between ICA-based mu components and empathic concern also did not vary from study to study, $\chi^2(1) = -.15$, $p= .18$. A one-way ANOVA revealed that there was a significant difference in mu component and mu ratio scores between studies, $F(5,219) = 2.43$, $p = .036$ and $F(5,246) = 4.01$, $p = .002$ respectively. A Tukey post hoc test revealed that the mu ratio score was significantly smaller in Study 3 (M=-.220, SD= .196) compared to Study 1 (M= -.100, SD= .121), $p = .013$ and Study 5 (M= -.077, SD= .117), $p =.004$. For the mu component, Study 1 (M= -16.39, SD= 3.46) had a significantly smaller mu component score than Study 4 (M= -13.32, SD= 3.76), $p = .015$. Despite the differences in mu suppression, the additional multi-level modeling analysis emphasizes that the slight differences in the studies' stimuli and methods did not have an impact on the main IRI subscale and mu suppression associations of interest.

Taken together, our component-based analyses confirm that, if mu suppression is isolated successfully from occipital alpha, there is most likely no relationship between it and the personal distress, perspective taking, and fantasy empathy facets, though we did find suggestive (anecdotal) evidence for a positive association between sensorimotor resonance and empathic concern.

4. Discussion

Mu suppression is gaining popularity as a measure of sensorimotor resonance, often used as an index of one's ability to empathize and simulate another's experiences (e.g. Cheng, Yang, Lin, Lee, & Decety, 2008; Fabi & Leuthold, 2017; Gutsell & Inzlicht, 2010; Li, Meng, Li, Yang, & Yuan, 2017; Perry, A., Bentin, S., Bartal, I. B. A., Lamm, C., & Decety, J. 2010; Pineda & Hecht, 2009). Previous research suggests that mu suppression is related to various forms of trait empathy (Yang et al, 2009; Cheng et al., 2008, Woodruff et al., 2011a), but these studies are most likely underpowered and their findings are inconsistent. Our high-powered study did not find support for any preregistered associations between sensorimotor resonance – measured by EEG mu suppression at the C3 electrode in response to simple actions – and specific subscales of the IRI (perspective taking and personal distress), with Bayesian analysis providing anecdotal to strong evidence in favor of a null relationship. However, after isolating the mu component through ICA analysis to confirm the localization of mu suppression to the sensorimotor region, we found an association with the empathic concern subscale, suggesting that those who resonate more with a simple action also reported feeling more empathic concern for others, although this effect was relatively small.

Taken together, these findings highlight that the previously shown relationships between mu suppression during action observation and the personal distress and perspective taking subscales should be interpreted with caution and require further investigation; moreover, future research should further explore the relevance of empathic concern in the simulation of another's actions. At least one previous study (N=28) did also find a correlation between empathic concern and mu suppression (electrode C4; r=-0.612, p=0.001) in response to observed actions used in creating artwork (brush strokes of paint on paper) (Hoenen et al., 2017). This finding and our current work suggests that it is important to consider the role of resonance-based experience sharing in empathy, and that with proper emotion regulation and self-other distinction, this experience sharing will likely result in a sympathetic regard for the other (Decety & Meyer, 2008).

Given that previous research has largely confirmed a relationship between mu suppression and empathic abilities, specifically with personal distress and perspective taking (Cheng, Yang, et al., 2008; Woodruff & Klein, 2013; Woodruff et al., 2011; Yang et al., 2009), our lack of significant findings with these subscales contribute novel, relevant data to the field. Our results highlight that the perspective taking subscale, a measure of cognitive empathy and top down mechanisms associated with understanding another's perspective, is likely not related to the bottom-up, resonance-based experience sharing indexed by mu suppression. Additionally, personal distress, an aversive, self-focused response to others' distress, is also likely not associated with greater resonance and experience sharing.

4.1 Differentiating Sensorimotor Resonance from Attention

An important consideration of our initial results is that we could not ensure that mu suppression effects were limited to central electrodes. Due to a marginally significant correlation between personal distress and mu suppression at C3, as well as significant correlation between personal distress and suppression and frontal and occipital electrodes, it is likely that personal distress is mostly related to general attention and cognitive processing rather than sensorimotor resonances specifically.

While ICA is a useful tool for isolating mu from occipital alpha, our study could have benefitted from additional conditions to control for attentional differences between stimuli and to better clarify the relationship with mu suppression assessed on the electrode level. Additionally, an execution condition where participants performed the action they observed could have been included, as this has been emphasized in previous research as another important way to separate mu suppression from occipital alpha (Bowman et al., 2017; Hobson & Bishop, 2017). It is possible that some of the suppression findings in central electrodes from prior work could be due to contributions from occipital alpha (Woodruff & Klein, 2013); therefore, it is important to also re-evaluate the source localization of mu suppression effects in a larger study.

4.2 Interpreting Mu suppression in response to actions

Our study did not find support for a relationship between action-induced mu suppression and subscales of the IRI, but that does not mean that EEG mu suppression is not related to trait empathy more generally. Following previous research that had shown an association between mu suppression during the observation of hand actions and trait empathy (Cheng, Lee, et al., 2008), our study's stimuli consisted of videos of hands performing the basic action of squeezing a stress ball. Additionally, however, the degree of sensorimotor resonance elicited differs whether participants observe facial expressions or simple action movement videos (Leslie, Johnson-Frey, & Grafton, 2004; Schulte-Rüther, Markowitsch, Fink, & Piefke, 2007). Watching someone give a consoling touch to a person in pain elicits a larger change in mu suppression from baseline compared to watching simple action videos (Peled-Avron, Goldstein, Yellinek, Weissman-Fogel, & Shamay-Tsoory, 2016; Perry, Bentin, Bartal, Lamm, & Decety, 2010; Whitmarsh, Nieuwenhuis, Barendregt, & Jensen, 2011; Yang et al., 2009b). These differences might be caused by two separate mirror neuron networks: a sensorimotor mirror system concerned with hand actions, like reaching and grasping, and a limbic anatomical pathway that links the motor movements of the mouth or face with limbic regions involved in communication and emotions (Bowman et al., 2017). Although the relationship between action-induced resonance and empathy has been both theoretically and empirically supported (Can, Lacoboni, Dubeau, Mazziotta, & Lenzi, 2013; Cheng, Yang, et al., 2008; Gallese, 2001; Hoenen et al., 2017; Hoenen, Schain, & Pause, 2013; Yang et al., 2009) this link can be difficult to find due to various experimental factors, therefore it is necessary to take this research a step further and conduct other well-powered studies using different stimuli of a more emotional nature, especially since such stimuli might be more likely to elicit an experience sharing response as compared to a motor movement without any emotional relevance.

Furthermore, mu suppression may respond more directly to situational factors not captured by our straightforward stimuli. The IRI does not correlate strongly with measures of situational empathy (e.g., Davis, 1983; Eisenberg, Fabes, Nyman, Bernzweig, & Pinuelas, 1994 Light et al., 2015), and so it may be that the lack of relationship in our data is reflective of two separate, unrelated processes—a situational mirroring of observed experiences and trait tendency to empathize.

Previous research has found that mu suppression of a neutral action can be modulated by empathic top-down processes such as being asked to take the perspective of another (Hoenen et al., 2013). Therefore, future research should also investigate this relationship with a large sample size to see if the actual induction of an empathic response or mindset, not just trait tendency to empathize, impacts the resonance of an observed action that is devoid of any emotional relevance.

Finally, although used heavily as an index of trait empathy in the context of neural resonance, it is possible that the IRI subscales do not appropriately capture the shared neural representations resulting from sensorimotor resonance. The current subscales lack the ability to evaluate sharing the emotions of a specific target individual (identified as emotion contagion), but rather focus more on a variety of social, emotional and cognitive processes (Jordan et al, 2017). Future studies should aim to isolate an individual's experience-sharing capacity and its relationship to sensorimotor resonance using novel subscales proposed in the literature that specifically evaluate the tendency to share the emotions or mimic the behaviors of others (Jordan et al., 2017). Research has confirmed that caring about the feelings of others (empathic concern) is psychologically distinct from sharing the feelings of others (Jordan et al, 2017), highlighting the need for a better index of the resonance-based experience sharing that occurs specifically during sensorimotor resonance.

4.3 Future Directions

In our study, we further clarify the association between action-specific sensorimotor resonance and different components of trait empathy as measured through the Interpersonal Reactivity Index (Davis, 1980). However, previous research found that trait empathy of the person perceiving another's emotions was unrelated to the ability to be empathically accurate about another's emotion (Zaki, Bolger, & Ochsner, 2008). Moreover, self-report measures are prone to egocentric biases and social desirability, such that at least in one study self-report trait measures of empathy only correlated with empathic accuracy after controlling for social desirability (Klein & Hodges, 2001). Engaging in empathy and doing so accurately are distinct, and, in many situations, accuracy is particularly important; empathic accuracy was found to be associated with an increased tendency to help and was more predictive of pro-social behavior than gender, mood, or empathic trait scales (Marsh, Kozak, & Ambady, 2007). Moreover, impairments in the ability to accurately identify emotions in others have been identified in several populations characterized by antisocial behavior and a lack of empathy (Blair, Colledge, Murray, & Mitchell, 2001; Kropp & Haynes, 1987; Montagne, Kessels, Frigerio, De Haan, &

Perrett, 2005; Stevens, Charman, & Blair, 2001). Therefore, future research should focus on how mu suppression might relate to the ability to correctly infer the emotional states of others.

Lastly, we combined data from six studies that had different stimuli and somewhat different designs. It is possible that within study differences across trials may have added noise to the mu suppression measure for each individual study, such as the different levels of attractiveness or dominance for the facial expressions in Study 1 and Study 2, the different lengths of the videos in Study 5 and the presence of in-group and out-group hand presentations within the motor perception task in Study 4 (for all study specifics, please see supplementary materials). Although we did not find a difference in the strength of our effect across the different studies, single studies with adequate power and consistently similar stimuli across trials are greatly needed in the field to better understand the construct of sensorimotor resonance and its relationship to empathy.

4.4 Conclusions

The application of mu suppression to understand sensorimotor resonance in various realms is becoming increasingly popular, especially in clinical settings. Many researchers use this measure to investigate impaired social and emotional processing in disorders like schizophrenia and autism (e.g. Brown, Gonzalez-Liencres, Tas, & Brüne, 2016; Horan, Pineda, Wynn, Iacoboni, & Green, 2014; McCormick et al., 2012; Oberman et al., 2005). Future research in this area could have widespread implications for our understanding of healthy and clinically impaired empathy as well as for the development of interventions. However, there has been criticism and doubt concerning the extent to which mu suppression is an index of empathic abilities, specifically using it as a measurement of mirror neuron activity (e.g. Hobson & Bishop, 2017). The goal of this research was to help clarify whether mu suppression is indeed related to healthy variations in people's trait ability and propensity to empathize. Our results did not find robust evidence for a relationship between mu suppression and the empathic traits of perspective taking, personal distress, and fantasy, and Bayesian analysis provided strong evidence against relationships with both perspective taking and fantasy subscales. Given our somewhat inconclusive results surrounding the personal distress relationship and suggestive evidence for an association with empathic concern and mu suppression – both of which traits arguably are associated with experience sharing - experience sharing might be a promising direction for future research, especially considering that the IRI currently lacks a facet that assesses experience sharing directly.

The ability to understand and infer the actions, intentions and inner states of others is crucial for human social interaction, which is necessary for psychological well-being and survival. Research and theory over the last two decades has emphasized the relationship between sensorimotor resonance and empathic abilities; previous research has linked EEG mu suppression in response to actions with empathic traits suggesting that mu suppression could be a biomarker for empathic mimicry (Cheng, Lee, et al., 2008). Given our present findings that suggest no relationship between mu suppression and all but the empathic concern sub-scale of the IRI, action-related mu suppression may only be associated with very specific forms of empathy, and not necessarily in the way that previous research has continuously proposed. Our work stresses the importance of larger sample sizes when studying mu suppression, particularly when correlating with individual difference measures, and suggests a more nuanced differentiation of the sub-components of empathy as well the use of a variety of empathy measures including measures of state empathy and empathic accuracy to further clarify the relationship between action-related sensorimotor resonance and empathy.

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Conflict of Interest

The authors declare that they have no conflicts of interest.

Supplementary Material

Methods

Descriptions of Studies

Below are descriptions of each of the separate studies used in this manuscript. See Table S1b for information on additional tasks presented before and after the action video during the motor perception task as well as additional self-report measures beyond the Interpersonal Reactivity Index administered in each study. See Figure S1 for depictions and numbers of motor perception task trials in each study.

Study 1. For the motor perception task in this study, participants saw faces of varying attractiveness prior to seeing the action video of a hand squeezing a ball (Stycyznski & Gutsell, unpublished data).

Study 2. Participants saw faces of varying characteristics related to dominance prior to seeing the action video of a hand squeezing a ball (Stycyznski & Gutsell, unpublished manuscript).

Study 3. Prior to the motor perception task, participants were required to watch various videos of individuals sharing emotional autobiographical memories and to rate how they felt the person in the video was feeling at the time they were speaking. They then watched the action video of a hand squeezing a ball (DiGirolamo & Gutsell, unpublished data).

Study 4. Participants were asked to write about a day in the life of a racial out-group member while either taking the target's perspective or taking an objective perspective. They then watched action videos with hands that matched their own race, as well as hands of the out-group race squeezing a ball (Gutsell, Simon, & Jiang, under review).

Study 5. In this study, stimuli were manipulated on two criteria - stimulus length and whether the target was animated. The motor perception task, therefore, consisted of participants watching different length action videos of human, wire, or mesh hands squeezing a ball (Acker & Gutsell, unpublished data). Only those trials in which participants saw the human hand were used in the current study.

Study 6. Participants were introduced to nine nameless targets who were purported to be other participants in the study (called Participant A, Participant B, etc.). These targets were presented prior to the action videos as silhouettes with high, medium, or low ratings on the dimensions of warmth and competence (Hager, Yang, & Gutsell, 2018; Simon, Stycyznski, & Gutsell, under review).

Multi-level modeling analyses

In order to test the variation in the relationship between personal distress and mu suppression across the six studies, we set up a series of multi-level models with personal distress as the predictor variable and mu suppression ratio scores at C3 as the outcome variable. The two-level models contained individual participants nested within studies. Thus, first-level units were each of the 252 participants and second level units were each of the six studies. The first-level predictor was the personal distress score for each participant, represented by the following equations:

Level 1 equation: $Y_{ij} = \beta_{0j} + \beta_{1j} (X_{ij}) + e_{ij,}$

where Y_{ij} represents the mu suppression ratio score for person i within study j, X_{ij} represents the Level 1 predictor (personal distress score) for person i within study j, β_{0j} is the intercept for mu suppression for study j, β_{1j} is the slope representing the relationship between mu suppression and the Level 1 predictor (personal distress) for study j, and e_{ij} is the random error of prediction for the Level 1 equation.

Level 2 equations: $\beta_{0j} = \gamma_{00} + \mu_{0j}$,

Where γ_{00} represents the overall intercept (grand mean) of mu suppression, and μ_{0j} is the unique effect of study j on the intercept and

$\beta_{1j} = \gamma_{10} + \mu_{1j}$,

where β_{1j} is the slope of the Level 1 predictor (personal distress score) on mu suppression for each study j, γ_{10} is the intercept of each study, and μ_{1j} is the deviation of a study j's slope from the overall slope.

Since our focus was on testing the variation of the Level 1 predictor (personal distress) across studies, we started with a model including the between-study variance of the slope of personal distress (μ_{1j}) across the studies:

$Y_{ij} = \gamma_{00} + \gamma_{10}$ (Personal Distress_{ij}) + μ_{0j} + μ_{1j} (Personal Distress_{ij}) + e_{ij}.

Next, we tested a model without the between-study variance of the slope of personal distress scores:

$Y_{ij} = \gamma_{00} + \gamma_{10}$(Personal Distress_{ij}) + μ_{0j} + $e_{ij.}$

Likelihood ratio testing (LRT) was used to compare the two models, testing the null hypothesis that $\mu_{1j} = 0$. There was no difference between the models, $\chi^2(1) = .15$, $p= .70$, failing to reject the alternate hypothesis and suggesting that the slope of personal distress does not vary randomly across studies.

To test for the variation in the relationship between the mu component and empathic concern across the six studies, this same analysis was run again, replacing mu suppression ratio score at C3 with the mu component during action observation and personal distress with empathic concern. There was again no difference, $\chi^2(1) = -.15$, $p = .18$, suggesting that the slope of empathic concern did not vary randomly across studies. For details concerning both models, see Table S2b.

Table S1b

Measures and stimuli used in addition to the Interpersonal Reactivity Index and Motor Perception Tasks in each of the 6 studies.

Study	Tasks prior to action video	Stimuli prior to action video	Measures completed post action video
1	None	Facial expressions of varying attractiveness	Self-Sufficiency Scale Big Five Inventory (BFI; John & Srivastava, 1999) Implicit Theories Questionnaire (Hong, Dweck, Chiu, Lin, & Wan, 1999) Beliefs in Genetic Overlap (Kang, Plaks, & Remedios, 2015; Plaks, Malahy, Sedlins, & Shoda, 2012) Need for Power Scale
2	None	Facial expressions of varying dominance	(Same as Study 1)
3	<u>Heartbeat Detection Task</u> (Schandry, 1981): Participants silently counted their heartbeats by simply focusing inward and listening to their body, without taking their pulse, for specific time intervals. <u>Empathic Accuracy</u> (Zaki, Bolger, & Ochsner, 2008): Participants watched 20 videos (2.25 min in length) of target individuals discussing emotional autobiographical events (balanced for positive and negative events), while continuously rating the individual's feelings using a sliding 9-point Likert scale.	None	Empathy Quotient (Baron-Cohen & Wheelwright, 2004) Body Perception Questionnaire (Porges, 1993) Mindfulness Attention Awareness Scale (MASS; Brown & Ryan, 2009)
4	<u>Perspective Taking Task</u> (Todd, Bodenhausen, Richeson, & Galinsky, 2011) Participants were asked to write about an	None	Beliefs in Genetic Overlap (Kang et al., 2015; Plaks et al., 2012)

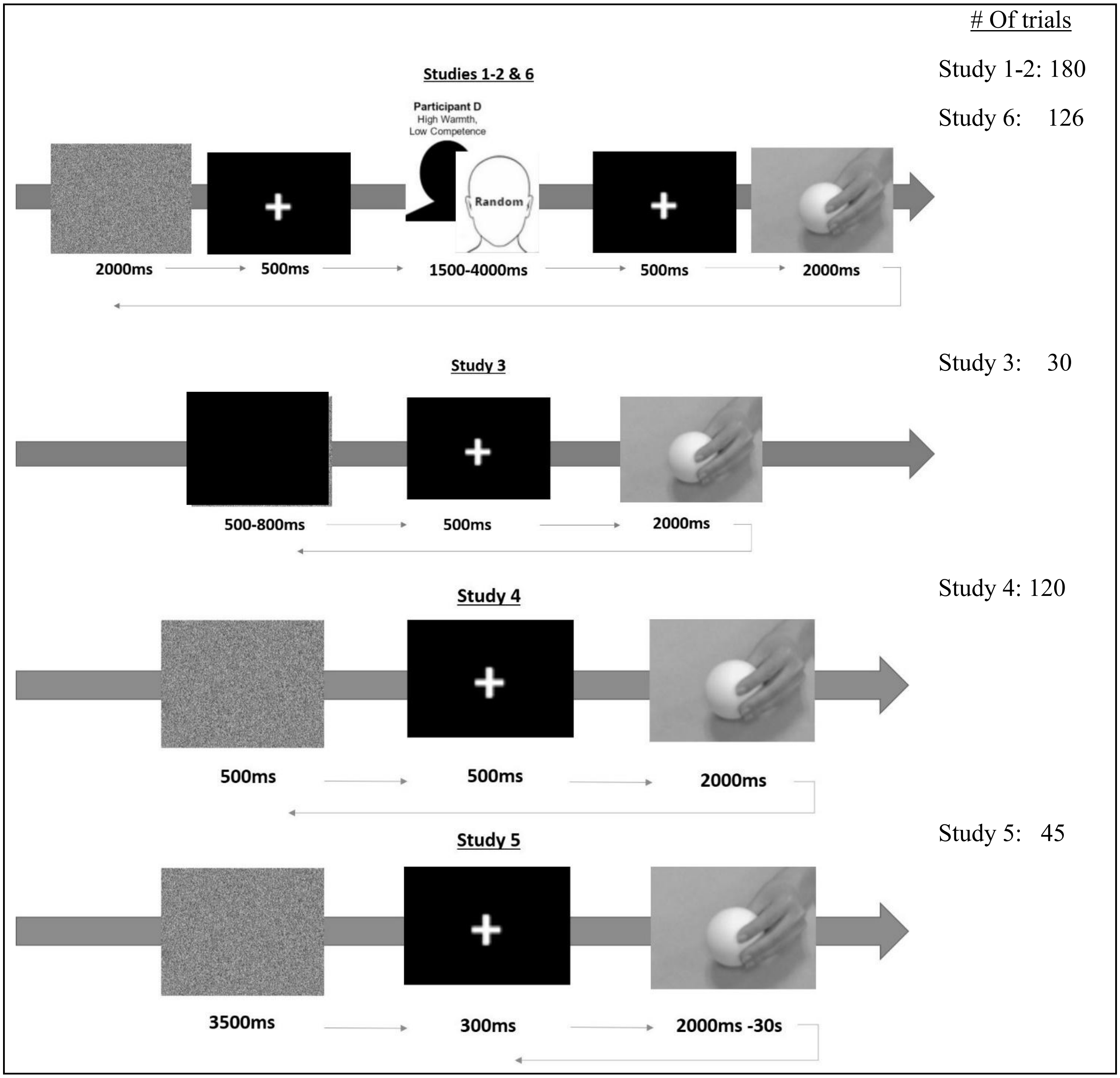
	African American target objectively (control), or to take their perspective (manipulation). Introduced to two African American and two racial in-group targets whose hands they would then be viewing in the action observation videos.		
6	Personality Test (adapted from Horchak, Giger, & Garrido, 2016): Participants were asked to choose from a list of adjectives which words they tend to be perceived as. Told that nine other people took the same test and were given the ratings of those people.	9 faceless targets with trait labels of High/Low Warmth and High/Low Competence	Active/Passive Help and Harm Behavioral Task (adapted from Cuddy, Fiske, & Glick, 2008) Multi-dimensional Assessment of Interoceptive Awareness (MAIA) (Mehling et al., 2012) Implicit Theories Questionnaire (Hong et al., 1999) Big Five Inventory (BFI; John & Srivastava, 1999) Self-ball squeezing task

Table S2b.
Personal Distress (C3) and Empathic Concern (Mu Component) Models Allowing Slopes to Vary by Study

	C3 Mu Ratio: Fixed Slopes			**C3 Mu Ratio: Random Slopes**			**Mu Component: Fixed Slopes**			**Mu Component: Random Slopes**		
Predictors	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	-0.21	-0.30 – -0.13	**<0.001**	-0.21	-0.30 – -0.13	**<0.001**	-11.28	-13.81 – -8.75	**<0.001**	-11.28	-13.81 – -8.75	**<0.001**
Personal Distress	0.02	-0.01 – 0.05	0.118	0.02	-0.01 – 0.05	0.145						
Empathic Concern							-0.92	-1.61 – -0.23	**0.009**	-0.92	-1.61 – -0.23	**0.009**
Random Effects												
σ^2			0.02			0.02			15.67			15.67
τ_{00}	0.00 Studynumber			0.00 Studynumber 0.00 Studynumber.1			0.00 Studynumber			0.00 Studynumber 0.00 Studynumber.1		
ICC	0.05 Studynumber			0.02 Studynumber 0.00 Studynumber.1			0.00 Studynumber			0.00 Studynumber 0.00 Studynumber.1		
Observations	252			252			225			225		
Marginal R^2 / Conditional R^2	0.010 / 0.063			0.010 / 0.032			NA			NA		

Figure Captions

Figure S1. Depiction of a typical trial in the motor perception task across Studies 1-6, and the number of trials for each study.



Of trials
Study 1-2: 180
Study 6: 126
Studies 1-2 & 6
Participant D
High Warmth,
Low Competence
Random
2000ms
500ms
1500-4000ms
500ms
2000ms
Study 3: 30
Study 3
500-800ms
500ms
2000ms
Study 4: 120
Study 4
500ms
500ms
2000ms
Study 5: 45
Study 5
3500ms
300ms
2000ms -30s

Figure S1.

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***Credit Author Statement**

CRediT author statement

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