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The infant EEG mu rhythm: Methodological considerations and best practices

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ABSTRACT

The EEG mu rhythm, recorded from scalp regions overlying the sensorimotor cortex, appears to exhibit mirroring properties: It is reactive when performing an action and when observing another perform the same action. Recently, there has been an exponential increase in developmental mu rhythm research, partially due to the mu rhythm's potential role in our understanding of others' actions as well as a variety of other social and cognitive processes (e.g., imitation, theory of mind, language). Unfortunately, various methodological issues impede integrating these findings into a comprehensive theory of mu rhythm development. The present manuscript provides a review of the infant mu rhythm literature while focusing on current methodological problems that impede between study comparisons. By highlighting these issues and providing an in depth description and analysis we aim to heighten awareness and propose guidelines (when possible) that will promote rigorous infant mu rhythm research and facilitate between study comparisons. This paper is intended as a resource for developmental scientists, regardless of EEG expertise.

Introduction

What was once an electroencephalogram (EEG) rhythm noted primarily for its association with motor activity may now provide a window into our understanding of others' actions as well as a variety of other social and cognitive processes (e.g., imitation, theory of mind, language; for review, see Pineda, 2005). The EEG mu rhythm (adult 8–13 Hz), recorded from scalp regions overlying the sensorimotor

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cortex, appears to exhibit mirroring properties: It is reactive when performing an action and when observing another perform the same action. Converging neuroscience evidence using functional magnetic resonance imagining (fMRI; e.g., Buccino et al., 2004), transcranial magnetic stimulation (TMS; e.g., Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995), magnetoencephalography (MEG; e.g., Hari et al., 1998), and single-cell recording (Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried, 2010) suggests that the human brain may have a neural mirroring system that is analogous to the mirror neuron system found in rhesus macaques (but see Gallese, Gernsbacher, Heyes, Hickok, & Iacoboni, 2011; Hickok, 2009; for reviews of the human mirror neuron debate). Clearly, the potential implications for understanding the development of a neural mirroring system are widespread. There has been an exponential increase in developmental EEG mu rhythm research over the last few years, and the primary goal of this paper is to suggest guidelines that will facilitate cross laboratory comparisons toward a comprehensive understanding of the development of the EEG mu rhythm. To this end, we begin by providing a brief overview of the EEG mu rhythm with a focus on infant mu rhythm research. Next, we present a detailed analysis of methods used in infant mu rhythm research (from behavioral protocols to psychophysiology) and recommend steps that can be taken to facilitate between laboratory comparisons.

Initial evidence of mirror neurons was discovered in 1992 via single-cell recordings in area F5 in the ventral premotor cortex of rhesus macaques (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; see also Gallese, Fadiga, Fogassi, & Rizzolatti, 1996). Specifically, these researchers reported that there were individual motor neurons that fired during both the execution of a goal-directed action and the observation of another completing the same action. Since their discovery, there has been much interest in determining whether the human brain exhibits similar neural mirroring properties. The adult 8–13 Hz mu rhythm, recorded over the sensorimotor cortex (e.g., scalp electrodes C3, C4), is prominent during periods of rest (i.e., quiet wakefulness) and is attenuated during the execution or observation of goal-directed actions (see Pineda, 2005 for a review). Recently, simultaneous EEG and fMRI recordings have suggested that activation of portions of the human neural mirroring system—inferior parietal lobe, dorsal premotor cortex, primary somatosensory cortex—are correlated with mu attenuation (Arnstein, Cui, Keysers, Maurits, & Gazzola, 2011).

EEG is one of the most preferred neuroimaging techniques for developmental populations. As compared to other neuroimaging techniques, it has excellent temporal resolution, is noninvasive, and is relatively resistant to motor artifacts (Casey & de Haan, 2002). Marshall and Meltzoff (2011) provided an informative review of the infant mu rhythm literature, while also highlighting theoretical questions that are essential to this developing field. In the relatively brief time since their review, the infant mu rhythm literature has more than doubled. Unfortunately, various methodological issues impede integrating these findings into a comprehensive theory of mu rhythm development. Although Marshall and Meltzoff noted important methodological issues, the focus of their review was to suggest guidelines for tying mu suppression to action perception. The goal of the present manuscript is to outline methodological considerations for infant mu rhythm research and propose guidelines that will promote cross laboratory comparisons for infant mu rhythm work.

Infant EEG mu rhythm

A brief summary of infant mu rhythm studies during action observation only and action observation plus execution can be found in Tables 1 and 2, respectively. As can be seen, infant mu rhythm research has examined a variety of topics. The most common theme has been comparing mu reactivity (i.e., less mu power [a measure of neural activity] is associated with more reactivity of the mu rhythm) during the observation of goal-directed versus non-goal-directed actions. Evidence of greater mu reactivity during goal-directed actions has been found with 8- to 9-month-olds (Nyström, Ljunghammar, Rosander, & von Hofsten, 2011; Southgate, Johnson, El Karoui, & Csibra, 2010), which parallels findings with 4- to 11-year-olds (Lepage & Théoret, 2006) and adults (e.g., Muthukumaraswamy, Johnson, & McNair, 2004; Nyström, 2008). Six-month-olds, on the other hand, failed to exhibit a difference in mu power between goal-directed and non-goal-directed actions (Nyström, 2008). The developmental trajectory may be complex, however, as a different pattern of results has been found in 18- to 36-month-olds—greater mu attenuation to mimicked actions than goal-directed actions (Ruysschaert, Warreyn, Wiersema, Metin, & Roeyers, 2013; Warreyn et al., 2013).