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The guilty brain: the utility of neuroimaging and neurostimulation studies in forensic field

Abstract: Several studies have aimed to address the natural inability of humankind to detect deception and accurately discriminate lying from truth in the legal context. To date, it has been well established that telling a lie is a complex mental activity. During deception, many functions of higher cognition are involved: the decision to lie, withholding the truth, fabricating the lie, monitoring whether the receiver believes the lie, and, if necessary, adjusting the fabricated story and maintaining a consistent lie. In the previous 15 years, increasing interest in the neuroscience of deception has resulted in new possibilities to investigate and interfere with the ability to lie directly from the brain. Cognitive psychology, as well as neuroimaging and neurostimulation studies, are increasing the possibility that neuroscience will be useful for lie detection. This paper discusses the scientific validity of the literature on neuroimaging and neurostimulation regarding lie detection to understand whether scientific findings in this field have a role in the forensic setting. We considered how lie detection technology may contribute to addressing the detection of deception in the courtroom and discussed the conditions and limits in which these techniques reliably distinguish whether an individual is lying.

Keywords: deception; lie detection; neuroimaging; neurostimulation.

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Introduction

To date, scientific research has demonstrated that in a face-to-face meeting, the average individual is able to detect deception at a rate that is only slightly better than 50%, which indicates that most individuals are no better at detecting deception than expected from pure guessing (Ekman and O'Sullivan, 1991). These data have led courts to search for a technology-based method of lie detection, which may objectively improve the natural inability of humankind to detect deception.

Older methods that have relied on physiological and emotional arousal (i.e. polygraphs) have fallen short of generating effective techniques that provide a useful contribution within the forensic field (Grubin and Madsen, 2005; Vrij et al., 2010). The major limitation of these methods is that affective arousal is nonspecific to deception, which may lead to inflated rates of false positives. The emotions that are generated by attempts at deception often include fear and anxiety, which may be indistinguishable from the emotions of an honest individual who endures stressful questioning (Vrij et al., 2010).

Legal debates concerning lie-detecting technology have existed since the 1920s; however, with few exceptions, laws prohibit the use of polygraphs and other technologies and instead rely on a judge and jury (Church, 2012). In the previous 15 years, increasing interest from neuroscientists has opened new possibilities to investigate and interfere with the ability to lie directly from the brain. The interest has precisely focused on the investigation of the neural correlates that enable the brain to effectively produce a lie, the specific structures and cognitive functions involved, and how it may be possible to interfere with them.

From a cognitive perspective, deception is cognitively more demanding than truth telling (Spence et al., 2004). A lie involves one or more of the following mental operations: the decision to lie, withholding the truth, fabricating the lie, monitoring whether the receiver believes the lie, and, if necessary, adjusting the fabricated story and maintaining a consistent lie. These mental operations make lying a cognitively demanding task.

This paper focuses on the literature regarding neuroimaging and neurostimulation studies to understand whether scientific findings in this field may have a crucial role in the detection of deception in the forensic setting. Furthermore, we only selected papers that referred to the detection of deception in adults because even if children exhibit an ability to make untrue statements, in contrast to adults, they are unable to cover up their misdeed.

We used the PubMed online database to select papers published from January 2001 to December 2015. Our key search terms were 'Deception' combined with 'fMRI' or 'tDCS' or 'TMS'. All studies selected for review were conducted in humans and were written in English.

Detection of deception from brain scans

Since the publication of these pioneering reports, the functional neuroimaging of deception has rapidly increased, which has led to the development of the cognitive neuroscience of deception. Several studies have focused on the identification of the areas involved in lie production and the underlying cognitive processes, whereas other studies have focused on creating experimental settings more similar to real life.

In this section, we discussed findings regarding the use of functional magnetic resonance imaging (fMRI) to map the liar brain; therefore, we did not consider scientific articles on malingering or studies focused on testing the validity of the fMRI technique or research conducted in the social field.

To map the liar brain

The first fMRI protocol to investigate the deceitful brain regarding autobiographical and episodic memory was created by Spence et al. (2001). They used two computerized lying protocols, which included auditory and visual procedures, with a forced yes or no response regarding daily activities. The results indicated substantial activation in the bilateral ventrolateral prefrontal cortex (VLPFC) and the anterior cingulate cortex (ACC) in combination with an increasing reaction time in deceptive responses.

For testing neuroimaging as a Lie Detector, Langleben et al. (2002) used a modified version of the Guilty Knowledge task (GKT), a questioning technique that has been extensively utilized in the forensic field (Lykken, 1991).

In this study, the participants were given playing cards and were instructed to deny the possession of the cards. The results demonstrated that increased activity in the superior frontal gyrus (SFG), ACC, premotor, motor, and anterior parietal cortices was associated with deception (Langleben et al., 2002).

In these studies focused on mapping the liar brain, the authors have indicated that the lie should not be summarized in a single cognitive process, much less in a specific area of the brain; in contrast, depending on the type of lie, the activation of different areas may be considered. For example, in the study by Ganis et al. (2003), they tested the differences between two dimensions of lies: spontaneous lies and the capability to deceit according to a memorized scenario regarding personal work experience. They determined that both lie conditions activate the bilateral anterior prefrontal cortex (PFC) and bilateral parahippocampal gyro, which were quiescent during the truth condition. Specifically, for the well-rehearsed lie condition, the authors identified substantial activation in the right anterior frontal cortices compared with spontaneous lies, which elicited activation in the ACC and posterior visual cortex. Furthermore, in the study by Nunez et al. (2005), the participants were instructed to respond truthfully or untruthfully to a series of yes/no questions regarding 'autobiographical' and 'nonautobiographical' content. The results indicated an interference effect (longer reaction times for false versus true responses) that was accompanied by increased activation within the anterior cingulate, caudate and thalamic nuclei, and dorsolateral prefrontal cortex (DLPFC), which comprises a circuit that has been implicated in response conflict and cognitive control. Furthermore, a correlation between the reaction time and left caudate activity supported the presence of increased response inhibition when falsifying responses. The neural and behavioral data were more robust when falsifying autobiographical responses, and the mesial prefrontal and posterior cingulate cortices were recruited. The authors concluded that the process of interference is inherent to the act of falsifying information, and the amount of conflict induced and the cognitive control needed to successfully execute false responses are greater when dealing with personal information.

To determine whether neural activity correlates with changes in electrodermal activity (EDA), Kozel et al. (2004a) implemented a modified Control Question test paradigm, in which it was required to provide both truthful and deceitful answers regarding the location of money. The results demonstrated that the orbitofrontal and ACC were significantly activated during deception. Moreover, the activities in these regions were correlated with changes in the EDA.

To attempt to improve the consistency of the individual results, Kozel et al. (2004b) subsequently replicated the previous study. During the scan, the subjects were required to indicate whether money was under the objects presented in the picture. Blood oxygen level-dependent fMRI significance maps were generated for subjects who provided a deceptive answer minus a truthful answer (lie minus true) and the reverse (true minus lie). Consistent with previous studies, the lie minus true group analysis indicated significant activation in the right orbitofrontal, inferior frontal, middle frontal cortex, cingulate gyrus, and left middle frontal area, whereas there was no significant activation for true minus lie. Unfortunately, the present technique lacks good predictive power for individuals.

Langleben et al. (2005) also performed a quantitative analysis in individual subjects. They assessed the accuracy of fMRI in conjunction with a Formal Forced-Choice paradigm (GKT) to confirm brain activation during lie responses in the superior medial and inferolateral PFC. The combination of the fMRI technique and GKT appeared sensitive in the detection of deception with an accuracy of 78%.

Three studies have focused on determining whether errors are differentiable from deceptive responses during a task. To address this topic, two studies were conducted (Abe et al., 2008; Bhatt et al., 2009; Lee et al., 2009). Abe et al. (2008) proposed an experiment to identify brain activity consequent to memory, false memory, and deception. They used word lists that consisted of semantic associations that produce memory errors with an increased probability. The results demonstrated that prefrontal activity was specifically associated with the generation of deceptive responses, whereas the difference between true recognition and false recognition was identified in the left temporo-parietal regions likely engaged in the encoding of auditory presented words.

Lee et al. (2009) used a Word List Learning Recognition paradigm to determine whether brain activity associated with intentional faked responses is different compared with the activity associated with errors committed unintentionally. The findings of this event-related fMRI study clearly indicated that the brain activity associated with intentional faked responses was different compared with the activity associated with errors committed unintentionally. For intentional faked responses, significant activation was identified in the VLPFC, posterior cingulate region, and precuneus. No significant activation was identified for unintentional errors.

Bhatt et al. (2009) investigated the neural correlates of intentionally misidentifying individuals (deception) versus truth telling using a Facial Identification task. For the truth condition, the participants were required to select previously viewed faces in a line up, whereas for the deception condition, they were required to select different figures instead of the figure they had stored. fMRI deception scans indicated a strong activation in the right middle frontal gyrus, red nucleus, inferior frontal gyrus, supramarginal gyrus, SFG, ACC, DLPFC, and bilateral precuneus. These findings provide information regarding facial misleading, which was mediated by prefrontal and parietal networks.

Interestingly, research has applied functional connectivity analysis to investigate the deception network, an investigation that reflects statistical dependencies between distinct and distant regions of information processing of neuronal populations. To examine the brain network of deception, researchers used a Picture Choice task that comprised three conditions: a 'true' condition (the participants were required to provide an honest response), an 'inverse' condition (the participants were required to provide an opposite response), and a 'lie' condition (the participants were required to devise a strategy to deceive other individuals, with the goal of skillfully lying and avoiding detection). In this study, whole-brain functional connectivity networks from correlations among brain regions were used for the lie-telling and truth-telling conditions for each subject (Jiang et al., 2015). The results indicated that lie-telling could be differentiated from truth-telling with an accuracy of 82.81% (85.94% for lie-telling and 79.69% for truth-telling). The connectivity of the fronto-parietal networks, cerebellum, and cingulo-opercular networks is most discriminating, which thereby implies that these three networks are crucial in the processing of deception (Figure 1).

Finally, to assess the possibility that fMRI may be subject to countermeasures employed to confuse deception detection procedures, Ganis et al. (2011) conducted an fMRI study using a modified Concealed Information Test, in which the participants were trained to use a covert countermeasure while lying about knowing their birth date. The results indicated robust differences between deceptive and honest responses without countermeasures, but not with countermeasures. Furthermore, in individual participants, the deception detection accuracy decreased from 100% without countermeasures to 33% with countermeasures.

Collectively, the current findings have demonstrated that the PFC plays a pivotal role in human honest behavior. These studies have successfully demonstrated that fMRI is a technique able to discriminate brain-activity patterns of deception and differentiate the neural activations involved in making unintentional errors from intentionally faking
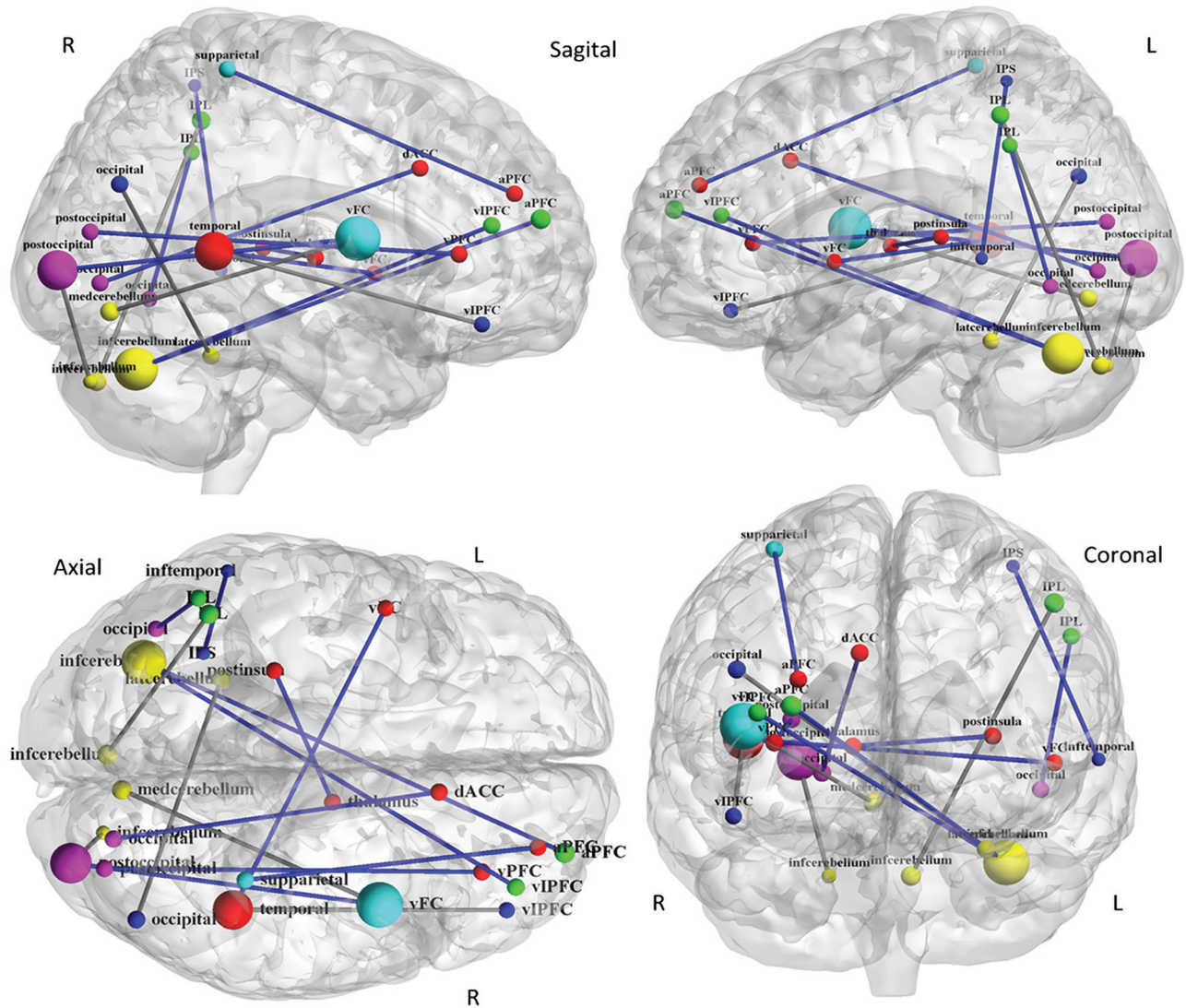
Figure 1: Deception-modulated functional connectivity.
Regions are color-coded by category. Red represents the cingulo-opercular network, green represents the fronto-parietal network, dark blue represents the default network, light blue represents the sensorimotor network, purple represents the occipital network, and yellow represents the cerebellum. Functional connectivities are also color-coded, with blue lines representing stronger connections and gray lines representing weaker connections. [Adapted from Jiang et al. (2015) with permission from BioMed Central Society].

responses; however, critical aspects emerge with respect to its utilization in forensic settings and the possibility of adopting countermeasures to confuse the detection of deception and the low reliability in individual subjects.

Detection of deception in real settings

Previous fMRI studies on deception have implemented tasks less comparable to the daily situations in which individuals lie. To overcome this limitation, researchers have attempted to adapt the experimental settings to improve their similarity to real conditions. For example, Phan et al. (2005) used a novel real-time fMRI technology to simulate a polygraph experience to evoke performance anxiety regarding the generation of lies and aimed to ascertain the neural correlates of deception. They used an adaptation form of the GKT previously described by Langleben et al. (2002). Subjects reported performance anxiety during the task. The results confirm a specific activation of the VLPFC, DLPFC, dorsal medial prefrontal cortex, and superior temporal sulcus.

To understand the brain mechanisms related to deception and compare the results with a standard polygraph situation, Mohamed et al. (2006) used a mock shooting scenario to elicit a similar reaction in committing a crime in which participants were required to deny involvement in a shooting. Subjects were divided into two groups: one group was instructed to tell the truth, whereas the other group was instructed to deliberately lie about having shot in the hospital. The results indicated that deceptive responses activated specific areas of the frontal lobe (left medial and left inferior frontal lobes), temporal lobe (right hippocampus and right middle temporal gyrus), occipital lobe (left lingual gyrus), ACC, right fusiform gyrus, and right sublobar insula. The polygraph examination indicated 92% accuracy in deceptive subjects.

Furthermore, in a study by Kozel et al. (2009), a mock sabotage scenario was implemented. In the experimental setting, the Mock-crime group damaged and stole compact discs, which contained incriminating video footage, whereas the No-crime group did not perform a task. Both groups were instructed to report that they picked up an envelope; however, they did not sabotage video evidence. The participants were subsequently scanned while being asked questions regarding the mock crime. Moreover, the participants performed Ring-Watch testing, which comprised a simple laboratory-based fMRI deception test that consisted of 'stealing' a watch or ring. The participants were instructed to report that they did not steal the objects. The results indicated that deception was correctly identified during the Ring-Watch testing in 25 of 36 participants (Validated Group). In this Validated Group for whom a determination was made, computer-based scoring correctly identified nine of nine Mock-Crime participants (100% sensitivity) and five of 15 No-crime participants (33% specificity). The use of blood oxygen level-dependent fMRI to detect deception regarding previous events exhibited high sensitivity and low specificity.

To investigate the brain maintenance of deliberate deception, Kireev et al. (2015) implemented positron emission tomography (PET) and event-related fMRI. They used an experimental paradigm that presupposed free choices between equally beneficial deceptive or honest actions. The experimental task simulated the 'Cheat' card game, which aims to defeat an opponent via sequential deceptive and honest claims. They obtained two types of results. The first result is connected to the action of lying or being honest and activated a fronto-parietal brain network formed by the inferior and middle frontal gyri, precentral gyrus, caudate nucleus, and inferior parietal lobule; the second result, which included a comparison between decision making of gains and losses, indicated an activation of areas specifically associated with deception execution: the precentral gyrus, caudate nuclei, thalamus, and inferior parietal lobule.

In these studies, the researchers have attempted to create experimental settings that are more similar to real life; however, the results do not exhibit important differences compared with previous studies.

Other correlates of deception

To provide a better marker of deception that differs from executive functions, Lee et al. (2013) focused on perceptual functions. During a Face Recognition task, participants were instructed to lie about the familiarity of a set of photos: the faces of individuals who were personally familiar to the participants and the faces of unfamiliar persons. The authors identified activity in the left precuneus during the perception of familiar faces accurately marked in 11 of 13 subjects who lied about not knowing faces that were familiar to them. These findings provide preliminary evidence that neural activity associated with perception but not executive processes may provide an alternative marker of deception with regard to face familiarity.

Other authors have measured the impact of the affective valence of lying. Ito et al. (2011) investigated the neural correlates of deception when remembering neutral versus emotional events. The experimental procedure was created in two steps: prior to fMRI, subjects were presented with a series of neutral and emotional pictures and were asked to rate each picture for arousal; then, during fMRI, subjects were presented with the studied and non-studied pictures and were asked to make an honest recognition judgment in response to half of the pictures and a dishonest response in response to the remaining half. The results indicated that deception related to the memory of neutral pictures was associated with increased activity in the bilateral DLPFC, left VLPFC, and left orbitofrontal cortex. They also demonstrated that deception when remembering emotional pictures was associated with increased activity in the bilateral DLPFC.

Studies have also analyzed specific phases of the deception process. For example, to identify the neural basis of the preparatory processes that create deception, Ito et al. (2012) instructed participants to memorize and judge a series of photographs and determine whether they were living or non-living prior to scan initiation. During the fMRI, they were instructed to provide an honest recognition memory response or a deceptive response, whereas

in the other condition, no information about honest and dishonest behavior was provided. These findings provide evidence that the DLPFC was activated not only during deception but also during the preparation of both deception and truth telling.

Other studies have focused on the important role of deception as an inhibition process. These studies used a match-mismatch detection task in which it was expected that in each trial, a string of identical digits would be presented (e.g. 666666); in the match condition, the number of digits was equal to the number represented in the opposite mismatch. In every trial, the participants were instructed to lie or tell the truth. The results suggest an activation of the same fronto-parietal network of working memory, specifically the right rostrolateral PFC and ACC.

Finally, to investigate other deceptive behaviors, Farrow et al. (2015) focused on self-deception and impression-management. Participants were required to complete the Balanced Inventory of Desirable Responding Questionnaire under two conditions: 'fake good' to provide the best possible self-impression and 'fake bad' to be undesirable. The results suggested that self-deception, impression management, and faking bad activated the medial prefrontal cortex, and VLPFC. In addition, impression management was associated with an activation of the left PFC and left posterior middle temporal gyrus. Faking bad is connected with activity in the right VLPFC, left temporal-parietal junction (TPJ), and right cerebellum.

Collectively, these studies confirm the primary role of the PFC in all stages of lie production. Moreover, it appears to be active prior to producing a lie as a general preparatory process, regardless of whether an individual is telling a lie or the truth. Other potential markers of deception include the left precuneus, left TPJ, and right cerebellum.

Deception studies in clinical populations

To provide empirical data on individuals diagnosed as 'pathological liars', a controversial condition in which liar behavior is compulsively produced without an apparent benefit to the subject (Mameli, et al., 2016), Yang et al. (2005) assessed the volume of the prefrontal grey and white matter with structural brain imaging in participants who lie, cheat, or deceive. In this study, they assessed subjects with a history of pathological lying, subjects with antisocial personality disorder (without pathological lying), and a group of normal controls. Compared with both the antisocial and control groups, the

pathological liars exhibited an increased volume of white matter in the PFC and a decrease in the grey/white ratio in the liar group (Yang et al., 2005). The liar group exhibited a 22.2% increase in the prefrontal white matter and a 41.7% decrease in the grey/white ratio compared with the normal controls; compared with the antisocial controls, they exhibited a 25.7% white matter increase and a 35.7% decrease in the prefrontal grey/white ratio.

In a subsequent study using the same approach, Yang et al. (2007) further demonstrated that the increased prefrontal white matter in pathological liars occurred in the inferior frontal cortex, orbitofrontal cortex, and middle frontal cortex. It is unclear whether the findings reflect cause or effect; however, these studies implicate the prefrontal areas as a neurobiological correlate necessary for deception.

Behavioral studies have consistently demonstrated that individuals with autism have difficulty making use of deception; intriguingly, brain neurodevelopmental studies of autism indicate a converse pattern of grey/white ratios compared with the liar group. When 2- to 3-year old children with autism reach 9.5–11 years of age, their white matter increases only 13% compared with 45% in normal children (Sodian and Frith, 1992; Carper and Courchesne, 2000). These anatomical differences were confirmed in an experimental study in which children with autism were less able to cover up their initial lie compared with typically developing children (Baron-Cohen, 1992; Li et al., 2011).

Only two studies have investigated the ability to tell a lie in patients with movement disorders who have impairments in cognitive functions, such as executive dysfunction (Abe et al., 2009; Mameli et al., 2013). It is interesting that patients with Parkinson's disease (PD) have been described as 'honest' because they have a tendency to not deceive (Menza, 2000; Ishihara and Brayne, 2006).

In the first study by Abe et al. (2009), deception was investigated in PD patients who exhibited an increased difficulty in making deceptive responses in an experimental lie compared with healthy controls. Furthermore, resting-state 18F-fluorodeoxyglucose PET indicated that lie difficulty was significantly correlated with decreased metabolic rates in the left dorsolateral and right anterior prefrontal cortices, which confirms the critical contribution of these prefrontal regions to deception.

Mameli et al. (2013) confirmed these results in PD and Essential Tremor patients. Truthful and deceptive responses were assessed using a computer-controlled procedure, a simplified version of the GKT. Their findings indicated that patients with Essential Tremor and PD are less accurate in producing deception compared with healthy subjects (Mameli et al., 2013).

These studies conducted on individuals with neurological diseases represent an additional confirmation of the crucial role of the frontal cortex in deception. To date, there is a lack of studies regarding patients with frontal cortex lesions.

The current findings suggest that although brain imaging comprises a more direct index of cognition compared with a traditional polygraph, it is subject to many of the same caveats; thus, neuroimaging does not appear to indicate processes that are necessarily unique to deception.

Despite the different experimental protocols implemented in previous studies, the area that was invariably associated with deception is the frontal executive system. The always activated areas include the DLPFC, VLPFC, ventromedial prefrontal cortex (VMPFC), anterior PFC, and ACC. Additional posterior areas, such as the temporal-parietal cortex and cerebellum, were active in several studies (Langleben et al., 2002; Phan et al., 2005; Mohamed et al., 2006; Farrow et al., 2015; Kireev et al., 2015). These activations were confirmed in an analysis of connectivity that demonstrated an involvement of the fronto-parietal networks, cerebellum, and cingulo-opercular networks (Jiang et al., 2015). Collectively, these neuroimaging studies have indicated differences in brain activation between deceptive and honest responses; however, despite these similarities, the specific methodology utilized to generate a deceptive response varied across experiments and involved differences in the context, motivation, spontaneity of behavior, and response modalities. Therefore, considering that neuroimaging techniques are operator dependent and may be vulnerable to countermeasures, caution is required before applying these methods to real-world situations.

Non-invasive brain stimulation interferes with the cognitive mechanism that underlies deception

Non-invasive neurostimulation techniques, including transcranial magnetic stimulation (TMS) and transcranial direct current stimulation (tDCS), have been used to assess the validity of brain imaging findings and attempt to establish a direct correlation between activity in a cortical region and deceptive behavior by transiently inhibiting cortical excitability (Luber et al., 2009).

In this section, we discuss findings regarding the use of non-invasive neurostimulation in deception research.

Studies with TMS

TMS with targeted magnetic fields that temporarily disrupt neural processing in a focal area may alter brain activity in a specific cortical region (Luber et al., 2009). Through the measurement of small but functionally important changes in behavior, this technique enables researchers to investigate functioning in a specific brain area in relation to an existing behavior. Repetitive TMS (rTMS) alters cortical excitability by increasing or decreasing it, depending on the stimulation variables. Stimulation at approximately 1 Hz typically induces inhibition, whereas stimulation at higher intensities elicits excitation (Hallett, 2000).

In the first study that investigated TMS effects in deception (Lo et al., 2003), stimulation was applied to the left and right motor cortices (at 110% of the resting motor threshold), and motor-evoked potentials (MEPs) were recorded before and immediately after questions that elicited a false response (Lo et al., 2003). The subjects were instructed to provide 'Yes' or 'No' answers to questions that involved simple lies or truths or complex lies or truths. The results suggested that the generation of a false response was associated with increased excitability in the corticospinal tract, which may reflect increased motor readiness or a general arousal effect. This finding demonstrated that TMS may be used to detect differences in cortical excitability between deceptive and truthful responses; however, the study did not examine the neural substrate for deceptive processing by investigating whether TMS could alter deceptive responding.

Testing the hypothesis that withholding the truth critically depends on the inferior frontal region, Verschuere et al. (2012) experimentally manipulated the neural activity level in the right inferior frontal sulcus (IFS) in response to neuronavigated continuous theta-burst stimulation (cTBS). Participants underwent three separate sessions. In the first session, the investigators obtained MRI anatomical brain measurements from all participants. In the second session, they provided participants with information regarding the experiment and stimulation procedure, administered an autobiographical questionnaire, and initially tested deception. They subsequently applied a cTBS protocol or sham TBS using a placebo rTMS coil. Immediately after rTMS/sham stimulation, they tested deception again. The cTBS-induced right IFS disruption left response rates and error rates unchanged from the

sham stimulation. These findings do not support a critical role of the IFS in deception.

To determine whether competing responses in the primary motor cortex may be used to detect deception, Hadar et al. (2012) administered a Lie task in which participants were instructed to respond truthfully or deceitfully regarding facial familiarity (with their little finger or thumb). When preparing to lie, the MEPs of the non-responding digit (i.e. the plan corresponding to the truth) exceeds the MEP of the responding digit (i.e. the lie), whereas a mirror-reversed pattern occurs when telling the truth. This giveaway response conflict interacts with the time of stimulation during a speeded reaction period. The authors suggest that lies may activate digit-specific cortical representations when only verbal responses are made. This finding suggests a potential novel index for discriminating between honest and intentionally false facial recognition.

Finally, to determine whether asymmetric functions in the PFC influence the propensity to lie, Karton and colleagues conducted three experiments (Karton and Bachmann, 2011; Karton et al., 2014a,b). In the first study (Karton and Bachmann, 2011), they applied rTMS to the left and right DLPFC in conjunction with a Spontaneous Lie task. Immediately after stimulation, they conducted a Lie task in which the participants could freely choose whether to lie or tell the truth. They applied stimulation to the left and right DLPFC and left and right parietal cortex as a control area. The Lie task consisted of naming the color of discs that appeared in a quasi-random order on a computer screen. The subjects were instructed to name the color correctly or lie about it, naming the other color that was not presented in this trial, while being free to choose whether to lie. When the subjects could name the color of the presented objects correctly or incorrectly at their free will, the stimulation succeeded in manipulating the tendency to stick to truthful answers. Their results demonstrated that right-hemisphere DLPFC disruption decreased lying compared with the control condition, whereas left-hemisphere DLPFC disruption increased the propensity to lie. In the second experiment, they investigated whether the application of an opposite rTMS effect (facilitating the DLPFC) could reverse the propensity to be more truthful to the propensity to produce relatively more deceptive responses during right-DLPFC stimulation and vice versa (Karton et al., 2014a). When 10-Hz pulses were delivered in trains to the right DLPFC, the propensity to lie increased, whereas similar left-hemisphere DLPFC stimulation left untruthful response rates unchanged. The authors concluded that how the right DLPFC and other areas functionally associated with it are involved

in the production of truthful or deliberately deceptive statements about perceived objects critically depends on the stimulation variables used to manipulate the system. Finally, in the last experiment, Karton et al. (2014b) examined the role of rTMS applied to the DLPFC in conditions in which they motivated subjects better to lie than they did in their earlier studies and in all possible conditions (left and right DLPFC inhibition with 1-Hz and sham rTMS; left and right DLPFC excitation with 10-Hz and sham rTMS). Before each block, in the experiment testing inhibitory stimulation, the subjects received 1-Hz rTMS train or sham stimulation to the left or the right DLPFC followed by the experimental task requiring them to name circles. In the experiment testing excitatory stimulation (lasting 2 days), subjects received 24 one-second trains at 10-Hz or sham stimulation to the left or right DLPFC, followed by a 10-s long 'window' without rTMS. During this 'window' subjects did an experimental task requiring them to name five circles per 'window'. The results showed that rTMS exciting the left DLPFC decreased lying more than rTMS exciting the right DLPFC, but inhibition had no different effects. These findings suggest that non-invasive excitatory stimulation targeted at the DLPFC can modulate the propensity to lie and the direction the excitatory effect on lying tasks depends on the cortical target locus.

Collectively, these findings support that the use of the TMS on primary motor cortex can help to detect differences in cortical excitability between deceptive and truthful responses (Lo et al., 2003; Hadar et al., 2012), while the application of rTMS to the DLPFC produces different effects in propensity to lie depending on the hemisphere stimulated and the stimulation variables (Karton and Bachmann, 2011; Karton et al., 2014a,b). Although the right hemisphere stimulation seems to have more influence on the production of deception, it is not clear to what extent contribute the two hemispheres. The cTBS on the right IFS does not seem to interfere with deception (Verschuere et al., 2012).

Studies with tDCS

tDCS is a non-invasive technique that is able to manipulate brain neuroplasticity and modulate cortical function by delivering weak direct currents. It induces long-term potentiation-like synaptic changes that facilitate cortical excitability, neuroplasticity, and learning. Anodal tDCS increases whereas cathodal tDCS decreases excitability in stimulated areas (Priori, 2003). As previous research predicted, tDCS may effectively balance cognitive functions,

such as memory, attention, learning, and language, with motor functions in healthy and clinical populations (Utz et al., 2010; Floel, 2014).

The first systematic study that investigated tDCS-modulated lying indicated that tDCS (1.5 mA for 10 min) applied on the bilateral DLPFC (F3/F4 according to the 10–20 EEG system) interferes with deceptive responses (Priori et al., 2008). Truthful and deceptive abilities were assessed with a GKT using a computer-controlled exercise. Accuracy and reaction times (RTs) were determined when a participant produces a false response ('denial lies' but not for 'false fact generation') or truthful response. All participants were instructed to perform tasks before and immediately after anodal and cathodal tDCS and sham sessions (offline procedure). They determined that anodal tDCS over the bilateral DLPFC significantly increased RTs when the participants denied for 'denial lies' but not for 'false fact generation' or 'truth' responses. These findings indicated that non-invasive brain stimulation may modulate deceptive processing, thereby slowing the responses of participants when they attempted to lie.

To assess tDCS effects directly during deception test administration, Karim et al. (2010) modulated excitability in the anterior PFC. Participants received cathodal, anodal, or sham tDCS (1 mA for 13 min) during a role-play interrogation (online procedure) using a modified version of the GKT. The results demonstrated that cathodal tDCS facilitated deceptive behavior, as measured by faster RTs, a decreased sympathetic skin conductance response, decreased feelings of guilt, and an increased behavioral pattern during skilful lying. The authors suggested that cathodal tDCS, a polarity demonstrated to suppress cortical excitability, relieved the moral conflict brought about by the act of deception, as represented in the anterior PFC, which thus facilitated deception.

To evaluate the tDCS effect in different types of deception, Mameli et al. (2010) investigated whether bilateral DLPFC stimulation specifically influences cognitive processing for general knowledge deception or influences the construct of personal information deception. They administered a modified GKT during a tDCS session (online procedure) and determined that following anodal tDCS (2 mA for 15 min), the RTs significantly decreased; however, this decrease only occurred for lies that involved general knowledge (Figure 2). These findings indicate that tDCS specifically modulates deceptive responses for general information deception, whereas responses related to personal information remain unchanged (Mameli et al., 2010).

To investigate the tDCS effect on untruthful responses in various contexts and response modalities (verbal and motor responses), Fecteau et al. (2013) applied tDCS over the DLPFC with three different electrode positions: right anodal/left cathodal, right cathodal/left anodal, and sham stimulation (2 mA for 20 min). Participants completed tasks before and immediately after the tDCS session (offline procedure). The results demonstrated that active tDCS over the DLPFC reduces the response latency for untruthful compared with truthful conditions across various contexts and response modalities. Furthermore, the hemispheric laterality differed according to the deception context. Right anodal/left cathodal DLPFC stimulation produced an improvement for untruthful answers of relatively guilt-free personal questions on daily activities through motor responses and the generation of memorized untruthful answers regarding the subjects' past through verbal responses. The opposite electrode arrangement (left anodal/right cathodal) also improves deceptive skills; however, this improvement only occurred for the generation of spontaneous and memorized untruthful answers about subjects' past experiences.
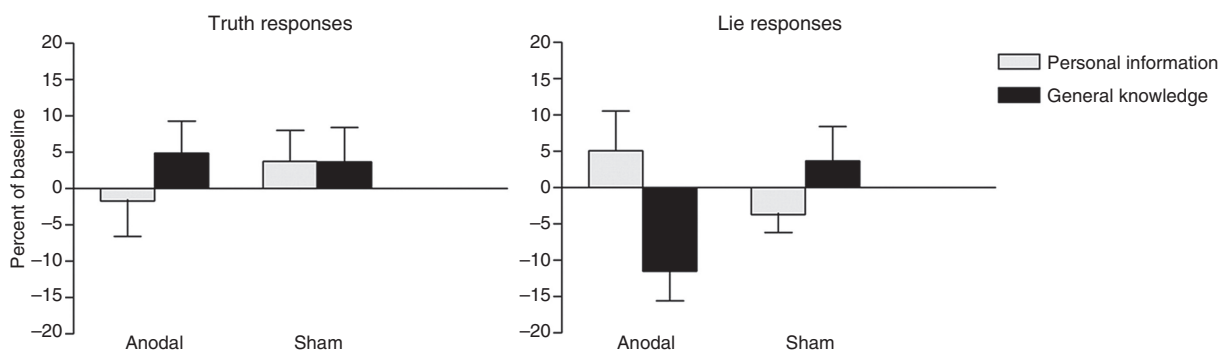

Figure 2: Reaction times (RT) for truthful (left) and lying (right) responses in the Guilty Knowledge Task (GKT).
The histograms are mean RTs for the tasks after tDCS expressed as percent of baseline (y axis) for anodal and sham tDCS (x axis). Error bars are SEM. *p < 0.05. [Adapted from Mameli et al. (2010) with permission from Elsevier Society].

Finally, to investigate tDCS effects on the TPJ, a crucial area for the ability to selectively represent the self or another individual, Sowden et al. (2015) determined whether inconsistency between an individual's own opinion and the stated opinion of another individual impairs the judgment of the veracity of the statement. tDCS was applied over the TPJ or a mid-occipital (MO) control region (1 mA for 10 min) prior to completion of a Video-Mediated Lie-Detection task. After watching each video, the participants were instructed to rate whether the opinion was truth or untruth. The results demonstrated that the participants who underwent TPJ stimulation were significantly more accurate when the individuals' expressed opinion was inconsistent with their own opinion compared with the individuals administered the MO control stimulation. In contrast, there was no significant difference in the lie-detection performance between the stimulation groups during trials in which the individuals (in the video) and the participants' opinions were consistent.

Collectively, these preliminary results regarding tDCS effects on deception clearly confirm, as in previous studies, the contribution of the PFC (Karim et al., 2010; Fecteau et al., 2013). Only one study investigated the effect of tDCS in a non-frontal area (Sowden et al., 2015). Interestingly, the improvement in the lie detection accuracy following TPJ stimulation may represent a confirmation of the frontal parietal network described in a connectivity study by Jiang et al. (2015).

The experimental conditions across these studies differ in several ways, including the parameter of stimulation (tDCS or TMS), stimulation location, and type of deception; moreover, additional studies are necessary to explain the results. Nevertheless, these findings clearly indicate that non-invasive neurostimulation interferes with the cognitive functions that underlie deception.

An overall view

Findings from neuroimaging and neurostimulation studies indicate that the liar brain is unquestionably located in the frontal executive system.

Neuroimaging studies have consistently demonstrated the crucial roles of the DLPFC, VLPFC, VMPFC, and ACC in deception; however, they also demonstrated the involvement of multiple brain areas, including the cerebellum and the temporal and parietal cortices (Langleben et al., 2005; Phan et al., 2005; Mohamed et al., 2006; Farrow et al., 2015; Kireev et al., 2015). It is not clear whether these regions are necessary to lie; however, the activation of the anterior-posterior network is confirmed by the analysis of connectivity that indicated a pattern of activation in the fronto-parietal networks, cerebellum, and cingulo-opercular networks (Jiang, et al., 2015). Further confirmations from structural neuroimaging studies have demonstrated that pathological liars have an increased volume of white matter in the PFC (Yang et al., 2005, 2007).

Neurodevelopmental studies have consistently demonstrated that individuals with autism, who have difficulty making use of deception, exhibited a converse pattern of grey/white ratios in the frontal lobe compared with pathological liars (Baron-Cohen, 1992; Li et al., 2011). Moreover, studies in clinical populations confirm that patients who have impairments in the frontal circuit, such as PD and Essential Tremor, exhibited difficulties in making deceptive responses in cognitive Lie tasks compared with normal controls (Abe et al., 2009; Mameli et al., 2013).

Brain stimulation studies provide the possibility to investigate causal effects in brain areas that mediate deceit or truth telling. TMS findings have indicated that the right hemisphere may have a crucial role compared with the left hemisphere (Karton and Bachmann, 2011; Karton et al., 2014a,b), although, surprisingly the IFS does not appear to have a critical role in deception as demonstrated by neuroimaging studies (Verschuere et al., 2012). Furthermore, tDCS studies clearly confirm the contribution of the PFC (Priori et al., 2008; Karim et al., 2010; Mameli et al., 2010; Fecteau et al., 2013), as well as the involvement of the posterior areas (Sowden et al., 2015). As shown in tDCS studies, stimulation of the frontal lobe and the TPJ interfered with deceptive processes, thereby slowing or accelerating the responses of participants when they attempted to lie (Priori et al., 2008; Karim et al., 2010; Mameli et al., 2010; Fecteau et al., 2013; Sowden et al., 2015).

With respect to the potential use of these results in the legal field, it is interesting to note that when deception is relative to personal information (autobiographical), the medial structures of the frontal lobe are strongly active (Nunez et al., 2005) compared with lies regarding general information (semantic memory). These data were also confirmed by a tDCS study (Mameli et al., 2010), which indicated that DLPFC tDCS was not able to interfere with lies related to personal information, only lies regarding general information (semantic memory).

Despite the many insights obtained from neuroscience to date, caution is required when incorporating this science into law. We believe that the current lie-detection technologies are not sufficient to accurately detect deception on an individual level, and several issues must be considered prior to admitting these neuroscientific tools into the courtroom. The principal areas that require

further attention include the limited data at the individual level and the sensitivity of novel technologies to countermeasures; moreover, a limited number of studies have calculated the accuracy in lie detection, and the results are not encouraging (Langleben et al., 2005; Ganis et al., 2011). fMRI studies have demonstrated that these values are in the range of approximately 80%–100%, whereas the accuracy decreases to 33% when monitoring the countermeasures (Ganis et al., 2011).

Neurostimulation approaches provide the possibility of detecting deception by altering an individual's ability to interfere with cognitive functions involved in deceit; however, the research in this field is at an early stage and must be validated. Additional major research efforts should aim to identify the optimal stimulation parameters (site, electrode montage and size, duration, intensity, and online vs. offline).

In future studies, approaches that emphasize converging evidence from multiple methods (neuroimaging and neurostimulation techniques) must be developed with the objective to identify a valid neuroscientific method for the detection of deception.

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