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Neurophysiological correlates of error monitoring and inhibitory processing in juvenile violent offenders

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ABSTRACT

Performance monitoring is crucial for well-adapted behavior. Offenders typically have a pervasive repetition of harmful-impulsive behaviors, despite an awareness of the negative consequences of their actions. However, the link between performance monitoring and aggressive behavior in juvenile offenders has not been closely investigated. Event-related brain potentials (ERPs) were used to investigate performance monitoring in juvenile non-psychopathic violent offenders compared with a well-matched control group. Two ERP components associated with error monitoring, error-related negativity (ERN) and error-positivity (Pe), and two components related to inhibitory processing, the stop-N2 and stop-P3 components, were evaluated using a combined flanker-stop-signal task. The results showed that the amplitudes of the ERN, the stop-N2, the stop-P3, and the standard P3 components were clearly reduced in the offenders group. Remarkably, no differences were observed for the Pe. At the behavioral level, slower stop-signal reaction times were identified for offenders, which indicated diminished inhibitory processing. The present results suggest that the monitoring of one's own behavior is affected in juvenile violent offenders. Specifically, we determined that different aspects of executive function were affected in the studied offenders, including error processing (reduced ERN) and response inhibition (reduced N2 and P3). However, error awareness and compensatory post-error adjustment processes (error correction) were unaffected. The current pattern of results highlights the role of performance monitoring in the acquisition and maintenance of externalizing harmful behavior that is frequently observed in juvenile offenders.

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1. Introduction

Crime and violent behavior continues to be a significant problem in Western societies despite investments in implementing delinquency-prevention programs and other education interventions (Greenwood, 2008). Despite the impact of criminal behavior, few neuroscientific studies have examined the role of cognitive control mechanisms in the regulation of violent behavior using fine-grained electroencephalographic measures (Event-Related Brain potentials, ERPs). These measures allow a very accurate evaluation of certain cognitive control processes such as error monitoring and inhibitory processing, by tracking specific ERP components that tap into their neural dynamics. At the temporal level these measures are very reliable and might allow a better characterization of the role of interindividual variability in certain cognitive control processes that could explain the association previously observed between cognitive control and aggressive-violent behavior (Blair et al., 2006, 2007; Giancola, 2004; Hoaken, Shaughnessy, & Pihl, 2003; Krakowski, 2003; Krämer et al., 2007; Krämer, Kopyciok, Richter, Rodriguez-Fornells, & Münte, 2011; LeMarquand et al., 1998). A common explanation for this relationship is that low values of cognitive control might be associated to a lack of capacity to control aggressive behavior, highlighting the important role of inhibitory processing in the regulation of violent behavior (Gorenstein & Newman, 1980). Another core aspect

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of cognitive control that has recently attracted a lot of attention is error monitoring, especially its relationship to individual differences in aggressive behavior (Brazil et al., 2009; Dikman & Allen, 2000; Krämer et al., 2011; Munro et al., 2007a). In the present study, we investigated both core aspects of cognitive control, error monitoring and inhibitory processing, in a selected sample of juvenile violent offenders using ERPs. In legal terms, the word offender refers to an individual who violates or transgresses the law and is often linked to violent behavior. Specifically, the term juvenile offender refers to an individual who has not yet reached adulthood (age range of 15–20 years old). This period between 15 and 20 years is critical for the development of cognitive control processes primarily because relevant prefrontal cerebral structures attain their neural maturation during this time (Diamond, 2002; Segalowitz & Dywan, 2009).

A central function of cognitive control is to monitor and regulate our behavior. Thus, an important aspect of cognitive control is the self-regulation of our own performance, which comprises several processes such as the constant monitoring of our actions, detection of conflict, implementation of cognitive control mechanisms after conflict-detection or error-commission and subsequent behavioral adjustments (Logan, 1985; Rabbitt & Rodgers, 1977; Ridderinkhof, van den Wildenberg, Segalowitz, & Carter, 2004). These crucial functions are supported, to a great extent, by the prefrontal cortex and, more specifically, by the medial prefrontal cortex (MPFC), which includes the anterior cingulate cortex (ACC), the inferior frontal gyrus (IFG), the dorsolateral prefrontal cortex (DLPFC), and the insular cortex (Carter, Braver, Barch, Botvinick, Noll, & Cohen, 1998; Gehring & Knight, 2000; Krämer et al., 2007; Marco-Pallarés, Camara, Münte, & Rodríguez-Fornells, 2008; Ullsperger & von Cramon, 2001).

As a component of the performance monitoring system, *error detection* plays a critical role in action regulation and cognitive control, which are critical processes of correct socialization and adaptive behavior (Logan, 1985; Rabbitt & Rodgers, 1977; Ridderinkhof et al., 2004). A negative event-related potential (ERP), labeled error-related negativity (ERN, or Ne), has been shown to appear immediately after committing errors (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993; Gehring, Coles, Meyer, & Donchin, 1995). The dopaminergic system from the basal ganglia to the MPFC (including the ACC) plays a key role in the generation of the ERN (Yeung, 2004). The ERN component exhibits a clear fronto-central topographical distribution; it peaks at approximately 60–80 ms after error commission and has been associated with the commission of errors and the processing of negative feedback (Holroyd & Coles, 2002; Yeung, 2004). According to the error detection theory (Falkenstein, Hohnsbein, Hoorman, & Blanke, 1991; Gehring et al., 1993) and the conflict monitoring theory (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter et al., 1998; Yeung, Botvinick, & Cohen, 2004), the ERN can be considered a reliable index of performance monitoring, thereby reflecting the output of a general evaluative system concerned with the motivational significance of the outcomes of our actions (reinforcement-learning theory of the ERN; Holroyd & Coles, 2002). It has been suggested that theta oscillatory activity recorded at frontal midline electrodes may be the electrophysiological mechanism that underlies the ERN (Cavanagh, Cohen, & Allen, 2009; Luu, Tucker, & Makeig, 2004; Trujillo & Allen, 2007). After the appearance of the ERN, a positive ERP component is observed (error positivity, Pe) which exhibits a centro-parietal distribution that peaks at approximately 200–600 ms after the error (Ullsperger, Harsay, Wessel, & Ridderinkhof, 2010). Despite the lack of a consensus regarding the specific functional significance of the Pe, it has been argued that Pe might reflect the following: (i) error awareness (Leuthold & Sommer, 1999; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001, Falkenstein, 2004), (ii) a motivational significance or emotional assessment of an error (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Overbeek, Nieuwenhuis, & Ridderinkhof, 2005; Ridderinkhof, Ramautar, & Wijnen, 2009), and (iii) an orienting response to an error commission (Arbel & Donchin, 2009, 2011; Davies, Segalowitz, Dywan, & Pailing, 2001; Hajcak, McDonald, & Simons, 2003; Overbeek et al., 2005; Ridderinkhof et al., 2009). Therefore, it appears that the Pe is primarily modulated by conscious error detection and the corresponding adjustments observed in future responses (Hajcak et al., 2003; Nieuwenhuis et al., 2001).

Few studies have been devoted to investigating error monitoring in adult offenders, with most studies focused on adult psychopathic violent offenders. However, to our knowledge, no previous studies have focused on juvenile non-psychopathic offenders. In adult offenders, Munro et al. (2007a) reported no amplitude differences for the ERN and Pe between offenders and healthy controls in a letter-flanker task. However, these authors encountered a reduced ERN amplitude in the face-flanker task for offenders (when psychopathic and non-psychopathic offenders were combined) compared with healthy controls. In contrast, Brazil et al. (2009) found no amplitude differences for the ERN, but they found decreased Pe amplitude for adult psychopathic violent offenders compared with healthy controls. Moreover, using measures of dispositional dimensions related to delinquency, some authors have reported only reduced ERN amplitude, but not reduced Pe amplitude, in adults with poor sociability scores (Dikman & Allen, 2000) and high scores in the personality trait of externalization (Hall, Bernat, & Patrick, 2007).

The spectrum of externalizing behaviors has been related to different personality traits associated with violent or offensive behavior. The core trait of the externalizing spectrum (Patrick & Bernat, 2006; Iacono, Carlson, Malone, & McGue, 2002) is the difficulty in inhibiting inappropriate responses or impulses (Gorenstein & Newman, 1980). Interestingly, compared with healthy control children, a reduced ERN amplitude was encountered in children with poor sociability (Santesso, Segalowitz, & Schmidt, 2005) and with high externalizing symptomatology (Stieben et al., 2007). In a more recent study, Bernat, Nelson, Steele, Gehring, and Patrick (2011) failed to identify differences in the feedback-related negativity (FRN, or theta oscillatory activity) in a comparison between high and low externalizing undergraduate students. This ERP component is an index of external performance monitoring (i.e., feedback related information regarding the outcome of an action), which is thought to be highly associated with the ERN component (Holroyd & Coles, 2002). Considering this pattern of results, Bernat et al. (2011) proposed that high externalizing individuals might have deficits in the endogenous (internally cued) performance monitoring signals (ERN) but not in exogenous (externally cued) performance monitoring (FRN).

Another cognitive control aspect that is very important in aggressive behavior is the ability to inhibit or avoid certain behaviors or thoughts (Gorenstein & Newman, 1980; Logan, 1994). Inhibitory processes have been studied using different electrophysiological measures and typically use the go/nogo or stop-signal tasks (Krämer et al., 2007; Logan, 1994; Rodríguez-Fornells, Kurzbuch, & Münte, 2002). For example, the stop-N2 component (with a fronto-central topographical distribution that peaks approximately 250–350 ms after the target to inhibit) is related to conflict detection, inhibition or revision of inappropriate response tendencies (Kok, 1986). Similar to the ERN component, the MPFC plays a critical role in the generation of the stop-N2 (Amodio, Master, Yee, & Taylor, 2008; Bekker, Kenemans, & Verbaten, 2005; Bokura, Yamaguchi, & Kobayashi, 2001; Gründler, Cavanagh, Figueroa, Frank, & Allen, 2009; Jonkman, Sniedt, & Kemner, 2007; Mathalon, Whitfield, & Ford, 2003; Ullsperger & von Cramon, 2001;

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