

SYSTEMATIC REVIEW

Open Access

# Using basic neurobiological measures in criminological research

Liza JM Cornet<sup>1,2</sup>

## Abstract

Research on the relationship between neurobiological factors and antisocial behavior has grown exponentially in recent decades. As a result, criminal behavior has been related to impairments in different biological systems, such as genetics, hormones and brain functioning. The development of innovative techniques, for example brain imaging techniques and physiological measurements, can partially explain the increase in neurobiological studies on criminal behavior. Despite a recent zeitgeist change, which has led to a greater acceptance of neurobiology as an additional approach for the study of criminal behavior, neurobiological measurements do not yet play a more significant role in criminological research and practice. This article aims to familiarize crime researchers and other interested readers with two important neurobiological measures, namely neuropsychological assessment and resting heart rate measurement, and with how these measures can play an important role in criminological research. It will argue that neuroscientific approaches might benefit the field of criminology in several important ways, from assessing the empirical validity of criminological theories to improving the effectiveness of correctional intervention programs. Furthermore, this article will provide insight into how to use these measures in research, to guide interested readers towards their application in their own studies.

**Keywords:** Neurobiology; Heart rate; Neuropsychology; Criminology; Methods

## Using basic neurobiological measures in criminological research

Research on the relationship between neurobiological factors and antisocial behavior has grown exponentially in recent decades. As a result, criminal behavior has been related to impairments in different (neuro) biological systems, such as genetics, hormones and brain functioning. The development of innovative techniques, for example brain imaging techniques and physiological measurements, can partially explain the increase in neurobiological studies on criminal behavior. Furthermore, a recent zeitgeist change seems to have led to a greater acceptance of neurobiology as an additional approach for the study of criminal behavior.

One of the current, main neurobiological research areas within criminology focuses on the question which neurobiological characteristics are associated with antisocial behavior. There is considerable evidence for reduced

physiological arousal, poor frontal brain functioning, hormonal deficits, and genetic predisposition associated with antisocial behavior (e.g. Beauchaine et al. 2008; Cornet et al. 2014; Moffitt 1990; Raine 2002a, 2002b; Van Goozen et al. 2007; Wilson and Scarpa 2012). Another important research area comprises the prediction with neurobiological factors of antisocial behavior later in life (e.g. Aharoni et al. 2013; Baker et al. 2013; Gao et al. 2010a; Jennings et al. 2013; Pardini et al. 2014; Raine et al. 2005; Van Bokhoven et al. 2005).

For example, Pardini et al. (2014) showed that, within a male cohort, a low volume of the amygdala, a brain structure involved in emotion processing, significantly predicts aggressive behavior during childhood and predicts proactive aggression at age 16. In addition, it appears that neurobiological factors are associated with chances of reoffending after arrest. Within a sample of male adolescents, De Vries-Bouw et al. (2011) found an association between an attenuated heart rate response to a stressor and the number of re-offenses.

Despite the increased knowledge about neurobiological correlates of antisocial behavior in recent years, neurobiological measures do not yet play a significant part in

Correspondence: L.Cornet@nscr.nl

<sup>1</sup>Netherlands Institute for the Study of Crime and Law Enforcement (NSCR), P.O. Box 71, 1008, BH, Amsterdam, The Netherlands

<sup>2</sup>Research and Documentation Centre (WODC), Ministry of Security and Justice, The Hague, The Netherlands

the field of criminology. However, ignoring biological influences on antisocial behavior may be something of a lost opportunity. Not only because the integration of substantial biological knowledge might modernize and extend the field of criminology, but especially because neurobiological mechanisms, in conjunction with social factors, often give rise to behavioral risk factors that are central to criminological theories. According to Walsh and Beaver (2009), both influential bio-criminologists, "(...) biosocial criminology is all about how similar environments have different effects on different people, and vice versa" (p. 8). In this way, integrating a biological perspective might give more insight into *why* some circumstances (e.g. childhood experiences, parental management) are meaningful and why they affect individuals differently.

Severe childhood maltreatment is an example of an important social risk factor for the development of antisocial behavior and plays a central role in different criminological theories (e.g. self-control theory, strain theory and coercion theory). However, some individuals tend to develop antisocial behavior after traumatic childhood experiences, whereas others do not. The question seems to be, therefore, how to explain this difference. An important study by Caspi et al. (2002) found out that different expressions of the so-called 'MAOA' gen influences the development of antisocial behavior problems later in life after experiencing childhood maltreatment. It appeared that children with a genotype conferring high levels of MAOA expression were less likely to develop antisocial behavior problems in response to childhood maltreatment. Another example in which biological factors moderate a behavioral outcome is a study that includes children with Disruptive Behavior Disorder (DBD) who receive behavioral therapy. It appears that subjects with a low resting heart rate are the ones to respond less favorably to this type of therapy (Stadler et al. 2008). These studies show that neurobiological factors are not merely related to criminal behavior, but are perhaps more strongly associated with existing/traditional criminological theories and concepts than most criminologists are currently aware of. For this reason, the integration of biological knowledge with current psychosocial perspectives on criminal behavior may increase insight into individual differences in the presence, persistence and development of antisocial behavior (Ratchford and Beaver 2009; Walsh 2009; Walsh and Beaver 2009).

One possible reason for the relative absence of neurobiological measurements in criminological research is the idea that it is more complicated to use these techniques compared to traditional instruments developed in sociology and psychology, such as self-report questionnaires or observational methods. This argument holds definitely for advanced and complex research techniques,

such as brain imaging techniques like functional magnetic resonance imaging (fMRI) and electroencephalography (EEG). Hormone sampling and genetic research, too, often require highly specialized researchers and laboratories and advanced statistical analysis techniques, which makes them relatively inaccessible to most researchers in the field of criminology. For this reason, this article will focus on 'basic' neurobiological measurements, including neuropsychological tasks and resting heart rate measurements that, as will become clear, are within the scope of most researchers, both in terms of required level of expertise and budget.

Another possible reason for the reluctance in criminology to embrace biology, is perhaps its heritage as a child of sociology, which is a field with a long history of refusing biological explanations (Walsh 2009). As a result, most criminological theories draw from the field of sociology and from psychological approaches. In 2004, Walsh and Ellis published a study based on a survey among criminologists at the American Society of Criminology conference. According to the questionnaire, criminologists of different ideological persuasions agreed on hormonal and genetic factors as 'less important' causes of criminal activity. In contrast, most criminologists agreed on predominantly 'psychosocial' causes of criminal activity, such as: 1) a lack of empathy; 2) peer influences; and 3) impulsiveness (Walsh and Ellis 2004). Past research has shown strong empirical support for the relationship between these causes and criminal behavior (e.g. Delisi et al. 2003; Gottfredson and Hirschi 1990; Jolliffe and Farrington 2004; McGloin 2009; Pratt and Cullen 2000; Van Langen et al. 2014; Weerman 2011). The results illustrate the absence of biological perspectives on crime among researchers in the field of criminology. However, it must be noted that the survey was held in 1997; it is possible that ideas about 'important' and 'less important' causes of criminal activity have changed during the past two decades.

Overall, it seems fair to conclude that the field of criminology is still dominated by biology-free theories. However, a growing acceptance of the biological perspective on crime has led to an increased awareness of the relatively unilateral perspective of some criminological theories on the causes of crime. One example in this regard is the self-control theory of Gottfredson and Hirschi (1990). Although the self-control theory is one of the most accepted theories about criminal behavior, only environmental factors (e.g. parental strategies) are central to the theory, leaving aside any genetic or biological explanations (Cauffman et al. 2005; Jackson and Beaver 2013). In addition, empirical research has shown that specific, individual-level characteristics related to crime, such as impulsiveness/low self-control and lack of empathy, may have a biological underpinning in the frontal

region of the brain (e.g. Beaver et al. 2007; Cauffman et al. 2005; Glenn and Raine 2014; Shirtcliff et al. 2009).

Again, the above suggests that neurobiological factors may provide additional information about traditional criminological concepts. This article aims to familiarize researchers in the field of criminology with two neurobiological measures, namely the neuropsychological assessment and resting heart rate measurement. The relevance and application of these basic research methods will be discussed with regard to the field of criminology, in order to stimulate criminologists to incorporate neurobiological research methods in future criminological research. First, this article will describe the relationship between antisocial behavior and prefrontal brain functioning and heart rate. Subsequently, it will discuss strengths and weaknesses of these research methods, before it provides application details. Finally, it will discuss future developments of neurobiological measures in criminological research. The article ends with several suggestions for further reading.

## Prefrontal brain functioning and resting heart rate

### Prefrontal brain functioning

As described, neurocriminological studies have revealed that specific individual characteristics related to antisocial behavior may have a biological underpinning in the frontal region of the brain (e.g. Beaver et al. 2007; Cauffman et al. 2005; Glenn and Raine 2014; Shirtcliff et al. 2009). The frontal part is the latest developing part of the brain and gives rise to our most complex behavioral functions, such as moral reasoning, behavioral inhibition, planning and empathy. There is evidence that both functional and structural deficits exist within the frontal brain region in individuals with antisocial behavior (Aoki et al. 2014; Raine 2002a; Yang and Raine 2009).

The improvement in imaging techniques has shed more light on the brain characteristics of individuals with antisocial behavior. Empirical research has shown that both functional and structural impairments of the frontal lobes appear to *bias* social behavior in an antisocial direction (e.g. Aoki et al. 2014; Brower and Price 2001; Koenigs 2012; Lotze et al. 2007; Morgan and Lilienfeld 2000; Ogilvie et al. 2011; Raine 2002a; Wahlund and Kristiansson 2009; Yang and Raine 2009). A lack of self-insight and noncompliance with societal rules, for instance, are both associated with impairments of the medial-polar prefrontal cortex, whereas impairments of the ventral-orbitofrontal cortex are associated with poor decision-making processes and disrupted emotional regulation. In addition, failure to desist from punished behavior and misperception of others' intentions/behavior appears to be associated with impairments of the dorsolateral prefrontal cortex<sup>a</sup> (see Table one in Raine 2008 for an overview of 'the translation from brain impairments to risk factors for antisocial behavior'). Neuropsychological

tasks, behavioral measures that assess frontal brain functions, appear to strongly differentiate antisocial individuals from normal controls, with a mean effect size ranging from  $d = .44$  to  $.68$  (for reviews see Brower and Price 2001; Morgan and Lilienfeld 2000; Ogilvie et al. 2011). Especially tasks that appeal to *working memory* skills appear to strongly distinguish antisocial from normal behavior (Ogilvie et al. 2011).

Overall, the above-mentioned findings imply a strong and robust relationship between frontal brain dysfunctioning and antisocial behavior. Nevertheless, the underlying causes for a child to suffer from brain deficits leading to antisocial behavior are still less unraveled. Many causes have been suggested, such as specific genes, environmental influences (e.g. poor parenthood), nicotine and malnutrition during pregnancy, and birth complications (for overview see Raine 2002a). In addition, not only antisocial behavior in general is associated with brain deficits, it appears that *between* individuals with antisocial behavior, a high variation exists in neuropsychological deficits. For example, inmates with high psychopathic traits appear to show more selective attention problems, compared to non-psychopathic inmates (Hiatt et al. 2004; Pham et al. 2003). Hoaken et al. (2007) demonstrated that incarcerated violent offenders performed significantly more poorly at a cognitive empathy task, compared to non-violent offenders. Furthermore, Broomhall (2005) showed impaired complex prefrontal functioning in offenders with reactive aggression and largely intact functions in offenders with primarily instrumental aggression.

### Resting heart rate

In addition to deficits in frontal brain functioning, antisocial behavior has also been associated with abnormal activity in specific physiological processes (e.g. Beauchaine et al. 2008; Patrick 2008; Scarpa et al. 2010; Van Goozen et al. 2007). Examples of such physiological processes are heart rate, respiration rate, hormone levels and sweat production. Meta-analyses have shown the association between antisocial behavior and reduced physiological activity (Lorber 2004; Ortiz and Raine 2004). For example, psychopathy/sociopathy appears to be associated with reduced electrodermal activity<sup>b</sup>, both in a resting state and during an active state (e.g. while performing a task) ( $d = -.25$  to  $-.30$ ). In addition, there seems to be a strong, but mixed, relationship between antisocial behavior and heart rate reactivity<sup>c</sup>. Lorber (2004) found an *increased* heart rate reactivity ( $d = .20$ ) in children with conduct disorder, whereas Ortiz and Raine (2004) found a *reduced* heart rate reactivity in children with antisocial behavior in general ( $d = -.76$ ). No significant association was found between heart rate reactivity in children and

adults with aggressive behavior ( $d = .10$ ), or in adults with psychopathy ( $d = .06$ ).

The most striking finding of these meta-analyses is the fact that a reduced *resting* heart rate is the most replicated correlate of antisocial/aggressive behavior in both children and adults. In other words, individuals with more severe antisocial behavior are likely to display a lower number of heart beats per minute in a state of inactivity. The effect sizes in this regard range from  $d = -.33$  to  $-.44$  (Lorber 2004; Ortiz and Raine 2004). The relationship between a reduced resting heart rate and antisocial behavior appears not only to be the strongest biological correlate of antisocial behavior to date, but is also related to both male and female antisocial behavior. In addition, a low resting heart rate is “diagnostically specific”. In other words, no other psychiatric disorder, including depression, anxiety or schizophrenia, appears to have been linked to a low resting heart rate (for overview see Raine 2002a).

Different physiological mechanisms have been proposed to account for the presence of a reduced heart rate in individuals with antisocial behavior. One possible mechanism is a reduced functioning of the right hemisphere of the brain (Baker et al. 2009; Raine 2002a). The right hemisphere controls autonomic functions, such as respiration and heart rate. Furthermore, brain imaging techniques and neuropsychological tasks have shown a reduced right hemisphere functioning in individuals with antisocial and violent behavior (Mezzacappa et al. 1997; Raine 2005). In addition, the right hemisphere appears to be involved in the so-called ‘withdrawal system’, a system that promotes escape from aversive and dangerous situations (Davidson 1998; Davidson et al. 1990). A dysfunctional right hemisphere might therefore explain the association between a reduced resting heart rate and individuals’ predisposition for higher chances of getting involved in criminal acts.

Another possible mechanism underlying the reduced heart rate – antisocial behavior relationship may be found in the two branches of the autonomic nervous system. It has been found that both parasympathetic activity (which slows down autonomic functioning) and sympathetic activity (which increases autonomic functioning) are reduced in individuals with antisocial behavior (Beauchaine et al. 2007). According to *polyvagal theory*, both branches are involved in facilitating prosocial behavior. A dysfunctional autonomic nervous system in individuals with antisocial behavior may, therefore, explain their inappropriate behavior and reduced heart rate (Porges 2000; Porges 2009).

The described mechanisms provide some insight into the relationship between antisocial behavior and reduced autonomic nervous system functioning. However, the underlying mechanisms of the relatively ‘simple’

relationship between a low resting heart rate and antisocial behavior remain highly complex and not well understood (Raine 2013, p. 108). On a behavioral level, two theoretical explanations have been suggested as mediators of the relationship between resting heart rate and antisocial behavior. One possible explanation underlying the relationship between antisocial behavior and low levels of physiological arousal is *fearlessness* (Raine 1996). This suggests that low arousal levels may lead to a reduced sensitivity to the negative consequences of behavior. This form of ‘fearlessness’ increases the likelihood that someone with reduced physiological arousal will commit a crime. In support of this line of reasoning, a lack of anticipatory fear and poor fear conditioning are well-replicated risk factors for antisocial behavior (Gao et al. 2010b; Van Goozen et al. 2004). In addition, *sensation seeking* is proposed as another explanation, which states that low physiological arousal is an unpleasant state, similar to a state of boredom (Quay 1965; Zuckerman 1979). The need to seek sensation in order to increase arousal levels puts someone at greater risk of committing a crime. Recently, it has been found that of the two proposed explanations, *sensation seeking* appears to be the strongest mediator for the heart rate – antisocial behavior relationship. Portnoy et al. (2014) showed that measures of impulsive sensation-seeking behavior explained around 36% percent of the total effect of heart rate on aggression and 27% percent of the effect of heart rate on non-violent delinquent behavior.

Even though a reduced resting heart rate appears to be the most replicated biological correlate of antisocial behavior in general, there is some evidence that within antisocial samples, the heart rate levels vary with different antisocial behavior traits. For example, it appears that ‘successful’ psychopaths (individuals who are not caught and convicted) have heart rate responses to stress comparable to normal individuals, whereas ‘unsuccessful’ psychopaths show blunted autonomic response (Raine 2013). Furthermore, some studies have shown that antisocial individuals with predominantly impulsive behavior and reactive aggression are more often characterized by *increased* levels of arousal (Hawes et al. 2009; Scarpa et al. 2010). In addition, it has been found that individuals with late-onset and adolescent-limited antisocial behavior are characterized by a higher resting heart rate compared to their persistent, early-onset antisocial peers (Bimmel et al. 2008; Raine et al. 1995).

To sum up, neurocriminological studies have revealed a lot of relevant information about the neurobiological correlates of antisocial behavior. There is evidence that these neurobiological impairments give rise to emotional, cognitive and behavioral risk factors, predisposing individuals to antisocial behavior. However, neurobiological deficits should not be viewed as direct *causes* of

antisocial behavior. This sort of view on neurobiological correlates of antisocial behavior would take us back to a time when neurocriminological research brought more harm than good to the field of criminology. Instead, a complex interplay between psychological, sociological and biological factors underlies the development of antisocial behavior. For this reason, neurobiological factors should be viewed as ‘just other’ correlates of antisocial behavior that may shed more light on the presence, persistence, prevention and treatment of antisocial behavior.

## Strengths and limitations of basic neurobiological measures

### Strengths

Perhaps the most important argument to incorporate neurobiological measures in the field of criminology relates to the *empirical validity* of criminological theories. Armstrong et al. (2009) phrased this issue as follows: “For a theory to have empirical validity, the theory must offer causal propositions that are consistent with “the facts.” (...) Although a theory does indeed have advantaged empirical validity to the extent that the causal propositions that it offers are consistent with empirical reality, so too does empirical validity vary with the extent to which the relevant facts are addressed” (p. 1135). As long as criminologists ignore relevant neurobiological ‘facts,’ the validity of criminological theories will remain undermined.

There are a few studies illustrating this issue by showing a relationship between resting heart rate/neuropsychological measurements and antisocial behavior net of the influence of traditional criminological concepts. In one such study, Cauffman et al. (2005) revealed that individuals with poor spatial span skills<sup>d</sup>, as measured with a neuropsychological task, and those with a low resting heart rate were, respectively, 2 and 1.05 times more likely to have an offender status. In comparison, individuals with low self-reported self-control were 1.58 times more likely to have an offender status. Logistic regression, including demographic variables (e.g. age, race, gender) and self-control measures, explained 13.2% of the variance of the offender status. The addition of neuropsychological and heart rate measures increased the amount of explained variance to 28.4%.

Armstrong et al. (2009) showed that, within a sample of healthy students, a low resting heart rate remained a significant predictor of higher levels of antisocial and aggressive behavior net of traditional criminological constructs, such as self-control, peer influence and parental attachment. In addition, Jennings et al. (2013) indicated that the predictive effect of resting heart rate on the total conviction frequency from age 18 to age 50, was not diminished when controlling for numerous criminological concepts such as impulsivity, harsh discipline/attitude of parents, criminal record of parents, poor housing, and low family income. Overall,

these results indicate that the relationship between neurobiological factors and antisocial behavior remains strong and significant, despite the inclusion of more traditional criminological constructs. For this reason, remaining silent about neurobiological correlates is a missed opportunity to improve our understanding of criminal behavior.

Beside the use of a neurobiological perspective on criminal behavior to increase empirical validity, the integration of specific neuropsychological and heart rate measures within criminological research is relatively easy and offers several advantages. For instance, both measures assess psychological constructs, such as low self-control and fearlessness, without measuring these constructs *directly*. This may have advantages, for example when studying a sample of individuals with antisocial behavior that is likely to manipulate responses in a certain direction. Social desirability is often a problem when using self-report questionnaires, which are common in criminology. With neurobiological measures, it is harder to influence the outcome in a more socially desirable direction.

An example in this regard is a study performed by Patrick et al. (1994), who measured physiological activity in order to assess a psychological construct. The authors investigated physiological responses to imaginary emotional situations (e.g. ‘you are taking a shower alone when you hear someone breaking into your house’) in psychopathic and non-psychopathic inmates. Although neither of these groups differed on self-reported levels of fearfulness, the psychopathic inmates showed reduced physiological responses to the imaginary emotional situations compared to non-psychopathic inmates, indicating deficient fearful responses in psychopaths. However, when the questionnaire about fearfulness was the sole subject of this study, differences in fearfulness were not observed. This example nicely illustrates the potential power of neurobiological measures to assess ‘unconscious’ processes and detect differences that would have remained hidden using traditional measures.

In addition to the problem of social desirability, impatience and carelessness often characterize individuals displaying antisocial behavior and may also influence response patterns to self-report questionnaires (Sibley et al. 2010). Furthermore, individuals may not always understand the formulation of the questions and some criminal individuals might feel unsafe in answering specific questions honestly, as they feel it might affect the circumstances of their incarceration or parole, for example. Limitations like these are less problematic when neurobiological measurements are applied. Furthermore, neurobiological measures do not rely on people’s ability to express themselves, making intellectual level and language skills less relevant and different age groups easier to study, compared to more traditional criminological measurements.

Lastly, basic neurobiological measures are often relatively inexpensive and easy to administer. Especially

neuropsychological tasks are non-invasive, relatively easy to interpret, appropriate to transport and usable in different settings (e.g. inside houses, prisons or other institutions). In addition, the selected heart rate measures in the following section are non-invasive and accessible to many researchers who are not familiar with these measures.

### Limitations

Although neurobiological measures offer several advantages, they are probably more sensitive than questionnaires to a properly controlled research setting, such as a quiet room, to conduct a neuropsychological assessment or, in case of measuring resting heart rate, a reliable baseline procedure. Furthermore, criminological studies often rely on 'static' information, such as the number of imprisonments and total income. Large-scale data including this information can be derived from police records or governmental and municipal data sets. However, neurobiological measures require individual-level and 'at the moment' testing. This requires a more exhausting process of recruiting, selecting participants and scheduling visiting appointments. Overall, a study including neurobiological measures may limit the research possibilities. Nonetheless, a recent, interesting criminological study used neurobiological data without examining any real participants. In an intergenerational transmission of crime study, heart rate levels were obtained from medical examinations during a military assessment (Van de Weijer, De Jong, Bijleveld, Blokland, & Raine, submitted). It appeared that the intergenerational transmission of violent behavior was only significant among men with a low resting heart rate. Although, in this study, limitations exist with regard to the measurement of heart rate and the reliability of the context in which heart rate was measured, it does show that alternative sources to obtain neurobiological information, such as medical files, are available to criminological research.

Another important disadvantage is the current absence of well-validated and large-scale studies investigating neurobiological factors in individuals with antisocial behavior that might provide normative data. Although this issue does not hold for many neuropsychological tasks, it is especially problematic with regard to the definition of 'low resting heart rate'. How many beats per minute should be defined as *low*? And is there one standard value for different age groups? It appears that different approaches are applied. One often-applied method is subtracting one standard deviation (SD) from the sample mean to create a 'low resting heart rate' group (e.g. Armstrong and Boutwell 2012; Armstrong et al. 2009; Raine et al. 1997; Wilson and Scarpa 2014). Nevertheless, this calculation method creates great differences in the values of low resting heart rate between studies. For example, Wilson and Scarpa (2014) included healthy students with an

average heart rate of 69.03 (SD = 13.31). According to the  $-1$  SD technique, the 'low resting heart rate' group includes values between 42.56 and 55.72, whereas the 'low resting heart rate' group in a similar sample in Armstrong and Boutwell (2012) includes values between 56.08 and 63.90. Overall, this suggests that 'low resting heart rate' has a relative meaning, which can only be defined *within* a research sample.

Finally, it is important to be aware of the ethical side effects of neurobiological research, also called 'neuroethics' (Farah 2012). Research on risk profiling with the help of neurobiological instruments may lead to stigmatization and labelling of individuals at a young age. Although, in general, the early detection of risk factors indicating a development of behavioral dysfunctions may lead to negative social reactions, this relation is probably stronger for neurobiological risk factors, since people often believe that neurobiological characteristics are static or deterministic (Horstkötter et al. 2012; Walsh 2009). As the body of research on the neurobiological correlates of antisocial behavior is growing, so do the neuroethical concerns and debates.

In sum, complementing traditional criminological measures with neurobiological methods potentially strengthens the empirical validity of criminological theories. Furthermore, neurobiological measurements may have a strong advantage, especially in antisocial samples, since these measurements are less sensitive to response biases. However, a neurobiological research set-up does limit the research possibilities and one must keep in mind the lack of normative data when incorporating neurobiological measures. Overall, this emphasizes the importance of combining biological measures with more traditional criminological research methods, not only because it enriches our understanding, but also because biological information in itself is not exhaustively informative.

## Introduction to basic neurobiological measures

### Neuropsychological assessment

As previously described, there is strong evidence for a relationship between criminal behavior and *frontal brain malfunctioning*. The goal of neuropsychological tasks is to study the brain through its behavioral outcome (Lezak et al. 2004). For example, neuropsychological measures regarding impulsive behavior (e.g. the Go/No-Go task, see below) assess the *frontal brain* mechanism underlying this criminological construct, whereas more traditional measures of impulsivity, like the Eysenck Impulsivity Scale, consider *behavioral* aspects of impulsive behavior. Although both measurements assess the same concept (impulsivity), they should not be viewed as mutually exclusive; they might function as complementary measures since they can reveal information about criminal behavior from different 'sources' (i.e. the behavioral aspect and

brain functioning aspect of impulsivity). This section will elaborate on what neuropsychological tasks entail, which tasks might be used in criminological research and how to assemble neuropsychological measurements.

### Frontal brain functioning and neuropsychological tasks

The prefrontal cortex is often subdivided into different areas associated with different behavioral outcomes<sup>e</sup>. One widely accepted division, based on anatomical connectivity and functional specialization, is that between the ventromedial (vmPFC) and dorsolateral sectors (dlPFC) (Koenigs and Grafman 2009). Generally, the dlPFC has been associated with a more 'generic' functioning, including controlling, regulating and integrating 'cognitive' functions (Lezak et al. 2004). The vmPFC, on the other hand, has generally been associated with emotional or affective functions such as emotional decision-making, judgments, socially appropriate behavior and impulsivity (Berlin et al. 2004; Clark et al. 2008).

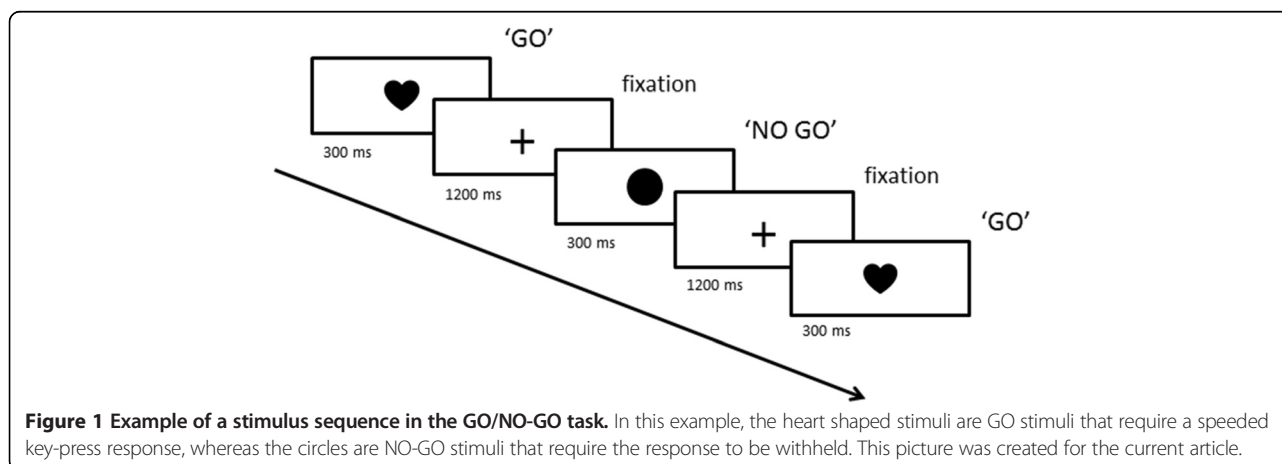
Brain imaging studies provide evidence that neuropsychological tasks can activate different frontal brain parts. For example, complex versions of the Go/No-Go task, a task that assesses response inhibition by presenting participants with a binary decision on each stimulus ('Go' or 'No Go') as presented in Figure 1, appear to activate primarily right-lateralized prefrontal-parietal circuits (Simmonds et al. 2008). In general, there is extensive empirical evidence showing activation of different frontal brain regions during cognitive, demanding tasks (e.g. Cole et al. 2012; Levy and Wagner 2011; Malisz et al. 2005; Miller 2000; Mull and Seyal 2001; Nee et al. 2007; Petrides and Milner 1982). For this reason, neuropsychological measures are '(...) indirect behavioral expressions of brain functioning' (Gao et al. 2012, p. 67).

### The selection of neuropsychological tasks

In order to familiarize the reader with some neuropsychological measurements, a selection of neuropsychological

tasks and associated behavioral traits is presented in Table 1. The selection of neuropsychological tasks is based on the meta-analysis by Ogilvie et al. (2011). Only neuropsychological measures with weighted effect sizes above .5 (which indicates a medium to high effect size) are included. Table 1 shows that most neuropsychological measures assess 'working memory' skills. This is not surprising, since working memory is believed to represent a supervisory control system that monitors cognition and self-regulatory behavior (Burgess et al. 2007; Endres et al. 2011; Koechlin et al. 1999; Miller 2000). In addition, there is evidence suggesting that working memory is associated with indicators of impulsive/sensation-seeking behavior and antisocial/unconventional personality traits (Bogg and Finn 2010; Finn et al. 2009). It seems that working memory is an overarching concept, which might underlie different aspects of antisocial behavior and differentiates antisocial from normal behavior. It would be interesting to compare working memory skills with more traditional concepts in criminology, such as self-control and cognitive empathy, to find out to what extent working memory is another relevant individual-level correlate of antisocial behavior.

In what follows, the Self-Ordered Pointing Task (SOPT) serves as an example to illustrate the application of a neuropsychological measure. The SOPT was originally developed more than thirty years ago by Petrides and Milner (1982). For the SOPT, both a paper-pencil and a computerized version are available. Choosing either one of these presentation forms depends on the research setting and sample used (e.g. is there a fixed lab? Does the sample include very young or very old participants who are unable to deal with a computer?). If possible, it is recommended to choose a digital version of neuropsychological tasks, as this avoids instruction bias and simplifies the output. The SOPT is relatively easy to administer and takes about 20 minutes for most persons (Ross et al. 2007). Different versions exist but, in general, participants are provided



**Table 1 Selected neuropsychological tasks with high weighted effect size**

Neuropsychological task	Behavioral aspects	N studies	Effect size	References
Self-Ordered Pointing task	Capacity to regulate behavior using plans and strategies and working memory	4	.83	(e.g. Lezak et al. 2004; Malisza et al. 2005; Petrides and Milner 1982; Ross et al. 2007)
Porteus Maze Task	Ability to plan, foresight, change problem-solving approach	22	.71	(e.g. Lezak et al. 2004; Morgan and Lilienfeld 2000; Porteus 1959; Riddle and Roberts 1977)
Sequential Matching to Memory task	Maintaining information in working memory	3	.69	(e.g. Gorenstein 1982; Hare 1984; Lueger and Gill 1990; Mull and Seyal 2001)
Delayed Matching to Sample task	Short term visual memory, working memory	3	.59	(e.g. Bergvall et al. 2001; Dolan and Park 2002; Fray et al. 1996; Mishkin 1982)
Go/No-Go task	Inhibition of ongoing behavior	12	.56	(e.g. Malloy et al. 1993; Nee et al. 2007)
Spatial Working Memory task	Working memory	6	.54	(e.g. Owen et al. 1996a Owen et al. 1996b)

with different sets of stimuli (e.g. animal pictures). Each time, the stimuli are presented with a different spatial appearance. The goal of the task for the participant is to select a different picture each trial, until all of the pictures have been touched once. The participant is not allowed to start each trial at the same location. Often, different dependent variables result from tasks like these (e.g. the amount of errors, the span score) that might reflect different behavioral traits (e.g. accuracy, working memory). Depending on the research goal, one might decide to use all of these variables or select only the most relevant ones. The reliability study by Ross et al. (2007) can provide more information on issues like these.

It is recommended to gather information about different neuropsychological tests by reading comparable (criminological) studies and a neuropsychological assessment handbook (Brower and Price 2001; Lezak et al. 2004; Morgan and Lilienfeld 2000; Ogilvie et al. 2011). There is a helpful website that provides free digital versions of some tests described above (e.g. SOPT, Go/No-Go task) and other neuropsychological tasks central to the meta-analysis of Ogilvie et al. (2011) (e.g. the Trail Making Test, the Tower Of Hanoi)<sup>f</sup>. This particular website also includes relevant literature. In addition, there are a number of companies that sell neuropsychological tests online, such as PAR<sup>g</sup>, Pearson<sup>h</sup>, and Hogrefe<sup>i</sup>. A certain qualification level is often required, however, in order to buy specific neuropsychological tasks. Furthermore, the DMS and SWM tasks listed in Table 1 are subtests of well-known computer-based cognitive assessment software called CANTAB<sup>j</sup>. This is a frequently used test battery program in cognitive research, and has shown added value in criminological research (e.g. Cauffman et al. 2005).

### Research questions

One example of a possible research question concerns the early detection of antisocial behavior with neuropsychological measures. This sort of research can investigate neurocognitive skills in primary school children

and relate their neurocognitive functioning to expressions of antisocial behavior in adolescence. The advantage of using neurocognitive measures is the fact that researchers are no longer dependent on third-party informants (e.g. parents, teachers), since children are able to execute non-verbal neurocognitive tasks. In addition, there is evidence that neuropsychological measures might increase the explained variance in studies predicting antisocial status. It would be interesting to further investigate whether and which neuropsychological measures, such as the SOPT, Go/No-Go or Tower of Hanoi, can predict antisocial behavior above and beyond existing criminological measures. Finally, if specific neurocognitive deficits are associated with antisocial behavior, such as reduced working memory, it would be interesting to find out whether improving this neurocognitive skill decreases antisocial traits<sup>k</sup>.

### Measuring resting heart rate

As described previously, antisocial behavior is associated with a reduced activity of several physiological systems. The relationship between a low resting heart rate and antisocial behavior is one of the most replicated ones (e.g. Lorber 2004; Ortiz and Raine 2004). This methodological strength combined with the relative easiness of measuring resting heart rate might stimulate criminologists to incorporate a heart rate assessment in their research. The following provides information about the setting of measuring resting heart rate, the usage of resting heart rate data, and the selection of appropriate equipment.

Measuring resting heart rate is simple and only requires an appropriate “resting” baseline measurement that ideally should take a minimum of two minutes. In this baseline measurement, the participant is required to be relaxed without doing any bodily or cognitive activities. There is evidence that a relaxing aquatic video is more effective to achieve a resting state than the traditional “sit quietly” method (Piferi et al. 2000). Any bodily movement or posture change can affect the heart rate measure and therefore needs to be controlled.



Furthermore, researchers should keep in mind that any test setting will be mildly stressful for most participants. Measuring heart rate prior to the beginning of an assessment might therefore contain a modest element of anticipatory anxiety (Portnoy et al. 2014). For this reason, it is recommended to include more than one baseline measurement in the assessment and calculate the average heart rate over different baseline periods, or decide which measure best reflects a stress-free moment.

When interpreting the collected data, this will generally reveal resting heart rates between 60 and 100 beats per minute, at least in adult samples. However, the lack of normative data hampers the ability to define someone's heart rate as 'normal' or 'abnormal'. One solution to proceed with analyses is to define a cut-off technique (e.g. 1 SD below and over sample mean) in order to create 'extreme' resting heart rate groups. Depending on the central research question, one might decide to leave the data as it is without creating heart rate groups, and use raw heart rate data that can be used for e.g. correlational, regression, or latent classes analyses.

Although an absolute heart rate value that indicates antisocial behavior is (currently) lacking, there is evidence suggesting that, on a behavioral level, no other psychiatric condition is associated with a low resting heart rate except antisocial behavior (Raine 2002a). Nonetheless, moderating factors such as medication and age might cause a reduction in heart rate. For this reason, one should take into account certain control variables that can affect the resting heart rate – antisocial behavior relationship. Suggested confounders are: body mass index, socioeconomic status, physical fitness, smoking, medication use, age, gender and race (e.g. Armstrong et al. 2009; Portnoy et al. 2014; Scarpa et al. 2010). If a control variable correlates with both resting heart rate and the antisocial behavior outcome measure, it should be included in further analyses. However, at least in children, there is evidence that a low resting heart rate does not appear to be an artifact of confounding factors (Ortiz and Raine 2004, p. 159).

### The selection of heart rate equipment

This section provides an overview of relevant heart rate equipment. It has been suggested that a simple heart rate assessment (e.g. a wrist pressure cuff) produces just as strong an effect size as more sophisticated equipment does (e.g. a computerized assessment) (Ortiz and Raine 2004). Since the goal of this article is to introduce basic neurobiological measures to criminologists, only simple heart rate equipment will be described. Based on the meta-analyses by Lorber (2004) and Ortiz and Raine (2004), simple equipment with a medium to high effect size ( $d > 0.5$ ) has been selected and listed in Table 2. Website suggestions about where to collect the equipment are also included.

In addition to the methods listed in Table 2, more recent criminological studies investigating the relationship between resting heart rate and antisocial behavior have shown the usage of other simple heart rate instruments. Cauffman et al. (2005), for example, used a simple wrist pressure cuff, while Armstrong and Boutwell (2012) measured heart rate with the CONTEC CMS 50D finger pulse oximeter ([www.contecmed.com](http://www.contecmed.com)). For illustration of a finger pulse oximeter see Figure 2. Moreover, there are heart rate instruments that are currently used in daily life, such as heart rate monitor watches used for running. An example is the Polar heart rate monitor model RS800sd (i.e. Polar Monitor, Polar Electro, Lake Success, NY, USA) which was also used by Wilson and Scarpa (2014).

### Research questions

Overall, there is compelling evidence that resting heart rate is related to antisocial behavior net of the influence of traditional criminological factors (e.g. self-control, peer influence, education level). Like neuropsychological measures, resting heart rate may provide more insight into individual antisocial behavior differences (e.g. early-onset vs late-onset delinquency) and has a predictive value (e.g. in relation to the development of antisocial

**Table 2 Simple heart rate measurements derived from meta-analyses**

Study	Sample	Effect size	Equipment	Relevant websites
Bullock (1988)	Female adolescents	-1.5715	Finger plethismograph	e.g. <a href="http://www.contecmed.com">www.contecmed.com</a>
Pitts (1997)	Children	-0.6232	Pulse meter attached to non-dominant hand	e.g. <a href="http://www.contecmed.com">www.contecmed.com</a> , <a href="http://www.smiths-medical.com">www.smiths-medical.com</a>
Chiang et al. (2001)	Adults	-.79	Pulse oximeter	e.g. <a href="http://www.contecmed.com">www.contecmed.com</a> , <a href="http://www.nonin.com">www.nonin.com</a>
Davies and Maliphan (1971)	Adolescents	-.73/-1.4266	Ear lobe pulse meter	e.g. <a href="http://www.turnermedical.com">www.turnermedical.com</a>
Kindlon et al. (1995)	Children	-.52/-4.073	Lafayette instrument Corporation Pulse Rate Monitor, model 77065	<a href="http://www.lafayetteevaluation.com">www.lafayetteevaluation.com</a>
Van Goozen et al. (1998)	Children	-1.20/-5.512	Arm cuff HEM-750C	<a href="http://www.omron-healthcare.com">www.omron-healthcare.com</a>

Variance in  $d$  was caused by different calculation methods between the two meta-analyses. Two studies could not be obtained due to lack of authors' contact information (e.g. Pitts, 1993 and Hume, 1987).



**Figure 2** Example of a finger pulse oximeter. This illustration was created for the current article.

behavior, or in relation to reconviction rates). It is relevant to mention that the source of antisocial behavior assessment does not influence the relationship with resting heart rate. Armstrong et al. (2009) summarize that resting heart rate is associated with all different kinds of antisocial behavior measures, e.g. clinical diagnoses of antisocial behavior such as conduct disorder or disruptive behavioral disorder, but also observational measures of aggression, self-reports, and psychological assessment, and official measures of crime, such as convictions for violence or recorded delinquency.

Nevertheless, although neurobiological research on criminal behavior is rapidly growing, the relationship between resting heart rate and antisocial behavior remains poorly understood. Numerous issues regarding this relationship are therefore open for future investigations. One example is the question whether a *decrease* in antisocial behavior, due to medication or behavioral intervention, is associated with an *increase* in resting heart rate, and vice versa. There is evidence that specific neurobiological factors, such as cortisol levels and brain activity, associated with antisocial behavior, can change towards 'less abnormal' in response to correctional behavioral intervention, but it is currently unknown how this works for resting heart rate (Cornet et al. 2015a). Another possible question is whether a *high resting heart rate* functions as a protective factor that reduces the probability of criminal behavior. A recent overview article suggests that resting heart rate, along with other biological correlates, may have potentially protective effects (Portnoy et al. 2013). Nonetheless, since the current findings are mixed, future research on this issue is necessary.

In short, both the heart rate assessment and the neuropsychological tasks are rather easy to administer. Within a few minutes, one can assess a rather robust biological correlate of antisocial behavior (resting heart rate). Nevertheless, one should take into account several

control variables that might confound the heart rate – antisocial behavior relationship. In addition, the lack of normative data emphasizes the need to use not just basic neurobiological measures, but a combination of psychological, sociological and biological measures in research, in order to give meaning to biological aspects of antisocial behavior and to obtain a comprehensive perspective.

### Case study

This section discusses some of the author's work that made use of both traditional criminological concepts and neurobiological measures to investigate the issue of high variety in treatment success among prisoners. The literature reveals that some effect studies find a recidivism reduction of 50% while others find no effect of behavioral intervention on reoffending rates at all (Lipsey and Cullen 2007; Lipsey et al. 2007; McDougall et al. 2009). Traditionally, psychosocial factors have been suggested to underlie individual differences in treatment success. For example, age, motivation, verbal intelligence level and prior offence history are assumed to account for the variation in treatment effect (Andrews and Dowden 2007; Lipsey et al. 2007; Serin and Kennedy 1997; Sterling-Turner 2002). However, it remains unclear what exactly underlies the wide variety in treatment success.

In our research, we aimed to investigate whether neurobiological factors could shed more light on why some offenders respond well to treatment while others do not. We assessed different individual aspects; risk assessment data (e.g. index offence, recidivism risk), psychological data (e.g. self-reported childhood trauma, treatment motivation) and neurobiological data (neuropsychological functioning and heart rate assessment) to predict the treatment success of prisoners selected for cognitive behavioral therapy. We selected neuropsychological tasks, based on the following sources: relevant literature showing a relationship between cognitive dysfunctioning and antisocial behavior, cognitive domains specific to the therapy (planning, perspective taking, inhibition and social/moral reasoning/thinking) and studies that already found a predictive value of specific cognitive function tasks in relation to cognitive behavioral therapy for prisoners (Fishbein et al. 2009; Mullin and Simpson 2007). This resulted in the following eight neuropsychological tasks: the Stroop Color Word Task, the D2 Cancellation Task, the Wais-III Digit Span, the Modified Wisconsin Card Sorting Task, the Tower of Hanoi, the Stop it Task, the Reading the Mind in the Eyes task and the Controlled Oral Word Association Task.

Furthermore, we assessed heart rate using the 'VU-AMS' ambulatory monitoring system, which is a more sophisticated device than those listed in Table 2<sup>1</sup> (De Geus et al. 1995; Willemsen et al. 1996). We chose this device because we are also interested in sympathetic and parasympathetic

functioning and skin conductance level. We assessed both the resting heart rate and the heart rate *reactivity* (the difference between the resting heart rate and heart rate during the D2 Cancellation Task, which is assumed to elicit some cognitive stress).

One important treatment outcome measure is treatment attrition, since it is known that those who drop out of treatment are six to eight times more likely to reoffend (Dowden and Serin 2001; Seager et al. 2004). In total, 121 imprisoned offenders had been assessed before receiving cognitive behavioral therapy. All offenders were motivated to complete the neuropsychological tasks and only two offenders refused to cooperate with the heart rate assessment. Results indicate that a neuropsychological test, the D2 Cancellation Task, has a modest predictive power for treatment dropout, superior to, for instance, a 'conscious' self-report assessment of treatment motivation as given by the offenders (Cornet et al. 2015b). In addition, concentration performance appears to be unrelated to self-reported motivation level. Overall, the results of our study suggest that if we had not assessed concentration performance, a relatively high proportion of information on *what* individual characteristics underlie treatment dropout would have remained lacking. Nevertheless, most other neurobiological assessments we performed in our study were not found to be 'predictive' of treatment dropout.

### Conclusion and future developments

Research on neurobiological correlates of antisocial behavior has been increasing since the 1990s, indicating that this area of research is developing. Growing interest, the development of new techniques and a zeitgeist change, have expanded this field of research considerably. Despite convincing empirical evidence suggesting that the neurobiological perspective on criminal behavior provides added value to criminological research, a neurobiological perspective has by no means become part and parcel of the methodological toolkit of crime researchers. The aim of the present article was to familiarize criminologists with basic neurobiological measurements and to describe possible contributions of these methods for the field of criminology. I think this can advance the field and may contribute to an improved understanding, prediction and prevention as well as improved intervention methods to reduce criminal behavior.

After reading this article, one might wonder where to start with the incorporation of basic neurobiological measures in criminological research. Which criminological research questions might be addressed, using neurobiological measurements? The answer to this is: basically all questions dealing with unraveling the underlying mechanisms of criminal behavior. Nonetheless, this article does not merely stimulate researchers to do *more* neurocriminological research; instead, more *good* neurocriminological research is

needed in which a combination of psychological/sociological and biological factors are investigated that can inform efforts to tackle the problem of crime. Not surprisingly, there is still much to unravel with regard to neurobiological characteristics of criminal behavior. For example, longitudinal and large-scale studies are required, while specific samples with antisocial behavior, such as females and individuals with antisocial personality disorder, are currently still underrepresented in neurocriminological studies.

Examples of possible research questions concern the discriminative value of neurobiological characteristics associated with different antisocial traits. As described previously, 'successful' psychopaths are characterized by a similar heart rate response to stress as normal individuals have, whereas 'unsuccessful' psychopaths showed a blunted autonomic response. A comparable research question might be: is there any difference in neurobiological functioning between desisters from crime compared to non-desisters? Questions like these might shed more light on behavioral differences and perhaps provide more information about different criminogenic needs. Another interesting question is to what extent neurobiological mechanisms can actually change towards being 'less abnormal'? Since neurobiological mechanisms are assumed to be a correlate of antisocial behavior, reducing criminal behavior would change underlying neurobiological functioning, and vice versa. This question presents a promising, comprehensive area of future research, as it might generate opportunities to improve or develop alternative intervention programs, based on the neurobiological correlates of criminal behavior (for an overview, see Cornet et al. 2015a).

In addition to neurobiological measurements, the development of other innovative methods within the field of criminology is expanding. An example of this is the usage of Virtual Reality (VR) (see Van Gelder et al. 2014 in this special issue). Especially vignette studies, often applied in criminology, might benefit from VR, since it has been suggested that people are fairly limited in their capacity to predict future behavior, particularly in situations unusual to them (Exum and Bouffard 2010). One future avenue of investigation might be the combination of VR techniques with neurobiological measurements. An example in this regard is the study by Armstrong and Boutwell (2012), who investigated the relationship between resting heart rate and vignette scenarios. It appears that healthy individuals with a relatively low resting heart rate are more likely to report that they would engage in an assault (as described in the *bar fight* scenario), compared to individuals with a relatively high resting heart rate. However, because the corresponding vignette scenarios were written down, this design raises the question to what extent individuals were able to visualize and imagine a realistic *bar fight* scenario. It

would be interesting to replicate this kind of study, with more realistically displayed situations presented to (delinquent) individuals by means of VR, to find out which neurobiological and personality characteristics are most predictive of displaying antisocial behavior, such as the engagement in an assault.

To familiarize criminologists with neurobiological measurements, this article introduced 'basic' neurobiological measures, because most neurobiological measures may be too complicated to incorporate without any substantial knowledge on how to use them. However, the field of neuroscience is highly innovative and *wearable* versions have been developed of complicated equipment, such as EEG techniques (e.g. the IMEC system<sup>m</sup> and Mindo<sup>n</sup>). These techniques enable researchers to assess other neurobiological characteristics, besides frontal brain and heart rate functioning, related to antisocial behavior. EEG is used to measure the electrical activity of the brain and can provide accurate information about which part of the brain is under- or overaroused. There is literature suggesting that EEG abnormalities are common in individuals with antisocial behavior (Gao et al. 2012).

Other commercial devices, such as the iPhysioMeter, are also rapidly developing. The iPhysioMeter is a heart rate measurement application for smartphones that uses the flashlight of the camera to measure heart rate in the index finger tip. It appears to give valid measures for resting heart rate in comparison to more complex devices (Matsumura and Yamakoshi 2013). In addition, the Apple Watch stores heart rate, GPS information and body posture<sup>o</sup>. Modern applications like these make it possible to investigate neurobiological characteristics outside the laboratory setting and to collect data on a larger scale. Currently, some of this innovative equipment is costly, but with ongoing technological developments, it is likely to become more easily available in the future.

In closing, although a biopsychosocial view on antisocial behavior is much more accepted these days than it was 25 years ago and many studies have shown the added value of using neurobiological tools to investigate antisocial behavior, many criminologists still rely on traditional measurement tools such as questionnaires, vignettes or observational methods. Importantly, using neurobiological tools in a criminological research setting does not necessarily require extensive neurobiological knowledge or complicated and expensive equipment, but instead requires more creativity and a mind-set change of criminologists. This mind-set shift might begin by establishing 'Neurobiological Correlates of Antisocial Behavior' as a mandatory course in the curriculum of criminology, to teach students about different neurocriminological theories and the different measurement methods. Not only can this knowledge be of use in extending current theories on neurobiology and antisocial

behavior, but it can also help develop better treatment options for offenders and eventually prevent the development of antisocial behavior.

#### Recommended literature

Gao, Y., Glenn, A. L., Peskin, M., Rudo-Hutt, A. S., Schug, R., Yang, Y., & Raine, A. (2012). Neurocriminological Approaches. In D. Gadd, S. Karstedt & S. F. Messner (Eds.), *The SAGE handbook of Criminological Research Methods* (pp. 63–75). London: SAGE Publications. If the reader considers using neurobiological measurement tools, this reference can be used to gather more information about the specific technical aspects of the most commonly used neurobiological instruments in the field of criminology (including both basic and complex ones).

Van Gozen, S. H. M., Fairchild, G., Snoek, H., & Harold, G. T. (2007). The evidence for a neurobiological model of childhood antisocial behavior. *Psychological Bulletin*, 133(1), 149–182. This article increases the understanding of the influence of neurobiological factors on the development of antisocial behavior.

Walsh, A., & Beaver, K. (2009). *Biosocial Criminology: New Directions in Theory and Research*. New York: Taylor & Francis. A textbook designed to bring criminology into the 21<sup>st</sup> century, by showing how leading criminologists have integrated aspects of the biological sciences into their field. Included topics: molecular genetics, neuroscience, and how to apply them to various correlates of crime.

Glenn, A. L., & Raine, A. (2014). Neurocriminology: implications for the punishment, prediction and prevention of criminal behaviour. *Nature Reviews Neuroscience*, 15(1), 54–63. More information about the current state of the neurocriminological research field.

Farah, M. J. (2012). Neuroethics: The Ethical, Legal, and Societal Impact of Neuroscience. *Annual Review of Psychology* (63), 571–591. This article describes the neuroethical view on the usage of neurobiological tools in criminological settings.

Vaske, J., Galyean, K., & Cullen, F. T. (2011). Toward a biosocial theory of offender rehabilitation: Why does cognitive-behavioral therapy work? *Journal of Criminal Justice*, 39(1), 90–102. Further reading about the implementation of the neuroscientific perspective on rehabilitation programs for offenders.

Beauchaine, T. P., Neuhaus, E., Brenner, S. L., & Gatzke-Kopp, L. (2008). Ten good reasons to consider biological processes in prevention and intervention research. *Development and Psychopathology*, 20(3), 745–774. Provides an overview of why neurobiological measures might add value in studying antisocial behavior.

[http://www.ted.com/talks/daniel\\_reisel\\_the\\_neuroscience\\_of\\_restorative\\_justice](http://www.ted.com/talks/daniel_reisel_the_neuroscience_of_restorative_justice). Interesting and entertaining TED

talk by Daniel Reisel about neurobiological research on incarcerated psychopaths and brain plasticity.

## Endnotes

<sup>a</sup>See [http://homepage.smc.edu/russell\\_richard/Psych2/Graphics/2013\\_Brain\\_Orientation\\_pictures.pdf](http://homepage.smc.edu/russell_richard/Psych2/Graphics/2013_Brain_Orientation_pictures.pdf) for an illustration of the anatomy of the brain

<sup>b</sup>Also called 'skin conductance'. It assesses the electrical conductance of the skin, which depends on the amount of sweat production of the skin. Electrodermal activity reflects psychological or physiological arousal

<sup>c</sup>Heart rate expressed as a change from baseline to task measurement

<sup>d</sup>The ability to temporarily hold and manipulate information about places. Daily situations in which these skills are used are, for example: finding your way around in a new environment or judging the position of pedestrians while cycling and talking to your friend

<sup>e</sup>[http://homepage.smc.edu/russell\\_richard/Psych2/Graphics/2013\\_Brain\\_Orientation\\_pictures.pdf](http://homepage.smc.edu/russell_richard/Psych2/Graphics/2013_Brain_Orientation_pictures.pdf)

<sup>f</sup>[www.millisecond.com](http://www.millisecond.com)

<sup>g</sup>[www.parinc.com](http://www.parinc.com)

<sup>h</sup>[www.pearsonclinical.com](http://www.pearsonclinical.com)

<sup>i</sup>[www.hogrefe.co.uk](http://www.hogrefe.co.uk)

<sup>j</sup>[www.cambridgecognition.com](http://www.cambridgecognition.com)

<sup>k</sup><http://www.cogmed.com> offers a professional working memory training program

<sup>l</sup>[www.vu-ams.nl](http://www.vu-ams.nl)

<sup>m</sup><https://www.youtube.com/watch?v=lrebiyeXXkc>

<sup>n</sup><http://mindocom.tw/en/about.php>

<sup>o</sup>[www.apple.com/watch/technology/](http://www.apple.com/watch/technology/)

## Competing interests

The author declares that she has no competing interests.

## Acknowledgement

This work was supported by the Netherlands Society of Scientific Research (NWO: Brain and Cognition: Societal Innovation, Grant: 056-21-011), the Netherlands Institute for the Study of Crime and Law Enforcement (NSCR), and the Research and Documentation Centre (WODC), Ministry of Security and Justice. I gratefully acknowledge the insightful comments during the process of writing this article from the following individuals; Catharina H. de Kogel, Henk L.I. Nijman, Peter H. van der Laan and Maud van Bavel.

Received: 7 June 2014 Accepted: 6 February 2015

Published online: 19 April 2015

## References

- Aharoni, E, Vincent, GM, Harenski, CL, Calhoun, VD, Sinnott-Armstrong, W, Gazzaniga, MS, & Kiehl, KA. (2013). Neuroprediction of future rearrest. *Proceedings of the National Academy of Sciences of the United States of America*, 110(15), 6223–6228. doi:10.1073/pnas.1219302110.
- Andrews, A, & Dowden, C. (2007). The risk-need-responsivity model of assessment and human service in prevention and corrections: Crime-prevention jurisprudence. *Canadian Journal of Criminology and Criminal Justice*, 49(4), 439–464. doi:10.3138/cjccj.49.4.439.
- Aoki, Y, Inokuchi, R, Nakao, T, & Yamasue, H (2014). Neural bases of antisocial behavior: a voxel-based meta-analysis. *Social Cognitive and Affective Neuroscience*, 9(8):1223–1231.
- Armstrong, TA, & Boutwell, BB. (2012). Low resting heart rate and rational choice: integrating biological correlates of crime in criminological theories. *Journal of Criminal Justice*, 40(1), 31–39. doi:10.1016/j.jcrimjus.2011.11.001.
- Armstrong, TA, Keller, S, Franklin, TW, & MacMillan, SN. (2009). Low resting heart rate and antisocial behavior: a brief review of evidence and preliminary results from a New test. *Criminal Justice and Behavior*, 36(11), 1125–1140. doi:10.1177/0093854809342855.
- Baker, E, Shelton, KH, Baibazarova, E, Hay, DF, & Van Goozen, SHM. (2013). Low skin conductance activity in infancy predicts aggression in toddlers 2 years later. *Psychological Science*, 24(6), 1051–1056. doi:10.1177/0956797612465198.
- Baker, LA, Tuvblad, C, Reynolds, C, Zheng, M, Lozano, DI, & Raine, A. (2009). Resting heart rate and the development of antisocial behavior from age 9 to 14: Genetic and environmental influences. *Development and Psychopathology*, 21(3), 939–960. doi:10.1017/S0954579409000509.
- Beauchaine, TP, Gatzke-Kopp, L, & Mead, HK. (2007). Polyvagal Theory and developmental psychopathology: Emotion dysregulation and conduct problems from preschool to adolescence. *Biological Psychology*, 74(2), 174–184. doi:10.1016/j.biopsycho.2005.08.008.
- Beauchaine, TP, Hong, J, & Marsh, P. (2008). Sex differences in autonomic correlates of conduct problems and aggression. *Journal of the American Academy of Child and Adolescent Psychiatry*, 47(7), 788–796. doi:10.1097/Chi.0b013e318172ef4b.
- Beaver, KM, Wright, JP, & Delisi, M. (2007). Self-control as an executive function - Reformulating Gottfredson and Hirschi's parental socialization thesis. *Criminal Justice and Behavior*, 34(10), 1345–1361. doi:10.1177/0093854807302049.
- Bergvall, AH, Wessely, H, Forsman, A, & Hansen, S. (2001). A deficit in attentional set-shifting of violent offenders. *Psychological Medicine*, 31(6), 1095–1105.
- Berlin, HA, Rolls, ET, & Kischka, U. (2004). Impulsivity, time perception, emotion and reinforcement sensitivity in patients with orbitofrontal cortex lesions. *Brain*, 127, 1108–1126. doi:10.1093/Brain/Awh135.
- Bimmel, N, Van IJzendoorn, MH, Bakermans-Kranenburg, MJ, Juffer, F, & De Geus, EJC. (2008). Problem behavior and heart rate reactivity in adopted adolescents: Longitudinal and concurrent relations. *Journal of Research on Adolescence*, 18(2), 201–213. doi:10.1111/j.1532-7795.2008.00557.x.
- Bogg, T, & Finn, PR. (2010). A self-regulatory model of behavioral disinhibition in late adolescence: integrating personality traits, externalizing psychopathology, and cognitive capacity. *Journal of Personality*, 78(2), 441–470. doi:10.1111/j.1467-6494.2010.00622.x.
- Broomhall, L. (2005). Acquired sociopathy: a neuropsychological study of executive dysfunction in violent offenders. *Psychiatry, Psychology and Law*, 12(2), 367–387.
- Brower, MC, & Price, BH. (2001). Neuropsychiatry of frontal lobe dysfunction in violent and criminal behaviour: a critical review. *Journal of Neurology, Neurosurgery and Psychiatry*, 71(6), 720–726. doi:10.1136/jnnp.71.6.720.
- Bullock, J. (1988). *Tonic heart rate, social class, and antisociality in adolescent girls*. England: Department of Psychology. University of York.
- Burgess, PW, Dumontheil, I, & Gilbert, SJ. (2007). The gateway hypothesis of rostral prefrontal cortex (area 10) function. *Trends in Cognitive Sciences*, 11(7), 290–298. doi:10.1016/j.tics.2007.05.004.
- Caspi, A, McClay, J, Moffitt, TE, Mill, J, Martin, J, Craig, IW, & Poulton, R. (2002). Role of genotype in the cycle of violence in maltreated children. *Science*, 297(5582), 851–854. doi:10.1126/science.1072290.
- Cauffman, E, Steinberg, L, & Piquero, AR. (2005). Psychological, neuropsychological and physiological correlates of serious antisocial behavior in adolescence: The role of self-control. *Criminology*, 43(1), 133–175.
- Chiang, SSW, Schuetz, CG, & Soyka, M. (2001). Role of aggressivity on reactivity and craving before and after cue exposure in recently detoxified alcoholics: Results from an experimental study. *European Addiction Research*, 7(4), 184–192. doi:10.1159/000050739.
- Clark, L, Bechara, A, Damasio, H, Aitken, MRF, Sahakian, BJ, & Robbins, TW. (2008). Differential effects of insular and ventromedial prefrontal cortex lesions on risky decision-making. *Brain*, 131, 1311–1322. doi:10.1093/Brain/Awn066.
- Cole, MW, Yarkoni, T, Repovs, G, Anticevic, A, & Braver, TS. (2012). Global connectivity of prefrontal cortex predicts cognitive control and intelligence. *Journal of Neuroscience*, 32(26), 8988–8999. doi:10.1523/Jneurosci.0536-12.2012.
- Cornet, LJM, De Kogel, CH, Nijman, H, Raine, A, & Van der Laan, PH. (2015a). Neurobiological changes after intervention in individuals with antisocial behavior: a literature review. *Criminal Behaviour and Mental Health*, 25(1), 10–27. doi:10.1002/cbm.1915.
- Cornet, LJM, Van der Laan, PH, Nijman, HLI, Tollenaar, N, & De Kogel, CH. (2015b). Neurobiological Factors as Predictors of Prisoners' Response to a Cognitive Skills Training. *Journal of Criminal Justice*, 43, 122–132.

- Cornet, LJM, De Kogel, CH, Nijman, HLI, Raine, A, & Van der Laan, PH. (2014). Neurobiological factors as predictors of cognitive-behavioral therapy outcome in individuals with antisocial behavior: a review of the literature. *International Journal of Offender Therapy and Comparative Criminology*, 58(11), 1279–1296. doi:10.1177/0306624x13494694.
- Davidson, RJ. (1998). Anterior electrophysiological asymmetries, emotion, and depression: Conceptual and methodological conundrums. *Psychophysiology*, 35(5), 607–614. doi:10.1017/S0048577298000134.
- Davidson, RJ, Saron, CD, Senulis, JA, Ekman, P, & Friesen, WV. (1990). Approach withdrawal and cerebral asymmetry - emotional expression and brain physiology. *Journal of Personality and Social Psychology*, 58(2), 330–341. doi:10.1037/0022-3514.58.2.330.
- Davies, JGV, & Maliphan, R. (1971). Autonomic responses of male adolescents exhibiting refractory behaviour in school. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, 12(2), 115. doi:10.1111/j.1469-7610.1971.tb01055.x.
- De Geus, EJC, Willemsen, GHM, Klaver, CH, & Van Doornen, LJP. (1995). Ambulatory measurement of respiratory sinus arrhythmia and respiration rate. *Biological Psychology*, 31(3), 205–227.
- De Vries-Bouw, M, Popma, A, Vermeiren, R, Doreleijers, TAH, Van De Ven, PM, & Jansen, LMC. (2011). The predictive value of low heart rate and heart rate variability during stress for reoffending in delinquent male adolescents. *Psychophysiology*, 48(11), 1596–1603. doi:10.1111/j.1469-8986.2011.01233.x.
- Delisi, M, Hochstetler, A, & Murphy, DS. (2003). Self-control behind bars: A validation study of the Grasmick et al. scale. *Justice Quarterly*, 20(2), 241–263. doi:10.1080/07418820300095521.
- Dolan, M, & Park, I. (2002). The neuropsychology of antisocial personality disorder. *Psychological Medicine*, 32(3), 417–427. doi:10.1017/S0033291702005378.
- Dowden, C, & Serin, R. (2001). *Anger management programme for offenders: the impact of program performance measures*. Ottawa: Research Branch Correctional Service of Canada.
- Endres, MJ, Rickert, ME, Bogg, T, Lucas, J, & Finn, PR. (2011). Externalizing psychopathology and behavioral disinhibition: working memory mediates signal discriminability and reinforcement moderates response bias in approach-avoidance learning. *Journal of Abnormal Psychology*, 120(2), 336–351. doi:10.1037/A0022501.
- Exum, ML, & Bouffard, JA. (2010). Testing theories of criminal decision making: some empirical questions about hypothetical scenarios. In AR Piquero & D Weisburd (Eds.), *Handbook of Quantitative Criminology* (pp. 581–594). New York: Springer.
- Farah, M. J. (2012). Neuroethics: The Ethical, Legal, and Societal Impact of Neuroscience. *Annual Review of Psychology* 63, 571–591.
- Finn, PR, Rickert, ME, Miller, MA, Lucas, J, Bogg, T, Bobova, L, & Cantrell, H. (2009). Reduced cognitive ability in alcohol dependence: examining the role of covarying externalizing psychopathology. *Journal of Abnormal Psychology*, 118(1), 100–116. doi:10.1037/A0014656.
- Fishbein, D, Sheppard, M, Hyde, C, Hubal, R, Newlin, D, Serin, R, & Alesci, S. (2009). Deficits in Behavioral Inhibition Predict Treatment Engagement in Prison Inmates. *Law and Human Behavior*, 33(5), 419–435. doi:10.1007/s10979-008-9163-7.
- Fray, PJ, Robbins, TW, & Sahakian, BJ. (1996). Neuropsychiatric applications of CANTAB. *Int J Geriatr Psychiatry*, 11(4), 329–336.
- Gao, Y, Glenn, AL, Peskin, M, Rudo-Hutt, AS, Schug, R, Yang, Y, & Raine, A. (2012). Neurocriminological Approaches. In D Gadd, S Karstedt, & SF Messner (Eds.), *The SAGE handbook of Criminological Research Methods* (pp. 63–75). London: SAGE Publications.
- Gao, Y, Raine, A, Venables, PH, Dawson, ME, & Mednick, SA. (2010a). Association of poor childhood fear conditioning and adult crime. *American Journal of Psychiatry*, 167(1), 56–60. doi:10.1176/appi.ajp.2009.09040499.
- Gao, Y, Raine, A, Venables, PH, Dawson, ME, & Mednick, SA. (2010b). Reduced electrodermal fear conditioning from ages 3 to 8 years is associated with aggressive behavior at age 8 years. *Journal of Child Psychology and Psychiatry*, 51(5), 550–558. doi:10.1111/j.1469-7610.2009.02176.x.
- Glenn, AL, & Raine, A. (2014). Neurocriminology: implications for the punishment, prediction and prevention of criminal behaviour. *Nature Reviews Neuroscience*, 15(1), 54–63. doi:10.1038/Nrn3640.
- Gorenstein, EE. (1982). Frontal-lobe functions in psychopaths. *Journal of Abnormal Psychology*, 91(5), 368–379. doi:10.1037//0021-843x.91.5.368.
- Gottfredson, MR, & Hirschi, T. (1990). *A General Theory of Crime*. Stanford, CA: Stanford University Press.
- Hare, RD. (1984). Performance of psychopaths on cognitive tasks related to frontal-lobe function. *Journal of Abnormal Psychology*, 93(2), 133–140. doi:10.1037/0021-843x.93.2.133.
- Hawes, DJ, Brennan, J, & Dadds, MR. (2009). Cortisol, callous-unemotional traits, and pathways to antisocial behavior. *Current Opinion in Psychiatry*, 22(4), 357–362. doi:10.1097/Yco.0b013e32832bfa6d.
- Hiatt, KD, Schmitt, WA, & Newman, JP. (2004). Stroop tasks reveal abnormal selective attention among psychopathic offenders. *Neuropsychology*, 18(1), 50–59. doi:10.1037/0894-4105.18.1.50.
- Hoaken, PNS, Allaby, DB, & Earle, J. (2007). Executive cognitive functioning and the recognition of facial expressions of emotion in incarcerated violent offenders, non-violent offenders, and controls. *Aggressive Behavior*, 33(5), 412–421. doi:10.1002/Ab.20194.
- Horstkötter, D, Berghmans, R, & De Wert, G. (2012). *Prevention of antisocial behavior in children - Ethical implications of a neurobiological approach*. Paper presented at the EFCAP, Berlin. [https://www.academia.edu/4470651/Prevention\\_of\\_antisocial\\_behaviour\\_in\\_children\\_-\\_ethical\\_implications\\_of\\_a\\_neurobiological\\_approach](https://www.academia.edu/4470651/Prevention_of_antisocial_behaviour_in_children_-_ethical_implications_of_a_neurobiological_approach).
- Jackson, DB, & Beaver, KM. (2013). The influence of neuropsychological deficits in early childhood on low self-control and misconduct through early adolescence. *Journal of Criminal Justice*, 41(4), 243–251. doi:10.1016/j.jcrimjus.2013.05.002.
- Jennings, WG, Piquero, AR, & Farrington, DP. (2013). Does resting heart rate at age 18 distinguish general and violent offending up to age 50? findings from the Cambridge study in delinquent development. *Journal of Criminal Justice*, 41(4), 213–219. doi:10.1016/j.jcrimjus.2013.05.003.
- Jolliffe, D, & Farrington, DP. (2004). Empathy and offending: A systematic review and meta-analysis. *Aggression and Violent Behavior*, 9(5), 441–476. doi:10.1016/j.avb.2003.03.001.
- Kindlon, DJ, Tremblay, RE, Mezzacappa, E, Earls, F, Laurent, D, & Schaal, B. (1995). Longitudinal patterns of heart-rate and fighting behavior in 9-year-Old 12-year-Old boys. *Journal of the American Academy of Child and Adolescent Psychiatry*, 34(3), 371–377. doi:10.1097/00004583-199503000-00023.
- Koechlin, E, Basso, G, Pietrini, P, Panzer, S, & Grafman, J. (1999). The role of the anterior prefrontal cortex in human cognition. *Nature*, 399(6732), 148–151.
- Koenigs, M. (2012). The role of prefrontal cortex in psychopathy. *Reviews in the Neurosciences*, 23(3), 253–262. doi:10.1515/revneuro-2012-0036.
- Koenigs, M, & Grafman, J. (2009). The functional neuroanatomy of depression: Distinct roles for ventromedial and dorsolateral prefrontal cortex. *Behavioural Brain Research*, 201(2), 239–243.
- Levy, BJ, & Wagner, AD. (2011). Cognitive control and right ventrolateral prefrontal cortex: reflexive reorienting, motor inhibition, and action updating. *Year in Cognitive Neuroscience*, 1224, 40–62. doi:10.1111/j.1749-6632.2011.05958.x.
- Lezak, MD, Howieson, DB, & Loring, DW. (2004). *Neuropsychological Assessment* (4th ed.). New York: Oxford University Press.
- Lipsey, MW, & Cullen, FT. (2007). The effectiveness of correctional rehabilitation: A review of systematic reviews. *Annual Review of Law and Social Science*, 3, 297–320. doi:10.1146/annurev.lawsocsci.3.081806.112833.
- Lipsey, MW, Landenberger, NA, & Wilson, SJ. (2007). Effects of cognitive-behavioral programs for criminal offenders. *Campbell Systematic Reviews*, 6, 1–27. doi:10.4073/csr.2007.6.
- Lorber, MF. (2004). Psychophysiology of aggression, psychopathy, and conduct problems. A meta-analysis. *Psychological Bulletin*, 130(4), 531–552. doi:10.1037/0033-2909.130.4.531.
- Lotze, M, Veit, R, Anders, S, & Birbaumer, N. (2007). Evidence for a different role of the ventral and dorsal medial prefrontal cortex for social reactive aggression: An interactive fMRI study. *Neuroimage*, 34(1), 470–478. doi:10.1016/j.neuroimage.2006.09.028.
- Lueger, RJ, & Gill, KJ. (1990). Frontal-lobe cognitive dysfunction in conduct disorder adolescents. *Journal of Clinical Psychology*, 46(6), 696–706.
- Maliszka, KL, Allman, AA, Shiloff, D, Jakobson, L, Longstaffe, S, & Chudley, AE. (2005). Evaluation of spatial working memory function in children and adults with fetal alcohol spectrum disorders: A functional magnetic resonance imaging study. *Pediatric Research*, 58(6), 1150–1157. doi:10.1203/01.pdr.0000185479.92484.a1.
- Malloy, P, Bihle, A, Duffy, J, & Cimino, C. (1993). The orbitomedial frontal syndrome. *Archives of Clinical Neuropsychology*, 8(3), 185–201. doi:10.1016/0887-6177(93)90035-Y.
- Matsumura, K, & Yamakoshi, T. (2013). PhysioMeter: A new approach for measuring heart rate and normalized pulse volume using only a smartphone. *Behavior Research Methods*, 45(4), 1272–1278. doi:10.3758/s13428-012-0312-z.
- McDougall, C, Perry, A, Clabour, J, Bowles, R, & Worthy, G. (2009). Evaluation of HM prison service enhanced thinking skills programme. *Ministry of Justice Research Series*, 3(9), 1–60.

- McGloin, JM. (2009). Delinquency balance: revisiting peer influence. *Criminology*, 47(2), 439–477. doi:10.1111/j.1745-9125.2009.00146.x.
- Mezzacappa, E, Tremblay, RE, Kindlon, D, Saul, JP, Arseneault, L, Seguin, J, & Earls, F. (1997). Anxiety, antisocial behavior, and heart rate regulation in adolescent males. *Journal of Child Psychology and Psychiatry and Allied Disciplines*, 38(4), 457–469. doi:10.1111/j.1469-7610.1997.tb01531.x.
- Miller, EK. (2000). The prefrontal cortex and cognitive control. *Nature Reviews Neuroscience*, 1(1), 59–65. doi:10.1038/35036228.
- Mishkin, M. (1982). A memory system in the monkey. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 298(1089), 85–95. doi:10.1098/rstb.1982.0074.
- Moffitt, TE. (1990). The neuropsychology of juvenile delinquency: a critical review. *Crime and Justice. A Review of Research*, 12, 99–169. doi:10.1086/449165.
- Morgan, AB, & Lilienfeld, SO. (2000). A meta-analytic review of the relation between antisocial behavior and neuropsychological measures of executive function. *Clinical Psychology Review*, 20(1), 113–136. doi:10.1016/S0272-7358(98)00096-8.
- Mull, BR, & Seyal, M. (2001). Transcranial magnetic stimulation of left prefrontal cortex impairs working memory. *Clinical Neurophysiology*, 11(9), 1672–1675. doi:10.1016/S1388-2457(01)00606-X.
- Mullin, S, & Simpson, J. (2007). Does executive functioning predict improvement in offenders' behaviour following enhanced thinking skills training? An exploratory study with implications for rehabilitation. *Legal and Criminological Psychology*, 12, 117–131. doi:10.1348/13553250591560.
- Nee, DE, Jonides, J, & Berman, MG. (2007). Neural mechanisms of proactive interference-resolution. *Neuroimage*, 38(4), 740–751. doi:10.1016/j.neuroimage.2007.07.066.
- Ogilvie, JM, Stewart, AL, Chan, RCK, & Shum, DHK. (2011). Neuropsychological measures of executive function and antisocial behavior. *A Meta-Analysis\**. *Criminology*, 49(4), 1063–1107. doi:10.1111/j.1745-9125.2011.00252.x.
- Ortiz, J, & Raine, A. (2004). Heart rate level and antisocial behavior in children and adolescents: A meta-analysis. *Journal of the American Academy of Child and Adolescent Psychiatry*, 43(2), 154–162. doi:10.1097/01.chi.0000101373.03068.5c.
- Owen, AM, Doyon, J, Petrides, M, & Evans, AC. (1996a). Planning and spatial working memory: A positron emission tomography study in humans. *European Journal of Neuroscience*, 8(2), 353–364. doi:10.1111/j.1460-9568.1996.tb01219.x.
- Owen, AM, Evans, AC, & Petrides, M. (1996b). Evidence for a two-stage model of spatial working memory processing within the lateral frontal cortex: A positron emission tomography study. *Cerebral Cortex*, 6(1), 31–38. doi:10.1093/cercor/6.1.31.
- Pardini, DA, Raine, A, Erickson, K, & Loeber, R. (2014). Lower amygdala volume in Men is associated with childhood aggression, early psychopathic traits, and future violence. *Biological Psychiatry*, 75(1), 73–80.
- Patrick, CJ. (2008). Psychophysiological correlates of aggression and violence: an integrative review. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 363(1503), 2543–2555. doi:10.1098/rstb.2008.0028.
- Patrick, CJ, Cuthbert, BN, & Lang, PJ. (1994). Emotion in the criminal psychopath - fear image processing. *Journal of Abnormal Psychology*, 103(3), 523–534. doi:10.1037//0021-843x.103.3.523.
- Petrides, M, & Milner, B. (1982). Deficits on subject-ordered tasks after frontal-lobe and temporal-lobe lesions in Man. *Neuropsychologia*, 20(3), 249. doi:10.1016/0028-3932(82)90100-2.
- Pham, TH, Vanderstucken, O, Philippot, P, & Vanderlinden, M. (2003). Selective attention and executive functions deficits among criminal psychopaths. *Aggressive Behavior*, 29(5), 393–405. doi:10.1002/Ab.10051.
- Piferi, RL, Kline, KA, Younger, J, & Lawler, KA. (2000). An alternative approach for achieving cardiovascular baseline: viewing an aquatic video. *International Journal of Psychophysiology*, 37(2), 207–217. doi:10.1016/S0167-8760(00)00102-1.
- Pitts, TB. (1997). Reduced heart rate levels in aggressive children. In A Raine, PA Brennan, DP Farrington, & SA Mednick (Eds.), *The Biosocial Bases of Violence* (pp. 321–324). New York: Plenum.
- Porges, SW. (2000). The Polyvagal Theory: The phylogenetic substrates of a social nervous system. *International Journal of Psychophysiology*, 35(1), 2–2.
- Porges, S. W. (2009). The polyvagal theory: New insights into adaptive reactions of the autonomic nervous system. *Cleve Clinical Journal of Medicine*, 1–8. doi:10.3949/ccjm.76.s2.17.
- Porteus, SD. (1959). *The Maze Test and clinical psychology*. Palo Alto, CA: Pacific Books.
- Portnoy, J, Chen, FR, & Raine, A. (2013). Biological protective factors for antisocial and criminal behavior. *Journal of Criminal Justice*, 41(5), 292–299. doi:10.1016/j.jcrimjus.2013.06.018.
- Portnoy, J, Raine, A, Chen, FR, Pardini, D, Loeber, R, & Jennings, JR. (2014). Heart rate and antisocial behavior. *The Mediating Role of Impulsive Sensation Seeking. Criminology*, 52(2), 292–311. doi:10.1111/1745-9125.12038.
- Pratt, TC, & Cullen, FT. (2000). The empirical status of Gottfredson and Hirschi's general theory of crime: A meta-analysis. *Criminology*, 38(3), 931–964. doi:10.1111/j.1745-9125.2000.tb00911.x.
- Quay, HC. (1965). Psychopathic personality as pathological stimulation-seeking. *American Journal of Psychiatry*, 122(2), 180–183.
- Raine, A. (1996). Autonomic nervous system factors underlying disinhibited, antisocial, and violent behavior - Biosocial perspectives and treatment implications. *Understanding Aggressive Behavior in Children*, 794, 46–59. doi:10.1111/j.1749-6632.1996.tb32508.x.
- Raine, A. (2002a). Annotation: The role of prefrontal deficits, low autonomic arousal, and early health factors in the development of antisocial and aggressive behavior in children. *Journal of Child Psychology and Psychiatry*, 43(4), 417–434. doi:10.1111/1469-7610.0003.
- Raine, A. (2002b). Biosocial studies of antisocial and violent behavior in children and adults: A review. *Journal of Abnormal Child Psychology*, 30(4), 311–326. doi:10.1023/A:1015754122318.
- Raine, A. (2005). The interaction of biological and social measures in the explanation of antisocial and violent behavior. In DM Stoff & EJ Susman (Eds.), *Developmental Psychobiology of Aggression* (pp. 13–42). New York: Cambridge University Press.
- Raine, A. (2008). From genes to brain to antisocial behavior. *Current Directions in Psychological Science*, 17(5), 323–328. doi:10.1111/j.1467-8721.2008.00599.x.
- Raine, A. (2013). *The Anatomy of Violence: the Biological Roots of Crime: Phanteon*.
- Raine, A, Moffitt, TE, Caspi, A, Loeber, R, Stouthamer-Loeber, M, & Lynam, D. (2005). Neurocognitive impairments in boys on the life-course persistent antisocial path. *Journal of Abnormal Psychology*, 114(1), 38–49. doi:10.1037/0021-843x.114.1.38.
- Raine, A, Venables, PH, & Mednick, SA. (1995). High autonomic arousal and age 3 years predisposes to aggression at age 11 years: Evidence from the Mauritius Child Health Project. *Journal of the American Academy of Child and Adolescent Psychiatry*, 36(10), 1457–1464. doi:10.1097/00004583-199710000-00029.
- Raine, A, Venables, PH, & Williams, M. (1995). High autonomic arousal and electrodermal orienting at Age 15 years as protective factors against criminal behavior at Age 29 years. *American Journal of Psychiatry*, 152(11), 1595–1600.
- Ratchford, M, & Beaver, KM. (2009). Neuropsychological deficits, Low self-control, and delinquent involvement. Toward a biosocial explanation of delinquency. *Criminal Justice and Behavior*, 36(2), 147–162. doi:10.1177/0093854808325967.
- Riddle, M, & Roberts, AH. (1977). Delinquency, Delay of Gratification, Recidivism, and Porteus Maze Tests. *Psychological Bulletin*, 84(3), 417–425. doi:10.1037//0033-2909.84.3.417.
- Ross, TP, Hanouskova, E, Giarla, K, Calhoun, E, & Tucker, M. (2007). The reliability and validity of the self-ordered pointing task. *Archives of Clinical Neuropsychology*, 22(4), 449–458. doi:10.1016/j.acn.2007.01.023.
- Scarpa, A, Haden, SC, & Tanaka, A. (2010). Being hot-tempered: Autonomic, emotional, and behavioral distinctions between childhood reactive and proactive aggression. *Biological Psychology*, 84(3), 488–496. doi:10.1016/j.biopsycho.2009.11.006.
- Seager, JA, Jellicoe, D, & Dhaliwal, GK. (2004). Refusers, dropouts, and completers: Measuring sex offender treatment efficacy. *International Journal of Offender Therapy and Comparative Criminology*, 48(5), 600–612. doi:10.1177/0306624x04263885.
- Serin, R, & Kennedy, A. (1997). Treatment readiness and responsivity. Contributing to effective correctional programming. *Research Report R-54*. Ottawa, Toronto: Canada: Correctional Service.
- Shircliff, EA, Vitacco, MJ, Graf, AR, Gostisha, AJ, Merz, JL, & Zahn-Waxler, C. (2009). Neurobiology of empathy and callousness: implications for the development of antisocial behavior. *Behavioral Sciences & the Law*, 27(2), 137–171. doi:10.1002/Bsl.862.
- Sibley, MH, Pelham, WE, Molina, BSG, Waschbusch, DA, Gnagy, EM, Babinski, DE, & Biswas, A. (2010). Inconsistent Self-Report of Delinquency by Adolescents and Young Adults with ADHD. *Journal of Abnormal Child Psychology*, 38(5), 645–656. doi:10.1007/s10802-010-9404-3.
- Simmonds, DJ, Pekar, JJ, & Mostofsky, SH. (2008). Meta-analysis of Go/No-go tasks, demonstrating that fMRI activation associated with response inhibition is task-dependent. *Neuropsychologia*, 46(1), 224–232. doi:10.1016/j.neuropsychologia.2007.07.015.
- Stadler, C, Grasmann, D, Fegert, JM, Holtmann, M, Poustka, F, & Schmeck, K. (2008). Heart rate and treatment effect in children with disruptive behavior disorders. *Child Psychiatry & Human Development*, 39(3), 299–309. doi:10.1007/s10578-007-0089-y.

- Sterling-Turner, H. E. (2002). The effects of direct training and treatment integrity on treatment outcomes in school consultation (vol 17, pg 47, 2002). *School Psychology Quarterly*, 17(2).
- Van Bokhoven, I, Matthys, W, Van Goozen, SH, & Van Engeland, H. (2005). Prediction of adolescent outcome in children with disruptive behavior disorders: A study of neurobiological, psychological and family factors. *European Child & Adolescent Psychiatry*, 14, 153–163.
- Van de Weijer, SGA, De Jong, R, Bijleveld, CCJH, Blokland, AAJ, & Raine, A. (submitted). *The role of heart rate levels in the intergenerational transmission of crime*.
- Van Gelder, J, Otte, M, & Luciano, EC. (2014). Using virtual reality in criminological research. *Crime Science*, 3(10), 1–12.
- Van Goozen, SH, Snoek, H, Matthys, W, Van Rossum, I, & Van Engeland, H. (2004). Evidence of fearlessness in behaviourally disordered children: a study on startle reflex modulation. *Journal of Child Psychology and Psychiatry*, 45, 884–982.
- Van Goozen, SHM, Fairchild, G, Snoek, H, & Harold, GT. (2007). The evidence for a neurobiological model of childhood antisocial behavior. *Psychological Bulletin*, 133(1), 149–182. doi:10.1037/0033-2909.133.1.149.
- Van Goozen, SHM, Matthys, W, Cohen-Kettenis, PT, Gispen-de Wied, C, Wiegant, VM, & van Engeland, H. (1998). Salivary cortisol and cardiovascular activity during stress in oppositional-defiant disorder boys and normal controls. *Biological Psychiatry*, 43(7), 531–539. doi:10.1016/S0006-3223(97)00253-9.
- Van Langen, MAM, Wissink, IB, Van Vugt, ES, Van der Stouwe, T, & Stams, GJJM. (2014). The relation between empathy and offending: A meta-analysis. *Aggression and Violent Behavior*, 19, 179–189.
- Vaske, J, Galyean, K, & Cullen, FT. (2011). Toward a biosocial theory of offender rehabilitation: Why does cognitive-behavioral therapy work? *Journal of Criminal Justice*, 39(1), 90–102. doi:10.1016/j.jcrimjus.2010.12.006.
- Wahlund, K, & Kristiansson, M. (2009). Aggression, psychopathy and brain imaging - Review and future recommendations. *International Journal of Law and Psychiatry*, 32(4), 266–271. doi:10.1016/j.ijlp.2009.04.007.
- Walsh, A. (2009). *Biology and Criminology: the Biosocial Synthesis*. New York: Taylor & Francis.
- Walsh, A, & Beaver, K. (2009). *Biosocial Criminology: New Directions in Theory and Research*. New York: Taylor & Francis.
- Walsh, A, & Ellis, L. (2004). Ideology: Criminology's Achilles' Heel? *Quarterly Journal of Ideology*, 27, 1–25.
- Weerman, FM. (2011). Delinquent peers in context: a longitudinal network analysis of selection and influence effects. *Criminology*, 49(1), 253–286. doi:10.1111/j.1745-9125.2010.00223.x.
- Willemssen, GHM, De Geus, EJC, Klaver, CHAM, Van Doornen, LJP, & Carroll, D. (1996). Ambulatory monitoring of the impedance cardiogram. *Psychophysiology*, 33(2), 184–193. doi:10.1111/j.1469-8986.1996.tb02122.x.
- Wilson, LC, & Scarpa, A. (2012). Criminal behavior: the need for an integrative approach that incorporates biological influences. *Journal of Contemporary Criminal Justice*, 28(366), 366–381.
- Wilson, LC, & Scarpa, A. (2014). Aggressive behavior: an alternative model of resting heart rate and sensation seeking. *Aggressive Behavior*, 40(1), 91–98. doi:10.1002/Ab.21504.
- Yang, YL, & Raine, A. (2009). Prefrontal structural and functional brain imaging findings in antisocial, violent, and psychopathic individuals. *A meta-analysis. Psychiatry Research-Neuroimaging*, 174(2), 81–88. doi:10.1016/j.psychres.2009.03.012.
- Zuckerman, M. (1979). *Sensation Seeking: Beyond the Optimal Level of Arousal*.

Submit your manuscript to a SpringerOpen<sup>®</sup> journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Immediate publication on acceptance
- Open access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

---

Submit your next manuscript at ► [springeropen.com](http://springeropen.com)

---