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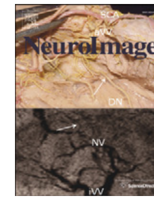

The development of inhibitory control: An averaged and single-trial Lateralized Readiness Potential study

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ABSTRACT

Inhibitory control (IC) is an important contributor to educational performance, and undergoes rapid development in childhood. Age-related changes in IC were assessed using an in-depth analysis of reaction time, the Lateralized Readiness Potential (LRP), and other event-related potential (ERP) measures to control for speed of processing. Five-year-olds, 8-year-olds and adults completed an adapted Stroop task. Both reaction time and ERP results suggest that IC does develop in this age range, over and above changes in speed of processing. The LRP identified two processes that contribute to IC. These processes develop at different rates — an early process, involving how the conflict is initially responded to is mature by age 5, while a later process, involving how the conflict is overcome is still developing after 8 years of age. We propose that these early and late processes reflect interference suppression and response inhibition, respectively. Further, a single-trial analysis of the LRP in the incongruent condition provides evidence that the LRP is consistent across trials and functionally similar in each age group. These results corroborate previous findings regarding the development of IC, and present a new and useful tool for assessing IC across development.

Introduction

The term ‘executive functions’ encompasses a range of skills used to monitor and control behavior flexibly in novel situations; these skills are important for education and child development. While executive functioning research originally emerged from research into adult clinical populations (e.g. Luria, 1973), these crucial skills have increasingly been investigated in children (Carlson, 2005; Epsy, 1997) and in an educational context (Blair and Razza, 2007; Meltzer, 2007). Further, in bridging the disciplines of neuroscience and education, executive functions may be fruitful skills to investigate as they are more specifically defined and discrete than the learning approaches they may contribute to or be precursors of, such as metacognitive skilfulness (Fernandez-Duque et al., 2000; Shimamura, 2000). Inhibitory control (IC), the ability to suppress thoughts or responses when they are inappropriate or no longer relevant (Deak and Narasimham, 2003), is one executive function which appears to be crucial to cognitive development. Here we provide an event-related brain potential (ERP) investigation of developmental changes of IC across three age groups (5-year-olds in Year 1 of primary school, 8-year-olds in Year 3 of primary school, and adults) using an adaptation of a Stroop task. Our aim was to understand how the temporal properties of covert response preparation, as well as the increasingly successful suppression of unwanted motor tendencies, contribute to the development of IC. Besides a thorough analysis of reaction time (RT) we exploited an ERP derivative, the Lateralized Readiness Potential (LRP), which is able to track motor response preparation before a behavioral response is given. Several other ERP parameters, usually associated with stimulus processing speed, were also examined as control measures.

Inhibitory control is a major contributor to educational performance. It has been associated with mathematical and reading ability in children at all stages of schooling: preschool (Deak and Narasimham, 2003; Espy et al., 2004), kindergarten (Blair and Razza, 2007; Brock et al., 2009), the beginning of primary school (Swanson, 2006) and the end of primary school (St Clair-Thompson and Gathercole, 2006). Aside from contributing to various academic subjects, inhibitory control appears to be crucial for coping with other demands of attending school. That is, Brock et al. (2009) found that a composite measure of ‘cool’ executive functions (that is, those with fewer emotional and more cognitive demands) predicted both a child's behavior in class, as reported by their teacher, and their engagement in learning, as observed by a researcher. IC has been associated with features of temperament important for formal school settings, such as activity level and impulsivity (Gonzalez et al., 2001) and social

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emotional competence (Rhoades et al., 2009). IC has also been linked to other milestones in cognitive development that are important for educational gains, such as working memory which is required when manipulating and maintaining information simultaneously (Alloway et al., 2005). Both Roberts and Pennington (1996) and Wilson and Kipp (1998) have proposed that IC and working memory are directly related, albeit in slightly different ways, and there is some debate regarding how this relationship changes with age (Davidson et al., 2006; Roncadin et al., 2007; Tsujimoto et al., 2007). Further, IC skills, in particular as relating to conflict resolution and not delay, are superior in bilingual children (Bialystok and Martin, 2004; Carlson and Meltzoff, 2008; Martin-Rhee and Bialystok, 2008), and aging bilingual adults (Bialystok et al., 2004) as compared to their monolingual peers, suggesting this is a malleable skill which is somewhat dependent on environment.

As yet, the majority of research into inhibitory control in young children has focused on developing age-appropriate tasks and determining how the skill develops. IC is normally assessed in the laboratory using tasks such as the Stroop (Stroop, 1935), Eriksen flanker (Eriksen and Eriksen, 1974), Go/NoGo (e.g. Pfefferbaum et al., 1985), and Stop-Signal (Logan, 1994) tasks; in more real-to-life settings, tasks such as delay of gratification (Mischel et al., 1972), A-not-B (Piaget, 1954), and the bear–dragon task (Reed et al., 1984) have been used. Accordingly, depending on the specific tasks used, there is variation in findings regarding the 'age of onset'. It can be concluded fairly confidently that a basic form of IC is present even from one year of age (see Davidson et al., 2006; Garon et al., 2008 for reviews) but it continues to develop until adolescence (Stop-Signal and Eriksen flanker tasks) or adulthood (Stroop task, Huizinga et al., 2006). Many researchers consider the first few years of formal schooling to be a period of intense growth in IC and related skills (Hughes et al., 2010), making this an interesting stage to examine.

Typically, developmental studies rely on accuracy or raw RT data to draw conclusions, an approach which has recently been challenged (Span et al., 2004) as some researchers highlight the need for speed of processing to be taken into account when comparing participants of different ages. Different statistical methods have been adopted to achieve this, including the use of standardized RT scores (Christ et al., 2001), proportional transformations of RTs (Christ et al., 2001; Johnson et al., 2003), and logarithmic transformations of RTs. Faust et al. (1999) posit that standardized RTs are superior to both log and proportional transformed RTs in terms of controlling for differences in processing speeds. However, it may not always be appropriate to transform raw RTs into standard scores, depending on the shape of the distribution. For instance, when standardized RTs are used, it is assumed that the raw RTs are distributed normally, when in fact often they are skewed (Jensen, 1992). A solution to the above issue is provided by fitting an exponential-Gaussian (ex-Gaussian) distribution to RTs (Leth-Steensen et al., 2000; McAuley et al., 2006; Mewhort et al., 1992; Myerson et al., 2007). This approach produces three parameter values: mu (μ), which reflects mean performance, sigma (σ), which reflects variance in performance, and tau (τ), which reflects the skewness of the upper tail of the distribution. Ex-Gaussian analysis was recently applied to a classic Stroop task with children aged 10–12 years and young adults (Fagot et al., 2009). The authors concluded that 'whereas for young adults, interference is reflected in a slowing of responses (μ) and lapses of attention (τ) in the incongruent condition, interference in children seems to be entirely accounted for by a slowing of responses (μ)' (Fagot et al., 2009). However, there are two caveats regarding this interpretation. First, the participants were not all performing the task in their native language which would impact the level of interference the color–words asserted on the participants. Second, the classic Stroop task is not ideal for comparing IC in children and adults, as word reading is more automatic in adults than in children. Therefore, it is unclear whether the inhibitory demands were equivalent for each group. A simplified version of the Stroop which is not affected by reading experience would be better able to address developmental effects. For this reason, in our research we have used such a task, and adopted a range of RT transformations in an attempt to control for differences in processing speed.

An important issue concerning RT and accuracy measures is that they represent the culmination of many cognitive processes. In contrast, exploiting its virtually unlimited temporal resolution, electroencephalography (EEG) provides a detailed insight into the cognitive processes that occur before behavioral responses are given. With regard to IC, most adult EEG studies have focused on understanding the functional significance of the centro-parietal P3 (henceforth referred to as P3b, as defined by Dien et al., 2004) and fronto-central N2 components. A series of studies, using different tasks, showed that greater P3b peak amplitudes and latencies were elicited for conditions requiring IC (continuous performance task: Davis et al., 2003; Stop-Signal task: Dimoska et al., 2006; Eriksen flanker task: Ridderinkhof and van der Molen, 1995). Subsequently, two studies that used cueing Go/NoGo paradigms in adults (Bruin et al., 2001; Smith et al., 2007) found that the P3b amplitude was larger in 'NoGo' as opposed to 'Go' conditions, and for incorrectly as compared to correctly cued trials (i.e. when the participant was cued to prepare the incorrect response and therefore the level of IC required was increased). Ramautar et al. (2004) found a similar effect using the Stop-Signal paradigm with adults. These findings suggest that the P3b component may be directly or indirectly sensitive to IC, as altering the IC demands of a task results in changes in features of the P3b. The N2 is usually observed in conjunction with the P3b, and dissociating their functional significance has been the focus of a number of studies. For instance, while Bruin et al. (2001) and Smith et al. (2007) found that the P3b was affected by the validity of cues, both also found the N2 was not. Similarly, Donkers and Van Boxtel (2004) introduced a third condition (called GO) of the classic Go/NoGo task, whereby in the 'GO' condition the adult participants were required to respond with maximum force (so there was conflict, but no response inhibition). The N2 was elicited in both NoGo and GO trials, and N2 amplitudes were greater if these trials were less frequent. These, and many other studies, suggest that the N2 reflects conflict monitoring, and not response inhibition.

Developmental EEG studies that have tested the N2 and P3b components in children in order to assess IC report that the peak latencies and amplitudes of the N2/P3b are reduced in older relative to younger children (continuous performance task: Davis et al., 2003; Go/NoGo task: Lamm et al., 2006; Eriksen flanker task: Ridderinkhof and van der Molen, 1995). Developmental fMRI studies have largely attributed the development of IC to the maturation of the prefrontal cortex (Bunge and Wright, 2007; Durston and Casey, 2006; Marsh et al., 2006; van der Molen, 2000). For example, Adleman et al. (2002) found that in a Stroop task, parietal lobe activation reaches adult levels by adolescence, but prefrontal cortex activation continues to develop in this period. Rubia et al. (2007) found similar results with the Stop-Signal task — that prefrontal cortex activation increases with development. Schroeter et al. (2004) also found increased dorso-lateral prefrontal cortex activation with age in a functional near-infrared imaging (fNIR) study using a Stroop task, and participants aged 7–29 years. These results have been interpreted as indicating that the prefrontal cortex is crucial for IC, and that children's IC is limited by this brain region being late maturing. However, a limitation of many fMRI and P3b and N2 studies is that the functional interpretation of findings is not clear.

It has long been theorized that there are at least two processes that contribute to IC. These can generally be grouped as 'early' (referred to as interference suppression or stimulus interference control) and 'late' (referred to as response inhibition or response interference control) processes. Hereafter we refer to these early and late processes as interference suppression and response inhibition, respectively. Interference suppression is defined as 'the ability to filter out irrelevant information in the environment' (Bunge et al., 2002) and can be considered an 'early' stage process because when interference is successfully suppressed initially, less response inhibition is required