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Topographic analysis of the development of individual activation patterns during performance monitoring in medial frontal cortex

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ABSTRACT

Age-related improvements in human performance monitoring have been linked to maturation of medial frontal cortex (MFC) in healthy youth, however, imaging studies conflict regarding age-related changes in MFC activation patterns. Topographical analysis of single-subject activation enables measurement of variation in location of MFC activation by age, as well as other potentially influential factors (e.g., performance on task). In this study, 22 youth (ages 8–17 years) and 21 adults (ages 23–51 years) underwent functional magnetic resonance imaging during a performance monitoring task examining interference and errors. Single-subject factors (extent of MFC activation, age and accuracy) were entered into a three-level hierarchical linear model to test the influence of these characteristics on location of MFC activation. Activation shifted from a rostral/anterior to a more dorsal/posterior location with increasing age and accuracy during interference. Inclusion of age and accuracy accounted for almost all of the unexplained variance in location of interference-related activation within MFC. This pattern links improvement of performance-monitoring capacity to age-related increases in posterior MFC and decreases in anterior MFC activation. Taken together, these results show the maturation of performance monitoring capacity to depend on more focal engagement of posterior MFC substrate for cognitive control.

1. Introduction

Behavioral capacity to monitor performance develops throughout childhood and into adulthood; including the ability to ignore distractors, identify correct response and correct performance after a mistake (Casey et al., 2010). The medial frontal cortex (MFC) plays a key role in performance monitoring (Ridderinkhof et al., 2004), and the maturation of this region is linked to age-related improvement in performance monitoring capabilities (Fitzgerald et al., 2010). However, the way in which MFC maturation contributes to the development of performance monitoring remains an open question. Development contributes to changes in white matter and gray matter development and

Abbreviations: MFC, medial frontal cortex; FC, frontal cortex; MSIT, Multisource Interference Task; RT, reaction time; LS, longitudinal spline; *R*, radius.

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contributes to changes in the degree of specialized in function within an area, the location of specific brain functions, and connectivity to other areas to support behavioral performance (Johnson, 2011). Within the MFC the literature is conflicting on whether MFC activation becomes more focal with development, whether shifts in MFC activation correlate with developmental performance improvements and whether the location of performance monitoring shifts within the MFC during development.

Performance monitoring has been associated with conflicting reports of age-related decreases (Durston et al., 2006; Marsh et al., 2006; Velanova et al., 2008) and increases (Adleman et al., 2002; Schroeter et al., 2004; Rubia et al., 2007; Fitzgerald et al., 2010) in magnitude of MFC activity. In addition, some work suggests that the extent of activation (measured by the number of voxels activated) becomes more focal (Schroeter et al., 2004; Durston et al., 2006; Lamm et al., 2006; Velanova et al., 2009) or broader with age (Adleman et al., 2002; Bunge et al., 2002). Cognitive developmental theories of interactive specialization identify the PFC as a region that is less specialized in childhood and becomes more specialized during development. Theoretically children should exhibit a more diffuse activation during than adults with a greater specialization with age (Johnson, 2011). Developmental differences in magnitude and extent of activation can be confounded by traditional group-averaged data, which may contribute to the instability of MFC findings across developmental studies. Specifically, group differences may either be minimized or spuriously introduced by individual subjects in whom magnitude and/or extent of activation in a particular location differs substantially from the group average (Stern et al., 2009). Large variance in the location of individual peaks of activation may reduce the power to identify group differences in averaged data. Individual peak activity may vary across a range of 8–10 cm activation within the medial frontal wall (Taylor et al., 2006). In addition, individual variability in performance may obscure developmental change in extent of PFC activation.

There are likely developmental differences in how the brain responds to the demands of performance monitoring tasks as performance improves with age. One study demonstrated an increase in dorsal/posterior MFC and a decrease in an anterior/rostral region with age while controlling for performance (Perlman and Pelphrey, 2010). However they also found the reverse pattern correlated with higher levels of fearful temperament. This may suggest that while children are performing a task at similar levels, some may view the task as more emotionally salient. Prior work has established that ventral regions of the MFC are activated in response to more emotionally salient information (Somerville and Casey, 2010). Emotional salience of cognitive tasks may change with age as well. Children may struggle more to maintain performance on a task with greater emotional arousal.

Age-related changes in location of aspects of performance monitoring function within MFC have not been well studied. However, given the role of dorsal MFC in successful performance monitoring (Ridderinkof et al., 2004), age-related increases in dorsal MFC activation should correspond with maturation of performance monitoring function. Other work differentiates between the use of rostral MFC for new rule learning and premotor dorsal FC for simple action rules (Badre and D'Esposito, 2009). There may be a developmental shift where children utilize new rule learning neuroanatomical regions (rostral MFC) to maintain the same level of performance on tasks that would be processed as simple action rules by adults (premotor dorsal FC). Better performing adults and children (i.e., those with well learned rule execution) should process in dorsal/posterior MFC during on low load tasks. However, as children develop, performance (i.e., accuracy) generally improves, necessitating the consideration of performance measures, as well as age, in mapping the development of performance monitoring function (Casey et al., 2008).

The present study seeks to examine the development of performance monitoring in children and adults ages 8–51. By analyzing topographical measures of MFC location (Stern et al., 2009). We sought to gain insight into the development of MFC-based performance monitoring function by analyzing single subject activation during the Multisource Interference Task (MSIT; Bush et al., 2003). The MSIT requires participants to respond to the different number out of three numbers presented onscreen. There are two conditions, congruent, in which the target number is flanked by Xs and incongruent where the target number is flanked by distracting numbers. Hierarchical linear modeling enabled us to examine the independent role of age, accuracy and activation extent on location of peak activations within the MFC. Based on work indicating a shift in location of activation from new rule learning to simple action rules, we hypothesized that better performance would predict a shift in location of activation from rostral/anterior to dorsal/posterior MFC independent of age. In addition, we hypothesized that the similar shift would be exhibited based on age, independent of performance. This hypothesis was based on prior work showing a dorsal developmental shift in function. Finally, based on the interactive specialization theory of developmental cognitive neuroscience, we predicted age and accuracy would associate with a shift from more diffuse MFC activation extent to more focal extent of activation within posterior MFC.

2. Materials and methods

Permission to conduct this study was obtained through the University of Michigan Institutional Review Board and the research conforms to the Code of Ethics of the World Medical Association (Declaration of Helsinki). According the IRB procedures, consent was obtained by adults and parents of children and children provide assent to participate in this study.

2.1. Participants

Healthy youth and adults were recruited through community advertisements, flyers and a university sponsored research recruitment website. Twenty-nine healthy children and adolescents between the ages of 8–17 (16 females; mean age = 12.9, *SD* = 2.8) and 21 healthy adults