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REVIEW

Brain fingerprinting: a comprehensive tutorial review of detection of concealed information with event-related brain potentials

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Abstract Brain fingerprinting (BF) detects concealed information stored in the brain by measuring brainwaves. A specific EEG event-related potential, a P300-MERMER, is elicited by stimuli that are significant in the present context. BF detects P300-MERMER responses to words / pictures relevant to a crime scene, terrorist training, bomb-making knowledge, etc. BF detects information by measuring cognitive information processing. BF does not detect lies, stress, or emotion. BF computes a determination of "information present" or "information absent" and a statistical confidence for each individual determination. Laboratory and field tests at the FBI, CIA, US Navy and elsewhere have resulted in 0% errors: no false positives and no false negatives. 100% of determinations made were correct. 3% of results have been "indeterminate." BF has been applied in criminal cases and ruled admissible in court. Scientific standards for BF tests are discussed. Meeting the BF scientific standards is necessary for accuracy and validity. Alternative techniques that failed to meet the BF scientific standards produced low accuracy and susceptibility to countermeasures. BF is highly resistant to countermeasures. No one has beaten a BF test with countermeasures, despite a $100,000 reward for doing so. Principles of applying BF in the laboratory and the field are discussed.

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Introduction and background

The state of the art prior to brain fingerprinting

Brain fingerprinting is an objective, scientific method to detect concealed information stored in the brain by measuring electroencephalographic (EEG) brain responses, or brainwaves, non-invasively by sensors placed on the scalp. The technique involves presenting words, phrases, or pictures containing salient details about a crime or investigated situation on a computer screen, in a series with other, irrelevant stimuli. Brain responses to the stimuli are measured. When the brain processes information in specific ways, characteristic brainwave patterns can be detected through computer analysis of the brain responses. When an individual recognizes something as significant in the current context, he experiences an "Aha!" response. This response is characterized by a specific brainwave pattern known as a P300-MERMER. Brainwave responses are analyzed to determine whether or not the specific information tested is stored in the brain of the subject or not. Brain fingerprinting computes a determination of "information present" – the subject knows the critical information, or "information absent" – he does not. The system also computes a statistical confidence for each individual determination, e.g., "information present, 99.9% confidence" indicates that there is a 99.9% probability that the subject knows the relevant information tested. If the statistics computed do not provide a statistical confidence high enough to meet a predetermined

criterion for either a determination of "information present" or "information absent," then no determination is made: the outcome is "indeterminate."

This tutorial review discusses the science of brain fingerprinting in light of the current state of the art in forensic science, the scientific principles on which the technique is based, published scientific data, successful field applications, applications in the judicial system and legal admissibility in court, scientific methods and standards for brain fingerprinting tests, correcting misconceptions and avoiding errors in applying the science, and the role of brain fingerprinting in criminal investigations and security.

Prior to the invention of brain fingerprinting, the state of the art in forensic science, investigations, and criminal justice was as follows. The goal is to reconstruct the crime and accurately identify the perpetrator. This is accomplished by connecting features of the crime scene with features associated with the perpetrator. The crime involves participants and a crime scene. The participants include one or more perpetrators, and may include one or more victims and/or witnesses.

The crime scene has two types of features that may be of use: permanent features and changes wrought by the crime. Permanent features pre-exist the crime and persist after the crime. These include buildings, streets, the lay of the land, etc. Changes that took place at the time of the crime include such things as the positioning of the body in the case of a murder, fingerprints, blood at the crime scene, etc..

The participants in the crime also have permanent and changed features. Permanent features of the participants include, for example, DNA and fingerprints. Changed features of the perpetrator may include, for example, wounds sustained in the course of the crime. Changes to the victim wrought by the crime can be considered along with the crime scene.

The fundamental task of investigations is to establish accurate and reliable connections between features of the crime scene and victim on the one hand and features of the perpetrator and witnesses on the other. The perpetrator may leave traces of a permanent feature of the perpetrator, such as DNA or fingerprints, at the crime scene. The perpetrator may take with him from the crime scene traces of a permanent feature of the crime scene, such as an unusual kind of soil on his shoes. The perpetrator may take with him from the crime scene traces of changed features of the crime scene, such as the blood of the victim.

In some cases, investigators may establish a connection directly between a feature of the crime scene and a permanent feature of the perpetrator himself. This can be the case with DNA and fingerprints. In other cases, investigators may establish a connection between the crime scene and something associated with the perpetrator. For example, the perpetrator may leave behind fiber samples at the crime scene that can be matched to clothing he owns.

The crime scene generally has many features that can be established with certainty. Every suspect also has many features that can be established with certainty. When and to the extent that specific features common to both are available, forensic science can establish objective, definitive connections between the crime and the perpetrator. Generally, however, in the past there have been only very few specific features of the crime scene that can be definitively and uniquely matched to features of a particular suspect.

Generally the most major change that takes place in the perpetrator and witnesses is something that has not been directly detectable through forensic science techniques. The perpetrator and witnesses to a crime virtually always know that they have observed and/or participated in the crime. They virtually always know more than a few small details about what took place and who was involved. The record stored in the brains of the witness and perpetrator is often a much more comprehensive account of the crime than what can be pieced together from connecting a few specific features of the crime scene with a few specific features of the perpetrator.

The record stored in the brains of witnesses and perpetrators, however, has not been accessible to scientific scrutiny. The only way to access this record has been through interrogation and testimony. The record of the crime stored in the brain of witnesses and revealed through testimony has the advantage of often providing by far the most comprehensive account of the crime available. Except in rare cases where a crime is recorded on

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video, witness testimony often provides much more information than is available through any other means.

Witness testimony, however, has several disadvantages. Even when the witness is deemed to be truthful, witness testimony is not a complete and accurate account of the crime. Witness testimony is a subjective report of the contents of memory. It is well known that human memory is not a perfect record of events. Memory is known to be limited and imperfect in a number of ways. It is approximate, sometimes distorted, selective, and subject to numerous influences. Memory is known to be affected by mental or physical illness, injury, passage of time, drugs, and many other factors.

The two primary disadvantages of witness testimony are the following: 1) Human memory is imperfect; and 2) The witness may lie.

In weighing the advantages and disadvantages of witness testimony, which constitutes subjective reports of the contents of human memory, every judicial system throughout history has reached the same three conclusions:

1) The brain is a sufficiently accurate recorder of events that testimony constituting subjective reports of the contents of memory is universally admitted and considered as evidence.

2) The brain is a sufficiently imperfect recorder of events that witness testimony is never taken to be absolute fact. Any proceeding that includes witness testimony must weigh the testimony in light of the well known limitations of human memory.

3) Any proceeding that includes witness testimony must consider the veracity of the witness.

The same principles that apply to the subjective reports of witnesses of the contents of their memory also apply to suspects, with the added disadvantage that perpetrators have a greater motivation to lie. Even in the case of confessions, the same limitations that apply to witness testimony apply to testimony by a suspect.

In an attempt to eliminate one of the three major limitations of testimony, investigators have developed psychophysiological methods to attempt to detect deception (Farwell, 1995a; 2013). The fundamental premise of the various techniques for detection of deception is that lying produces emotional stress and other psychological effects, which in turn produce physiological arousal and other physiological changes. These can be measured through changes in perspiration, blood pressure, breathing, etc. The commonly used control question test (CQT) in conventional detection of deception employs direct, relevant questions regarding participation in the crime, such as "Did you shoot Mr. Jones?"

Lykken (1959; 1960) originated a new technique for discovering more of the details of the record of the crime stored in the brain. It is known as the guilty knowledge test (GKT) or concealed information test (CIT) (Iacono 2007; 2008; Iacono and Lykken 1997; Iacono and Patrick 2006; Verschuere, Ben-Shakhar, and Meijer 2011). Rather than asking direct, ultimate questions about participation or non-participation in the crime, the subject is asked about a series of alternative details of the crime, only one of which is correct. For example, the interrogator may ask, "Regarding the murder weapon, do you know it was a pistol? Do you know it was a shotgun? Do you know it was a knife?"

All subjects are expected to answer "No" in response to each question. A subject who does not know the details about the crime will be telling the truth in every case, and will not know which item is crime-relevant. A subject who participated in the crime will recognize the "guilty knowledge" or concealed information contained in the correct, relevant item, and is expected to lie in response to the relevant question. The theory is that the resulting psychophysiological responses will reveal this lie and the subject's possession of the associated concealed information. As such, the conventional concealed information test is an adjunct to interrogation and testimony. It is a method not of directly detecting evidence of a crime, but of determining the veracity of a subject who is testifying regarding the evidence.

Methods for detection of deception or credibility assessment have met with limited success. They have been used primarily to guide investigations rather than to definitively establish the relevant facts. They have not generally been admissible in court.

Overview of brain fingerprinting science and technology

In summary, the state of the art in investigations, forensic science, and criminal justice has been a combination of two modes of establishing a connection between the crime scene and the perpetrator:

1) Objective data collection and forensic science: establishing objective, scientific connections between a few specific features of the crime scene and a few specific features of the perpetrator.

2) Interrogation and testimony: obtaining a subjective account of the contents of memory, and attempting to determine whether or not the subject is lying.

What is generally the most comprehensive repository of information about the crime, the record stored in the brains of participants, has not been available to scientific scrutiny or objective investigation. There has been no objective, scientific way to detect the record stored in the brain and thereby to connect the perpetrator with the crime scene.

Brain fingerprinting addresses this fundamental lack. Brain fingerprinting was developed to provide an objective, scientific way to connect the established features of the crime scene with the record of the crime stored in the brain of the perpetrator (Farwell 1992a; 1994; 1995a; 1995b; 2010; Farwell and Donchin 1991). The major benefit of brain fingerprinting is that it brings the record stored in the brains of participants within the realm of scientific scrutiny and objective investigation (Farwell and Smith 2001; Iacono 2007; 2008; Iacono and Lykken 1997; Iacono and Patrick 2006).

Brain fingerprinting provides an objective method to detect features of the crime that are stored in the brain of the suspect. This is accomplished by measuring the subject's brain response to stimuli in the form of words or pictures presented briefly on a computer screen. During a brain fingerprinting test, electroencephalograph (EEG) signals are recorded non-invasively from the scalp. When a subject recognizes and takes note of something significant in the present context, the brain emits an "Aha!" response. This involves the firing of neurons in a specific, identifiable pattern known as a P300-MERMER that can be detected by computer analysis of the EEG signals. When a subject recognizes a specific feature of the crime scene, such as the murder weapon, the brain fingerprinting system detects the "Aha!" response and its corresponding EEG pattern (Farwell, 1992a; 1995a; Farwell and Donchin 1991; Farwell and Smith 2001). This reveals that the subject knows the relevant information. If the subject does not possess the relevant knowledge, the tell-tale brain response is absent.

In a brain fingerprinting test, words or pictures relevant to a crime, terrorist act, terrorist training, or other investigated situation are presented on a computer screen, in a series with other, irrelevant words or pictures. (For brevity, the investigated situation will generally be referred to herein as the "crime," although other situations can of course also be investigated.) A subject's brainwave responses to these stimuli are measured non-invasively using a headband equipped with EEG sensors. A computer program then analyzes the data to determine if the crime-relevant information is stored in the brain. The specific, measurable brain response known as the P300-MERMER is emitted by the brain of a subject who has the details of a crime stored in his brain, but not by a subject lacking this record in his brain.

The P300 response has been extensively researched and widely published in scientific journals for more than 30 years. It has gained broad acceptance in the scientific field of psychophysiology (Harrington v. State 2001; Johnson 1988). The discovery of the P300-MERMER has allowed the results of brain fingerprinting testing to be more accurate, and has produced a higher statistical confidence in the outcomes (Farwell 1994; 2008; 2010; Farwell and Richardson 2006a; 2006b; Farwell, Richardson, and Richardson, 2011; in press; Farwell and Smith 2001).

Brainwave (EEG) measurements and event-related brain potentials (ERPs)

The neurons in the brain fire electrically, forming a vast network of electrical potential conduits. Electroencephalography (EEG) involves the measurement of these patterns of electrical voltage changes that originate in the brain. These measurements are made non-invasively from the scalp. When the brain conducts certain tasks,

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specific patterns of EEG (or "brainwave") activity are produced. An example of such a specific task is noticing, recognizing, and processing the information contained in a significant stimulus such as a murder weapon presented on a screen in a brain fingerprinting test. These specific patterns of brainwave activity are known as event-related brain potentials, or ERPs. Brain fingerprinting technique uses event-related brain potentials to determine what information is stored in a person's brain. This is based on how the brain processes specific information such as the features of a crime that are presented on a computer screen.

At the same time the brain is engaging in the information processing of interest in a scientific experiment, the brain is also engaging in many other activities. The result is that the brainwaves measured at any time are a mixture of the relevant (event-related) activity and other brainwave activity. In order to isolate the activity of interest, the standard procedure in event-related potential research is to present a stimulus many times and average the responses (Donchin, Miller, and Farwell 1986; Donchin, Ritter, and McCallum 1978; Farwell and Donchin 1988a; Miller, Bashore, Farwell, and Donchin 1987; Picton 1988). All of the brainwave activity that is not specifically related to processing this specific stimulus averages out to zero, since its timing is unrelated to the event of the appearance of the stimulus on the screen and its processing by the subject. High-frequency noise is also removed using analog and digital filters (Farwell, Martinerie, Bashore, Rapp, and Goddard 1993). What is left in the average response is the event-related potential: the brainwave pattern that is specifically related to the event of interest.

Each stimulus presentation and associated response is referred to as a "trial." The larger the number of trials in each average brainwave response, the more extraneous brainwave activity is eliminated by the averaging procedure (Farwell and Donchin 1988a). In order to obtain valid and reliable results, a minimum number of trials is required. Experimenters usually run several tests, each containing about 100 trials. Each separate test is referred to as a "block." Successive blocks may use the same stimuli or different stimuli relevant to the same event.

The P300 is a very well known event-related potential that is utilized in brain fingerprinting testing. Several thousand studies have been published in the scientific literature on the P300 brain response. This response takes place when the brain recognizes and processes a stimulus that is significant in a particular context (Fabiani, Gratton, Karis, and Donchin 1987; Farwell and Donchin 1988a; 1991; Miller et al. 1987). For example, the murder weapon is significant in the context of a brain fingerprinting test about a specific murder.

The first event-related potentials discovered were related to sensory processing of stimuli. These responses are referred to "exogenous" event-related potentials or evoked potentials. They are driven purely by sensory processing. They have nothing to do with the meaning of the stimulus or with any cognitive activity the subject may undertake.

Initially, scientists recorded and analyzed only a very short epoch after the stimulus was presented, under the assumption that anything later than a few milliseconds did not have to do with the processing of the stimulus. In early evoked potential research scientists used evoked potentials occurring in the first 100 milliseconds after a stimulus. These were used primarily to study sensory processing.

In the 1960s, scientists began to look at "late" potentials in excess of 100 milliseconds after the stimulus. They discovered that there were patterns of neural activity reliably measurable from the scalp that manifested cognitive processing rather than sensory processing. This cognitive processing was independent of which sense delivered the information to be processed. In their seminal research on the P300, Sutton, Braren, Zubin, and John (1965) showed that the response depended not on the physical characteristics of the stimulus but rather on how that stimulus was processed cognitively. The same stimulus would result in different brain responses depending on its significance in the context of the experiment and on the mental information-processing task performed by the subject. Sutton et al. used auditory stimuli to elicit these responses. Subsequent research has often utilized visually presented stimuli.

Brain responses that manifest cognitive activity are referred to as "endogenous" event-related potentials (Donchin et al. 1978; 1986; Miller et al. 1987; Gaillard and Ritter 1983; Picton 1988). Before they could see these endogenous potentials, scientists had to begin looking in the time range beyond the

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first 100 milliseconds after the stimulus. The discovery of endogenous event-related potentials opened the door to a host of potential applications not only in discovering how the brain works but also in applying these discoveries to practical situations in the real world.

The P300 is an electrically positive potential that occurs at 300 - 800 milliseconds after the stimulus (Sutton et al. 1965; Donchin et al. 1978, Long et al. 2011). The name refers to the fact that the response is electrically positive (P) and has a latency of at least 300 milliseconds (300). The P300 occurs when a subject recognizes a stimulus as significant in the context in which it is presented. It may be called an "Aha" response. In the early P300 research, the responses were elicited by very simple stimuli such as clicks or tones. These were made significant in context by the experimental instructions. When the stimulus and the task are simple, the P300 peak occurs at about 300 milliseconds after the stimulus.

As research progressed in the 1970s through the early 1990s, scientists began to use more complex stimuli such as a word flashed on a computer screen (Fabiani et al. 1987; Johnson 1988; Farwell 1992a). This had the advantage of providing the subject with more meaningful information. This enhanced the ability of event-related potential research to reveal cognitive brain processes. When the stimulus becomes more rich and complex, it takes longer for the subject to discern what the stimulus is and evaluate its significance. Thus the response is delayed. As scientists used more meaningful, rich, and complex stimuli, the P300 latency (elapsed time from the stimulus onset to the brain response) increased. By the 1990s it was not uncommon to measure a P300 that peaked 600 or 700 milliseconds after the stimulus. The name P300 still remained in use, however, because it was the same response, just delayed by the increased complexity of the cognitive processing taking place.

The discovery of the P300-MERMER

In the initial brain fingerprinting research, Farwell and Donchin used the P300 event-related brain potential (Farwell and Donchin 1986; 1988b; 1991; Farwell 1992a). Later Farwell discovered that the P300 can be considered to be part of a larger response he called a memory and encoding related multifaceted electroencephalographic response or P300-MERMER.

The discovery of the P300-MERMER was one more step in the ongoing progression from very short latency evoked potentials to longer and longer latency event-related potentials as the stimuli and the processing demanded by the experimental task become more rich and complex. In the 1990s when Farwell and FBI scientist Drew Richardson were conducting the brain fingerprinting research on FBI agents, P300 latencies of 600 to 700 milliseconds were typically found in experiments where the stimuli were information rich and the cognitive processing required was substantial (Farwell and Richardson, 2006a; 2006b; Farwell, Richardson, and Richardson, 2011; in press). At that time, in such research a new stimulus was typically presented every 1000 to 1500 milliseconds (1 to 1.5 seconds). In the first brain fingerprinting study, for example, Farwell and Donchin (1991) presented a stimulus every 1500 milliseconds.

In dealing with real-life situations, Farwell and Richardson (2006b; Farwell, Richardson, and Richardson, 2011; in press) found it necessary to use longer and more complex stimuli to accurately communicate the necessary information to the subject. In order to present realistic stimuli that accurately represented knowledge unique to FBI agents, they found it necessary to use stimuli consisting of several words, sometimes several words of several syllables each. It took the subjects longer to read the words and evaluate their significance than in previous experiments with simpler stimuli. To give the subjects time to process the stimuli and respond appropriately, Farwell and Richardson lengthened the interval between stimuli from 1500 milliseconds to 3000 milliseconds. They recorded a longer segment of brainwave data in each trial. Recall that in the 1960s when scientists looked farther out in time after the stimulus, they found previously unseen responses such as the P300 (Sutton et al. 1965). The same thing happened to Farwell and Richardson. They were looking for the P300 response, and indeed the brain responses contained a clear P300 peak at about 500 to 800 milliseconds. Surprisingly, however, this positive peak was followed by a negative peak with a latency as long as 1200 milliseconds. This unexpected late negative potential consistently followed the positive P300 peak. It was reliably

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elicited by the same "Aha" response that elicited the P300.

This more complex P300-MERMER response included both the P300 and a late negative peak (the Late Negative Potential or LNP). Farwell (Farwell 1994; 2010; Farwell and Smith 2001) called this a memory and encoding related multifaceted electroencephalographic response (MERMER), or P300-MERMER. The P300 is maximal in the parietal area. The late negative potential (LNP) that constitutes the latter part of the P300-MERMER is parietally maximal yet also frontally prominent (Farwell 1994; 1995b; 2010).

Experimentation (including recording without analog filters), scalp distribution (the relative amplitude at different scalp sites), and morphology (the latency and shape of the waveforms) proved that the LNP was not an artifact of the signal-detection or noise-reduction procedures or equipment, such as digital and analog filters (Farwell 1994; 1995b; Farwell et al., in press). The recording equipment is identical for all scalp sites and all subjects. If the LNP were an artifact of the equipment, the identical equipment would produce the same effects in different instances. On the contrary, Farwell at al. found that the relative latency and amplitude of the P300 and the LNP are very different for different subjects and for different scalp sites in the same subject.

Like any new discovery, the P300-MERMER raises questions both of nomenclature and substance. The classical P300 is also known by various other names, including the P3, N2-P3 complex, P3a and P3b, late positive complex, and LPC. There has been considerable discussion as to whether the P300 is a unitary response or in fact a constellation of several responses (Johnson 1989; Spencer, Dien, and Donchin 2001;). There has also been discussion over whether the various names refer to the same or slightly different phenomena (Spencer et al. 2001).

No doubt there will be considerable discussion as to whether the MERMER or P300-MERMER is a unitary phenomenon inclusive of the P300 and the late negative potential (LNP), or whether the late negative potential is a separate component from the component or components that make up the P300. The answers to these questions are empirical, to be settled by further research.

Differences in nomenclature also exist. Over a thousand published studies have associated the name "P300" with a positive peak. Farwell first reported the P300-MERMER, including the positive peak of the P300 and the late negative potential (LNP), in 1994 (Farwell 1994). By 2001, not only Farwell and Smith (2001) but also almost all other researchers brainwave-based in detection of concealed information were using the full P300-MERMER in data analysis. Such research now almost always includes both the positive peak of the P300 and the late negative potential (LNP) of the P300-MERMER. For example, in the algorithms that use amplitude computations, the amplitude of the response is typically computed as the sum of the amplitudes of the positive and negative peaks (that is, the difference between the highest and lowest points). Some authors, (Soskins, Rosenfeld, and Niendam 2001; Rosenfeld, Soskins, Bosh, and Ryan 2004) however, have used the name "P300" to refer to the entire P300-MERMER response, including not only the traditional P300 peak but also the late negative potential (LNP) of the P300-MERMER. In view of the fact that over a thousand previous publications have used the term "P300" to refer only to the positive peak, such usage is confusing and ambiguous. Authors may avoid confusion by using the term "P300" to refer to the positive peak alone and "P300-MERMER" to refer to the complex consisting of the positive peak followed by the negative peak (LNP).

Farwell and colleagues (Farwell 1994; 1995b; 2010; Farwell and Smith 2001) reported additional facets in the P300-MERMER brainwave response that occur simultaneously with the positive and negative peaks. These are detected through different signal-processing algorithms than the signal-averaging algorithm typically used to detect event-related potentials (Farwell 1994; Rapp, Albano, Schmah, and Farwell 1993). These include an event-related, short-term shift in the frequency of the EEG signal. The nature of these additional facets and their relationship to the more readily visible positive and negative peaks is also an empirical question to be resolved by further research (see Gu¨ntekin and Başar 2010).

The discovery of the P300-MERMER has allowed the brain fingerprinting results to be more accurate than the results obtained with the P300 alone. The P300-MERMER consists of a positive peak

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followed by a negative peak. The P300 includes only the positive peak. Thus, the full P300-MERMER contains more information and more distinctive features, and can be more reliably and accurately detected by a mathematical signal-detection algorithm than the P300 alone.

In all brain fingerprinting research using either the P300-MERMER or the P300 alone, there have been no false negatives and no false positives. 100% of determinations made have been correct. (See, however, the discussion below regarding the term "100% accurate.") When Farwell and colleagues have included the full P300-MERMER in the data analysis algorithm, there have also been no indeterminates. In brain fingerprinting research using the P300 alone, results have been indeterminate in 3% of cases overall, consisting of 12.5% in one experiment. As discussed below, an indeterminate response is not an incorrect response, but rather the determination that insufficient data are available to make a determination in either direction with high statistical confidence.

Neurodynamics, physiological mechanism, and signal characteristics of the P300-MERMER

Many important phenomena in science are not easily described in terms of characteristics and categories that existed before their discovery. For example, Heisenberg (Heisenberg 1958), Neils Bohr, and others showed that elementary particles appear as particles when measured with apparatus designed to detect particles, and as waves when measured with apparatus designed to detect waves (see Farwell and Farwell 1995 and Farwell 1999 for a detailed discussion). Like elementary particles, the characteristics of the P300-MERMER that are detected depend on how it is measured. Farwell and Smith (2001; see also Farwell, 1994) described the process of discovery of the characteristics of the P300-MERMER as reminiscent of the story of the blind men and the elephant. Touching the trunk, one may conclude the elephant is like a snake; touching the tail, one may conclude it is like a rope. Touching the leg, the tusk, or the abdomen, etc. lead to different impressions.

Originally, the P300 was discovered as an event-related potential, detected through signal averaging of scalp-recorded voltage patterns. As discussed above, event-related potentials are voltage changes that take place in the time domain that are measured from the scalp. They manifest specific information-processing activities in the brain. Much of the subsequent research has been directed towards discovering what structures and processes in the brain create the event-related potentials recorded at the scalp.

The phenomenon that manifests at the scalp as the P300, however, is much more complex and multifaceted than a simple average time-domain pattern at the scalp can reveal or characterize. Farwell and Smith (2001; see also Farwell 1994) described the phenomenon manifested as the P300-MERMER and the P300 as a "multifaceted electroencephalographic response (MER)." The different facets of the phenomenon, like those of elephants and the electrons, are discovered through different methods of data acquisition and analysis.

The P300 phenomenon has been explored through several different methodologies. Measurements of EEG electrical voltage patterns made non-invasively at the scalp have been analyzed in terms of time-domain analysis through signal averaging, frequency-domain analysis, relationships between voltage patterns at different areas of the scalp (e.g., event-related coherence), and various characteristics of the signal (e.g., dynamical systems/chaos/fractal analysis – see Rapp et al. 1993; Farwell et al. 1993). Mathematical analysis of multichannel scalp recordings of EEG has been used to explore the source of these patterns in the brain (Li, Hu, Liu, and Wu 2011).

Intracranial recordings have been analyzed in both the time and frequency domains, and in some cases have been analyzed with respect to relationships between sites (e.g., coherence). Animal models have allowed for intra-cranial recordings in all areas of the brain, whereas such recordings in humans are restricted to areas of interest during surgery. Functional imaging (e.g., functional magnetic resonance imaging, fMRI) and magnetoencephalography have served to further explore which areas of the brain are activated during the process.

Through a combination of these techniques, a reasonably clear and comprehensive picture of the phenomenon has emerged. Like elephants and elementary particles, however, the P300 pattern is not without paradox and even apparent contradiction. To begin with, signal averaging

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makes the event-related potential visible as a pattern in the time domain, but the same process eliminates any frequency-domain signals that are a part of the phenomenon. A full characterization of the phenomenon, even at the scalp, must include both time-domain and frequency-domain characteristics (Başar-Eroglu et al. 1992).

Intra-cranial recordings have clearly revealed patterns in several areas of the brain, both in the time and frequency domains, that respond to the same experimental manipulations and appear at the same time as the P300. Some of these undoubtedly contribute in large measure to the scalp-recorded potentials. Clear patterns of activation in some specific areas, however, appear to be an integral part of the phenomenon, but due to the physical positioning of the structures in which they occur, they apparently do not contribute significantly to the scalp-recorded potentials. Lesion studies combined with scalp recording have served to isolate the structures that contribute to the scalp-recorded potentials, and in some cases to show that deep structures that are activated in the phenomenon do not contribute to its manifestation at the surface of the scalp.

To further complicate the picture, the P300 is not a unitary phenomenon. As discussed above, it is a multifaceted electroencephalographic response. Different facets correspond to different sub-tasks and modality-specific tasks in the information-processing of which the scalp recorded potential is a manifestation. Some of the same structures, and some different structures, are involved in these various different sub-tasks. The P300 includes information processing related to both the novelty and the significance of the stimulus, which involve somewhat different neural processes and structures. Information processing, and the structures involved, also varies somewhat depending on the modality (usually auditory or visual) of the stimulus.

Combining the findings from the various methods of discovery reveals the following pattern (Baudena et al. 1995; Huster et al. 2010; Halgren et al.1995; Johnson 1993; Kiss et al. 1989; Sabeti et al. 2011; Smith et al. 1990; Wang et al. 2005; for a review, see Linden 2005.) Significance-related (or target-related) contributions to the response appear to be generated largely in the parietal cortex and the cingulate. Novelty-related contributions to the response appear to be generated mainly in the inferior parietal and prefrontal regions. Contributions specific to the visual modality appear to be generated in the inferior temporal and superior parietal cortex. Contributions specific to the auditory modality appear to be generated in the superior temporal cortex.

A number of subcortical structures appear to be integrally involved in the phenomenon, but do not contribute significantly to the scalp-recorded potentials. Both frequency-domain and time-domain signals, and polarity reversals indicating a local source, have been recorded in temporal structures, most significantly in the hippocampus and the amygdala (Halgren et al. 1986; Sochurková et al. 2006; Stapleton and Halgren 1987). Initially, temporal structures were thought to be major contributors to the scalp-recorded potentials. Lesion studies, along with the limited degree to which such electrical potentials from such deep sources are propagated to the scalp, however, have cast doubt on this conclusion. Lesions of the medial temporal lobe have little effect on the scalp-recorded potentials (Johnson 1988).

The early research on the phenomenon of interest generally focused on the positive peak of the P300. In experiments involving meaningful stimuli and relatively long inter-stimulus intervals such as those applied in detection of concealed information, the P300-MERMER has a triphasic shape. The positive P300 peak is preceded by a negative peak, the N200, and followed by another negative peak, the LNP. This triphasic negative-positive-negative pattern was observed at the scalp by Farwell and others (Farwell 1994; Farwell and Smith 2001) as a defining characteristic of the P300-MERMER. The same negative-positive-negative pattern was observed in intracranial recordings in various structures (Halgren et al. 1998), including the inferior parietal lobe/supramarginal gyrus, superior temporal sulcus (Halgren, et al. 1995), the amygdala and hippocampus (Halgren et al. 1986; Stapleton and Halgren 1987), dorsolateral and orbital frontal cortices, and the anterior cingulate (Baudena et al. 1995). By now virtually all of the researchers involved in detection of concealed information with brainwaves include in their computational algorithms both the positive peak of the P300 and the late negative potential (LNP) that constitutes the other major facet of the P300-MERMER. (As discussed above, however,

differences in nomenclature still exist; some have called the entire multifaceted P300-MERMER phenomenon "P3" or "P300.")

One hypothesis that may explain the simultaneous involvement of numerous cortical and sub-cortical structures in the P300-MERMER is that this phenomenon reflects phasic activity of the neuromodulatory locus coeruleus-norepinephrine (LC-NE) system (Murphy et al. 2011; Nieuwenhuis et al. 2005; Pineda et al. 1989).

The hypothesis is that the properties of the P300 reflect the function of the LC-NE system to potentiate the information-processing activities undertaken in response to significant events. According to this theory, the LC-NE system affects or is affected by each structure in the entire constellation of structures that are activated in the P300, and the activation of large pyramidal neurons in the cortex by the LC-NE system is the primary source of scalp-recorded potentials of the P300. Evidence converges from several types of studies. The LC responds to experimental manipulations similar to those that produce the P300. Lesion studies show that normal functioning of the LC-NE system is necessary for the generation of the P300. The projections of the LC are also consistent with this hypothesis. The LC is the sole source of NE input to the neocortex and hippocampus, and also projects to the amygdala and the thalamus. The LC receives afferent input from structures known to be involved in decision making, in signaling novelty, and in representing task goals and significance of stimuli, including the prefrontal cortex, the anterior cingulate cortex, and the orbitofrontal cortex. This is consistent with the activation of the LC in response to stimuli that are evaluated as novel or significant in the current context, in accord with the antecedent conditions for the P300. The timing of the LC-NE responses to events is also consistent with the timing of the P300 response to similar events.

Brain fingerprinting scientific protocol

Experimental design

Brain fingerprinting tests are conducted according to the following scientific protocols. In a brain fingerprinting test, stimuli are presented to the subject in the form of words, phrases, or pictures on a computer screen. (Auditory stimuli may also be presented.) Brain responses are measured non-invasively from the scalp, digitized, and analyzed to determine the presence or absence of information stored in the brain. Figure 1 outlines the stages of data acquisition and analysis in brain fingerprinting.

Three types of stimuli are presented: probes, targets, and irrelevants. (Farwell and Donchin 1986; 1991; Farwell and Smith 2001). Probes contain information that is relevant to the crime or other investigated situation. Probes have three necessary attributes (Farwell 1994; 1995a; 1995b; Farwell and Smith 2001; Iacono 2008):

1. Probes contain features of the crime that in the judgment of the criminal investigator the perpetrators would have experienced in committing the crime;

2. Probes contain information that the subject has no way of knowing if he did not participate in the crime; and

3. Probes contain information that the subject claims not to know or to recognize as significant for any reason.

For example, if a subject claims not to have been at the murder scene and not to know what the murder weapon was, a probe stimulus could be the murder weapon, such as a knife. Brain fingerprinting experimental protocols ensure that probes do not contain information that the subject knows from the news media, interrogations, etc.

The scientific question addressed by a brain fingerprinting test is whether or not the subject is knowledgeable regarding the crime or investigated situation. Specifically, the critical variable is his recognition of the information contained in the probes as significant in the context of the crime (or lack thereof). If, and only if, this is present, it is predicted that the probes will elicit a P300-MERMER. The amplitude, morphology and latency will be characteristic of the individual subject's response to such stimuli when the subject knows the relevant information.

For a subject who is knowledgeable or "information present," the probes contain information describing known features of the crime. For a subject who is "information absent," the probes contain information describing plausible features of the crime that are not known to be correct. To objectively classify the probe responses into one of these two categories, it is necessary to isolate the

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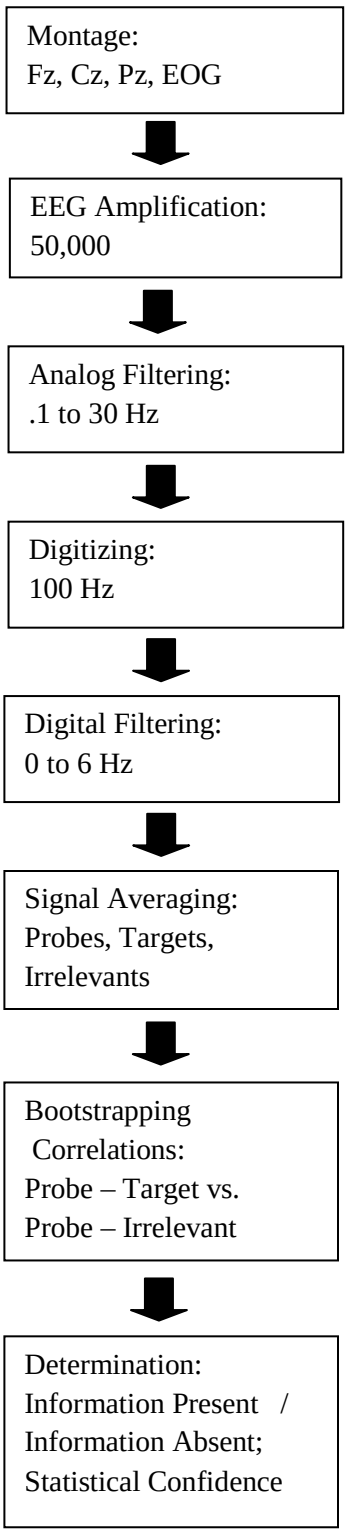
critical variable. To accomplish this, two standards are required: a standard for the response of this subject to stimuli containing known features of the crime, and a standard for the response of this subject to stimuli containing plausible but unknown (or incorrect) features of the crime.

Fig. 1 Stages of data acquisition and analysis



Target stimuli are details about the crime that the experimenter is certain the subject knows, whether or not he committed the crime. They may have been previously revealed through news accounts, interrogation, etc. In any case, the experimenter tells the subject the target stimuli and explains their significance in terms of the crime. Because they are significant in the context of the crime for all subjects, targets elicit an "Aha" response in all subjects. Targets elicit a P300-MERMER whether the subject knows the other salient features of the crime contained in the probes or not. For example, a target stimulus might be the name of the victim, which is revealed to the subject in the course of test instructions (and may be already known from news reports, etc.).

Irrelevant stimuli contain information that is not relevant to the crime and not relevant to the subject. They consist of incorrect but plausible crime features. Irrelevant stimuli are designed to be indistinguishable from correct crime-relevant features (probes) to someone who does not know the features of the crime. Since the irrelevant stimuli are not significant in context, they do not elicit a P300-MERMER.

If a probe stimulus is the murder weapon, a knife, then irrelevant stimuli could be other plausible (but incorrect) murder weapons such as a pistol, a rifle, and a baseball bat.

Thus, the targets and irrelevants both provide standard responses. The targets provide a standard for the subject's brain response to relevant, significant information about the crime in question. The irrelevants provide a standard for the subject's brain response – or rather lack of a response – to irrelevant information that is plausible as being crime-relevant.

It is vital in any science to isolate the critical variable. This three-stimulus design accomplishes this purpose. Targets and irrelevants differ only in whether or not they contain the critical feature being tested, that is, whether they contain known crime-relevant information. For an information-present subject, probe stimuli are virtually identical to target stimuli: both contain known features of the crime. The only difference is which button is pressed when the stimuli appear. For an information-absent subject, probes are

indistinguishable from irrelevants. The probe responses are classified as being more similar to targets or irrelevants. Everything except the critical variable, namely the subject's recognition of the probes as crime-relevant, is controlled.

The subject is given a list of the targets and instructed to press a specific button when a target appears and another button when any other stimulus appears. Since the subject does not know which of the three types of stimulus will occur on each trial, he must read and evaluate each stimulus, and demonstrate behaviorally in each trial that he has done so by pressing the appropriate button.

Table 1 outlines the types of stimuli and predicted brain responses in brain fingerprinting.

For a subject who knows the relevant details about the crime, the probes, like the targets, are significant and relevant. Thus, the probes produce an "Aha" response when presented in the context of the crime. This manifests as a P300-MERMER in the brainwaves that will be virtually identical to the target response. For a subject who lacks the knowledge contained in the probes, the probes are indistinguishable from the irrelevants. Probes do not produce an "Aha" response or the corresponding P300-MERMER: the probe response will be virtually identical to the irrelevant response.

The brain fingerprinting computerized data analysis algorithm computes a mathematical determination as to whether the probe response is more similar to

Table 1. Types of stimuli and predicted brain responses

Stimulus Type	Relative Frequency	Description	Instructions	Subject's Stimulus Evaluation	Predicted Brain Response
Target	1/6	Relevant to investigated situation; known to all subjects	Press left button	Relevant, rare for all subjects	P300-MERMER
Irrelevant	2/3	Irrelevant	Press right button	Irrelevant, frequent	No P300-MERMER
Probe	1/6	Relevant to investigated situation; known only to investigators and subjects who have the specific knowledge tested	Press right button (Treat like irrelevants)	**Information - Absent Subjects**: Irrelevant, frequent (Indistinguishable from irrelevants)	No P300-MERMER
				Information - Present Subjects: Relevant, rare	P300-MERMER

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that of the targets or that of the irrelevants. The former yields a determination of "information present"; the latter, "information absent." The information that is either present or absent in the brain of the subject is the information contained in the probes. The brain fingerprinting system also computes a statistical confidence for each individual determination, e.g., "information present, 99.9% confidence." If there is insufficient data to reach either an "information present" or an "information absent" determination with a high statistical confidence, the algorithm returns the outcome of "indeterminate."

Since the inclusion of the P300-MERMER in the brainwave data analysis algorithm, brain fingerprinting testing has made a definite determination in every case. All determinations have been correct. There have been no false negatives, no false positives, and no indeterminates. Error rate has been 0% in all studies and field applications. Accuracy has been 100%. (As discussed below, these are usually represented as "less than 1%" and "over 99%" respectively.) When brain fingerprinting data analysis has been conducted using the P300 alone, there have been no false positives or false negatives, and about 3% of the results have been indeterminate. All of these were in a single experiment (Farwell and Donchin 1991), wherein indeterminates comprised 12.5% of the results.

Note that an indeterminate result is not incorrect. It is not an error. It is neither a false negative nor a false positive. Rather, it is a determination that the data analysis algorithm has insufficient data to make a determination in either direction with a high statistical confidence.

Before conducting a brain fingerprinting test, the subject is interviewed to find out what he knows about the crime from any non-incriminating source such as news reports or prior interrogations. Any such information is excluded from the probes. (Such information may be contained in targets, since the targets are known to contain information that the subject knows.) The experimenter describes to the subject the significance of each probe in the context of the crime. The experimenter does not tell the subject which stimulus is the probe and which are similar, irrelevant stimuli. Only information that the subject denies knowing is used for probe stimuli.

Also, the experimenter shows the subject a list of all the stimuli including the probes, without of course identifying which ones are probes. As an extra precaution, the subject is asked if any of the stimuli are significant to him for any reason at all. Any stimuli that are significant to the subject for reasons unrelated to the crime are eliminated. If for example, a potential probe is the name of a known accomplice, and coincidentally it is also the name of the suspect's brother-in-law, it is not used.

Things are significant to a person in context. The context of the probe stimuli in relation to the crime is established in the interview prior to the brain fingerprinting test. Immediately before the test, the experimenter describes the significance of each probe in the context of the crime. Before the test, the subject has explicitly stated that he does not know which stimulus is the probe containing the correct information.

Under these circumstances, a large P300-MERMER in response to the probes provides evidence that the subject recognizes the probes as significant in the context of the crime. If the experimenter has followed the proper protocols, the subject has eliminated all plausible non-incriminating explanations for this knowledge by his own account prior to the test. Therefore, an information-present response can provide evidence that a judge and jury may reasonably evaluate as being probative regarding the subject's involvement in the crime. Note, however, that the question of whether or not the subject participated in the crime is in the domain of the judge and jury. The brain fingerprinting scientist provides evidence and testimony only regarding whether the crime-relevant information contained in the specific probes tested is stored in the brain of the subject.

Electroencephalograph (EEG) data are collected from midline frontal, central, and parietal scalp sites (Fz, Cz, and Pz respectively). Electrooculograph (EOG) data are collected from the forehead to monitor artifacts generated by eye movements. Data are amplified, digitized, filtered, and analyzed.

Stimuli are presented for a duration of 300 milliseconds at an inter-stimulus interval of 3000 milliseconds. A fixation point is presented for 1000 milliseconds prior to each stimulus presentation. Figure 2 outlines the timing parameters for stimulus presentation, data acquisition, and data analysis.

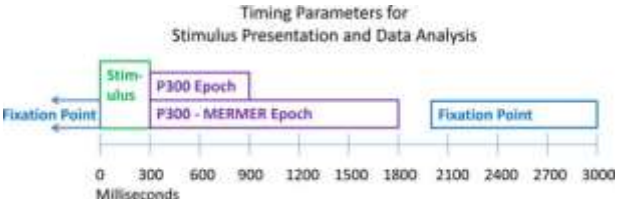

Fig. 2 Timing parameters. Timing of events for each individual trial in brain fingerprinting

The analysis epoch is 300 – 900 milliseconds post-stimulus for the P300 analysis, and 300 – 1800 milliseconds post-stimulus for the P300-MERMER analysis.

Data Analysis

The purpose of data analysis in brain fingerprinting studies is to determine whether the brain responses to the probe stimuli are more similar to the responses to the target stimuli or to the responses to the irrelevant stimuli, and to provide a statistical confidence for this determination. The determination and statistical confidence must be computed for each individual subject.

If the probe responses are mathematically more similar to the same subject's responses to target stimuli containing known features of the crime, the subject is determined to be "information present." If the probe responses are mathematically more similar to the same subject's responses to irrelevant stimuli containing plausible but unknown (or incorrect) features of the crime, the subject is determined to be "information absent."

To be valid, the statistical confidence for an individual determination of "information present" or "information absent" must take into account the level of variability in the individual brain responses that are aggregated in the average response. Farwell and Donchin (1988b; 1991) and their colleagues Wasserman and Bockenholt (Wasserman and Bockenholt 1989) applied bootstrapping to compute a statistical confidence for each individual determination that takes this variability into account. Bootstrapping is described in detail in these publications. It has now become a standard procedure in event-related brain potential research. Bootstrapping is a method to compute probability and statistical confidence regardless of the shape of the distribution of the data. It also provides a means to re-introduce the variability across single trials present in the original data, while preserving the feature of a smooth average that is necessary for comparing the waveforms of the three types.

The algorithm is as follows. Conduct the following procedure twice, once using the time epoch characteristic of the P300-MERMER (typically 300-1800 milliseconds after the stimulus) and once using the time epoch characteristic of the P300 alone (typically 300-900 milliseconds post-stimulus).

1) Sample randomly with replacement T target trials, P probe trials, and I irrelevant trials, where T, P, and I are equal to the total number of trials in the data set of the respective types. A trial consists of one stimulus presentation and the associated brain response data.

2) Average the trials by trial type, yielding three average waveforms: probe, target, and irrelevant. Compare the average waveforms to determine if the probe average is more similar to the target average or to the irrelevant average.

3) Repeat the above procedure 1000 times. Each iteration yields a new set of 3 averages containing probe, target, and irrelevant trials respectively. Keep a tally of the number of times the probe average is more like the irrelevant average than like the target average.

4) For each iteration, compare the probe, target, and irrelevant waveforms according to the following algorithm: a) subtract the grand mean of all trials, or grand average waveform, from each of the 3 averages, yielding 3 adjusted averages; b) compute the correlation between the adjusted probe average and the adjusted irrelevant average; c) compute the correlation between the adjusted probe average and the adjusted target average; d) compare the probe-irrelevant correlation with the probe-target correlation: if the probe-irrelevant correlation is greater, then increment the "information present" tally by one; otherwise, increment the "information absent" tally by one.

5) Compute the percentage of times that the probe – target correlation is higher than the probe –irrelevant correlation. This the percentage of times that the probe waveform is more similar to the target waveform than to the irrelevant waveform. This provides the probability or statistical confidence for an "information present" result. 100% minus this figure the provides the probability that the probe response is more similar to the irrelevant response, which provides the statistical confidence that for an "information absent" result.

6) Compare the computed statistical confidence to a decision criterion. If the statistical confidence for an "information present" result is greater than 90%, classify subject as information present. If the statistical confidence for an information absent response is greater than 70%, classify the subject as information absent. If neither criterion is met, no determination is made: the subject is not classified as either information present or information absent; this is an "indeterminate" outcome.

In other words, if the bootstrapping procedure produces a high statistical confidence that the probe response is more similar to the target response than to the irrelevant response, then the determination is "information present." If the bootstrapping procedure produces a high statistical confidence that the probe response is more

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similar to the irrelevant response, then the determination is "information absent."

If neither the statistical confidence for "information present" nor the confidence for "information absent" is high enough to meet established criteria, the subject is not classified in either category, and the result is "indeterminate." Typically a confidence of 90% is required for an "information present" determination. A lower criterion, typically 70%, is generally required for an "information absent" determination.

The outcome of brain fingerprinting data analysis consists of two determinations, each of the form "information present/absent, x% confidence," e.g., "information present, 99.9% confidence." One determination is computed using the full P300-MERMER, and one using the P300 alone. This allows us to report one result with the method that applies the most well established science and is most certain to meet the standard of general acceptance in the scientific community, and one with the method that applies the state of the art and generally produces the highest statistical confidence.

By computing bootstrapped correlation as described above, the brain fingerprinting data analysis algorithm takes into account the amplitude, latency, and morphology (shape and time course) of the brain response. This maximizes the information extracted from the data and also controls for individual differences in brain responses from different subjects.

Before applying the bootstrapping technique on correlations between waveforms, noise in the form of high-frequency activity is eliminated by the use of digital filters. Farwell et al. (1993) have shown that a specific type of filters known as optimal digital filters are highly effective for eliminating this high-frequency noise while preserving the brainwave pattern of interest in event-related brain potential research. These filters are optimal in the precise mathematical definition of the word.

In evaluating the error rate / accuracy of any technique, it is important to establish ground truth as objectively and certainly as possible. In any scientific test, ground truth is the true state of exactly what the test seeks to determine. In a DNA test, ground truth is not whether the suspect is a rapist or a murderer; ground truth is whether sample A (putatively from the subject) matches Sample B (putatively from the crime scene). In a fingerprint test, ground truth is not whether the suspect is a burglar, but whether the prints at the crime scene match the prints on the suspect's fingers. The same principle applies to brain fingerprinting. A brain fingerprinting test detects the presence or absence of specific information stored in the brain. Ground truth is the true state of that which is tested. Ground truth is whether or not the specific information embodied in the probe stimuli is in fact stored in the specific brain tested. Ground truth is not whether the suspect is a murderer, or a liar, or whether the experimental subject participated in a knowledge-imparting procedure consisting of a mock crime, or whether the experimenter thinks the subject should know the information tested. In evaluating the accuracy of a brain fingerprinting study, it is important to establish ground truth as objectively and certainly as possible. When subjects are cooperative (or eventually become cooperative), this is accomplished by post-test interviews to determine whether the subject knew the information tested at the time of the test. In field cases with any forensic science, establishing ground truth can be challenging. In brain fingerprinting field cases with uncooperative subjects, ground truth can never be known absolutely. It is established with as much certainty as possible through indirect means such as testimony, converging evidence, judicial outcome, and confessions.

Brain fingerprinting and other techniques

Advantages and disadvantages of brain fingerprinting

Brain fingerprinting has advantages and disadvantages with respect to other forensic science and investigative methods. Compared to previously available scientific methods for matching features of a crime scene with features of a suspect, the primary advantage of brain fingerprinting is that in most crimes very few such features can be found. In some crimes none are available. The record stored in the brain of the perpetrator is often a rich source of information that can be connected to the crime scene. Except in rare cases where the crime has been recorded on video, the record stored in the brain is generally the most comprehensive available record of the crime, even though it is not perfect.

Brain fingerprinting also has advantages in comparison to witness testimony. It provides an objective, scientific way to detect the record of the crime stored in the brain directly. Witness testimony provides an indirect, subjective account of this record. Witnesses may lie. The brain never lies. If the information is stored in the brain, it can be objectively detected regardless of the honesty or dishonesty of the subject. Brain fingerprinting thus eliminates one of the two major disadvantages of witness testimony, that of deception on the part of the witness.

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The primary disadvantage of brain fingerprinting in comparison to other forensic science methods of connecting features of a perpetrator to features of a crime scene is the same as the primary disadvantage of witness testimony: human memory is imperfect and limited. Just as all proceedings involving witness testimony must weigh the evidence obtained thereby in light of the limitations of human memory, all proceedings involving brain fingerprinting evidence must do the same.

Brain fingerprinting and "lie detection"

Brain fingerprinting and the guilty knowledge test or concealed information test

Brain fingerprinting has some the same features, and all of the advantages, of the conventional guilty knowledge test or concealed information test described above. It can be considered a type of guilty knowledge test (Farwell 2007; Iacono 2007; 2008; Iacono and Lykken 1997; Iacono and Patrick 2006). Brain fingerprinting takes advantage of the features of the guilty knowledge test that have made it well accepted in the relevant scientific community (Iacono 2008). Brain fingerprinting, however, is fundamentally different from the conventional guilty knowledge test in several important ways. These differences provide significant advantages over the conventional guilty knowledge test (Farwell 1994; 1995a; 2007).

Both brain fingerprinting and the conventional guilty knowledge test are concerned with the relevant features of the crime that are known to the perpetrator and not to an innocent suspect. Brain fingerprinting directly detects information stored in the brain based on information-processing brain activity. The conventional guilty knowledge test questions the subject, detects a stress-related response in an attempt to detect lies, and makes indirect inferences about what the subject knows on that basis.

A conventional guilty knowledge test asks two types of questions, relevant and irrelevant. The data analysis attempts to determine whether the stress-related response to the relevant questions is larger than the response to the irrelevant questions. If so, the subject is found to be deceptive. The determination of a conventional guilty knowledge test is "deceptive" or "non-deceptive."

A brain fingerprinting test, as described above, presents three types of stimuli. Two of these are relevant to the crime. Targets contain crime-relevant information that is known to all subjects. Probes contain information that is known only to the perpetrator and investigators. The information-processing responses to the probes are classified as being more similar to the irrelevant responses or to the target responses. The latter indicates that the probes, like the targets, contain information that the subject knows and recognizes as significant in the context of the crime.

Since brain fingerprinting measures an information-processing brain response rather than an emotional stress response, it does not depend on the emotional responses of the subject. It does not seek to assess the veracity of the subject. A subject neither lies nor tells the truth during a brain fingerprinting test. He simply observes the stimuli and pushes the buttons as instructed. The determination of a brain fingerprinting test is the same whether the subject tells the truth or lies about any subject at any time.

The determination of a brain fingerprinting test is "information present" or "information absent." An "information present" determination means that the subject possesses the specific knowledge tested. An "information absent" determination means that the subject does not possess this information. This is entirely independent of whether the subject tells the truth or lies about this information or anything else.

Conventional CQT polygraphy and fMRI

Conventional polygraphy involves questioning the subject, measuring a physiological response, and thereby attempting to determine if he is lying. A conventional control question polygraph test (CQT) measures peripheral responses, usually skin conductance (related to perspiration), cardiovascular activity/blood pressure, and breathing. Conventional polygraphy measures this peripheral physiological response in an attempt to detect changes considered to accompany lying (Farwell 2013; Iacono 2007; 2008; Iacono and Lykken 1997; Iacono and Patrick 2006; National Research Council 2003; Vrij 2008).

Scientists have recently introduced measurements of cerebral blood flow with functional magnetic resonance imaging (fMRI) in an attempt to detect lies. Like conventional polygraphy, fMRI does not directly measure lying. Since lying is not a unitary phenomenon, there is no unique "lie response." The underlying theory of fMRI detection is similar to the theory of conventional polygraphy. Instead of measuring stress, however, fMRI measures brain processes putatively connected with "conflict" or other processes considered to accompany lying.

As discussed above, there are two fundamental ways to attempt to obtain information regarding a suspect's participation in a crime: 1) collect objective data linking

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the subject to the crime, and 2) question the subject or a witness about the crime and attempt to discern if he or she is lying. Conventional CQT polygraphy and fMRI-based lie detection methods both fall into the latter category. Their purpose is lie detection. They serve as adjuncts to interrogation and testimony.

Brain fingerprinting is fundamentally different from lie detection. Mistakenly classifying brain fingerprinting as a form of lie detection (e.g., Verschuere, Rosenfeld, Winograd, Labkovksy, and Wiersema 2009; Rosenfeld 2005) arises from a fundamental misunderstanding of the science and technology (Farwell 2013; Farwell and Makeig 2005; Farwell and Smith 2001). Brain fingerprinting detects information stored in the brain, not lies (Farwell 1992a; 1994; 1995b; 2013; Farwell and Donchin 1991; Iacono 2008). Like fingerprinting and DNA, brain fingerprinting is a method to collect objective data linking the subject to the crime.

Origin of the term "brain fingerprinting"

Brain fingerprinting is so named based on the following analogy (Farwell 1994). Fingerprinting establishes an objective, scientific connection between fingerprints at a crime scene and the fingers of a suspect. DNA "fingerprinting," as it is sometimes called, establishes an objective, scientific connection between biological samples from the crime scene and biological samples from the suspect. Brain fingerprinting was so named because like fingerprinting it detects a match between evidence from the crime scene and evidence on the person of the suspect. It establishes an objective, scientific connection between features of the crime scene and the record stored in the brain of a suspect.

Principles of applying brain fingerprinting in the laboratory and the field

The purpose of brain fingerprinting is to determine whether or not specific relevant knowledge is stored in the brain of the subject (Farwell, 1994; in press a; Farwell and Smith 2001; Iacono 2008).

In field cases, the relevant knowledge generally is information that an investigator thinks represent the details of a crime. Alternatively, it may be information that is known only to a particular group of people, such as FBI agents (Farwell and Richardson 2006b; Farwell, Richardson, and Richardson 2011; in press), skilled bomb makers (Farwell 2009; Farwell, Richardson, and Richardson 2011; in press), trainees of an Al-Qaeda training camp, or members of a terrorist cell. The primary example used herein will be the case where the relevant knowledge constitutes information that an investigator believes constitutes salient features of a crime that the perpetrator experienced in the course of committing the crime. The relevant knowledge is provided by the criminal investigator to the brain fingerprinting scientist. The goal of brain fingerprinting is to determine whether or not the relevant knowledge is known to the subject.

Note that brain fingerprinting does not evaluate whether or not the investigator's account of the crime is accurate, or whether the putatively relevant knowledge actually correctly represents the crime. Brain fingerprinting does not detect guilt or innocence. The determination of whether the subject is guilty is a legal determination that is made by a judge and/or jury, not by a scientist or a computer.

Brain fingerprinting does not detect whether or not the subject committed the crime. It only detects whether or not the subject knows the relevant knowledge contained in the probes. The prosecution may argue that the best explanation for an "information present" determination is that the subject learned the relevant knowledge while committing the crime. (In a properly executed brain fingerprinting test, plausible alternative hypotheses such as the subject being told the information after the crime have been eliminated before the test.) The defense may argue that an "information absent" determination introduces a reasonable doubt that the subject is guilty of committing the crime, and provides support for his claims of innocence. The defense may argue, for example, that a subject should or would know the relevant knowledge if he had committed the crime.

Brain fingerprinting does not evaluate whether the subject should, could, or would know the information, and under what circumstances. It only determines whether or not the subject *actually does* know the relevant knowledge. The interpretation of the results of a brain fingerprinting test in terms of guilt or innocence, participation or non-participation in a crime, goes beyond the science and is outside the realm of expert testimony by a brain fingerprinting scientist.

Brain fingerprinting is similar to other forensic sciences in this regard. A DNA expert testifies that Sample A, which the investigators say came from the crime scene, matches Sample B, which the investigators say came from the subject. Similarly, an expert may testify that two fingerprints match. He does not testify, report, or attempt to scientifically determine "Therefore, the subject committed the murder." A brain fingerprinting scientist testifies regarding only one specific fact: the subject does or does not know the specific relevant knowledge tested (Harrington v. State 2001). The degree to which this fact is probative regarding the

subject's participation in a crime is outside the realm of science. That is a matter to be debated by the prosecution and defense and decided by a judge and/or jury based on their non-scientific, common sense judgment and life experience.

In a laboratory setting, the relevant knowledge is fabricated by the experimenter. One additional step is necessary before a test can be implemented to test whether or not the subject knows the relevant knowledge. The experimenter designs and implements a knowledge-imparting procedure to impart the relevant knowledge to the subject. The knowledge-imparting procedure generally constitutes a training session, a mock crime, or some combination thereof. The purpose of the knowledge-imparting procedure is to make certain that the subject knows the relevant knowledge. The accuracy of a method to detect the relevant knowledge can only be evaluated when the relevant knowledge is actually there to be detected. If the knowledge-imparting procedure fails to impart the knowledge to the subject, then the knowledge is not there to be detected. No method, no matter how perfect, can detect knowledge that is not there. As discussed above in the context of ground truth, in order to conduct a valid test of a knowledge-detection procedure in a laboratory study, the experimenter must independently assess whether the knowledge-imparting procedure actually succeeded in imparting the knowledge so it was there to be detected. This is accomplished by post-test interviews.

In a field case, the brain fingerprinting procedure begins after the criminal investigator has provided the relevant knowledge to the scientist. In a laboratory case, the brain fingerprinting procedure begins after the experimenter has fabricated the relevant knowledge and successfully implemented the knowledge-imparting procedure.

The relevant knowledge generally comprises 12 to 30 short phrases or pictures, along with an explanation of the significance of each in the context of the crime. The investigator also provides the scientist with a detailed account of which items in the relevant knowledge are or may be already known to the subject for any known reason. For example, the investigator notes any specific features of the crime that have been published in the newspaper or revealed to the subject in interrogation or previous legal proceedings.

The relevant knowledge generally contains six to nine or more items that have never been revealed to the subject. These will constitute the probe stimuli. If there is an insufficient number of features that are known only to the perpetrator and investigators (probes), a brain fingerprinting test cannot be conducted.

Generally there are also six or more items that have already been revealed to the subject or are commonly known. These will constitute the target stimuli.

The test requires an equal number of targets and probes. If there are too few features already known to the subject for non-incriminating reasons (potential targets), the experimenter may request additional information about the crime from the criminal investigator to use for target stimuli. Alternatively, if there are ample available features of the crime that are not commonly known and have not been revealed to the subject (potential probes), the experimenter may elect to inform the subject about some of these features and use these as targets instead of probes.

Scientific standards for brain fingerprinting tests

The following procedures comprise the scientific standards for a brain fingerprinting test (Farwell 1992a; 1994; 1995a; 1995b; Farwell and Donchin 1991; Farwell and Smith 2001).

1. Use equipment and methods for stimulus presentation, data acquisition, and data recording that are within the standards for the field of cognitive psychophysiology and event-related brain potential research. These standards are well documented elsewhere (Donchin et al. 1978; 1986; Fabiani et al. 1987). For example, the standard procedures Farwell introduced as evidence in the Harrington case were accepted by the court, the scientific journals, and the other expert witnesses in the case (Farwell and Donchin 1991; Farwell and Makeig 2005; Farwell and Smith 2001; Harrington v. State 2001). Use a recording epoch long enough to include the full P300-MERMER. For pictorial stimuli or realistic word stimuli, use at least a 1800 millisecond recording epoch. (Shorter epochs may be appropriate for very simple stimuli.)
2. Use correct electrode placement. The P300 and P300-MERMER are universally known to be maximal at the midline parietal scalp site (Fabiani et al. 1987; Farwell 1994), Pz in the standard International 10-20 system.
3. Apply brain fingerprinting tests only when there is sufficient information that is known only to the perpetrator and investigators. Use a minimum of six probes and six targets.

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4. Obtain the relevant knowledge from the criminal investigator (or for laboratory studies from the knowledge-imparting procedure). Use stimuli that isolate the critical variable. Divide the relevant knowledge into probe stimuli and target stimuli. Probe stimuli constitute information that has not been revealed to the subject. Target stimuli contain information that has been revealed to the subject after the crime.
5. If initially there are fewer targets than probes, create more targets. Ideally, this is done by seeking additional known information from the investigators. Note that targets may contain information that has been publicly disclosed. Alternatively, some potential probe stimuli can be used as targets by disclosing to the subject the specific items and their significance in the context of the crime.
6. For each probe and each target, fabricate several stimuli of the same type that are unrelated to the crime. These become the irrelevant stimuli. Use stimuli that isolate the critical variable. For irrelevant stimuli, select items that would be equally plausible for a non-knowledgeable subject. The stimulus ratio is approximately one-sixth probes, one-sixth targets, and two-thirds irrelevants.
7. Ascertain that the probes contain information that the subject has no known way of knowing, other than participation in the crime. This information is provided by the investigator for field studies, and results from proper information control in laboratory studies.
8. Make certain that the subject understands the significance of the probes, and ascertain that the probes constitute only information that the subject denies knowing, as follows. Describe the significance of each probe to the subject. Show him the probe and the corresponding irrelevants, without revealing which is the probe. Ask the subject if he knows (for any non-crime-related reason) which stimulus in each group is crime-relevant. Describe the significance of the probes and targets that will appear in each test block immediately before the block.
9. If a subject has knowledge of any probes for a reason unrelated to the crime, eliminate these from the stimulus set. This provides the subject with an opportunity to disclose any knowledge of the probes that he may have for any innocent reason previously unknown to the scientist. This will prevent any non-incriminating knowledge from being included in the test.
10. Ascertain that the subject knows the targets and their significance in the context of the crime. Show him a list of the targets. Describe the significance of each target to the subject.
11. Require an overt behavioral task that requires the subject to recognize and process every stimulus, specifically including the probe stimuli. Detect the resulting brain responses. Do not depend on detecting brain responses to assigned tasks that the subject can covertly avoid doing while performing the necessary overt responses.
12. Instruct the subjects to press one button in response to targets, and another button in response to all other stimuli. Do not instruct the subjects to "lie" or "tell the truth" in response to stimuli. Do not assign different behavioral responses or mental tasks for probe and irrelevant stimuli.
13. In order to obtain statistically robust results for each individual case, present a sufficient number of trials of each type to obtain adequate signal-to-noise enhancement through signal averaging. Use robust signal-processing and noise-reduction techniques, including appropriate digital filters and artifact-detection algorithms (Farwell et al. 1993). The number of trials required will vary depending on the complexity of the stimuli, and is generally more for a field case. In their seminal study, Farwell and Donchin (1991) used 144 probe trials. In the Harrington field case, Farwell used 288 probe trials (Harrington v. State 2001). In any case, use at least 100 probe trials and an equal number of targets. Present three to six unique probes in each block.
14. Use appropriate mathematical and statistical procedures to analyze the data (Farwell 1994; Farwell and Donchin 1991). Do not classify the responses according to subjective judgments. Use statistical procedures properly and reasonably. At a minimum, do not classify subjects in a category where the statistics applied show that the classification is more likely than not to be incorrect.
15. Use a mathematical classification algorithm, such as bootstrapping on correlations, that

isolates the critical variable by classifying the responses to the probe stimuli as being either more similar to the target responses or to the irrelevant responses (Farwell and Donchin 1991; Farwell 1994; Wasserman and Bockenholt 1989). In a forensic setting, conduct two analyses: one using only the P300 (to be more certain of meeting the standard of general acceptance in the scientific community), and one using the P300-MERMER (to provide the current state of the art).

16. Use a mathematical data-analysis algorithm that takes into account the variability across single trials, such as bootstrapping (Farwell 1994; Farwell and Donchin 1991; Wasserman and Bockenholt 1989).

17. Set a specific, reasonable statistical criterion for an information-present determination and a separate specific, reasonable statistical criterion for an information-absent determination (Farwell 1994; Farwell and Donchin 1991; Wasserman and Bockenholt 1989). Classify results that do not meet either criterion as indeterminate. Recognize that indeterminate outcome is not an error, neither a false positive nor a false negative.

18. Restrict scientific conclusions to a determination as to whether or not a subject has the specific crime-relevant knowledge embodied in the probes stored in his brain (Farwell and Makeig 2005; Farwell and Smith 2001; Harrington v. State 2001). Recognize that brain fingerprinting detects only presence or absence of information – not guilt, honesty, lying, or any action or non-action. Do not offer scientific opinions on whether the subject is lying or whether he committed a crime or other act. Recognize that the question of guilt or innocence is a legal determination to be made by a judge and jury, not a scientific determination to be made by a scientist or computer.

19. Evaluate accuracy based on actual ground truth (Farwell and Donchin 1991; Farwell and Richardson 2006b). Ground truth is the true state of what a scientific test seeks to detect. Brain fingerprinting is a method to detect information stored in a subject's brain. Ground truth is whether the specific information tested is in fact stored in the subject's brain. Establish ground truth with certainty through post-test interviews in laboratory experiments and in field experiments wherein subjects are cooperative. Establish ground truth insofar as possible through secondary means in real-life forensic applications with uncooperative subjects. Recognize that ground truth what the subject in fact knows, not what the experimenter thinks the subject should know, not what the subject has done or not done, and not whether the subject is guilty, or deceptive.

20. Make scientific determinations based on brain responses. Do not attempt to make scientific determinations based on overt behavior that can be manipulated, such as reaction time.

Error rate / accuracy standards for field applications

In the United States and many other jurisdictions, the error rate of a scientific technique is critical for admissibility as scientific evidence in court. The error rate is the percentage of determinations made that are either false negatives or false positives. In brain fingerprinting, this is the percentage of "information present" and "information absent" determinations that are false positives and false negatives respectively.[1]

In our view, in order to be viable for field use or any application with non-trivial consequences, a technique must have an error rate of less than 1% overall, and less than 5% in each and every individual study. As discussed in the section below on common errors in research, failure to meet the brain fingerprinting scientific standards generally produces error rates ten times higher than this standard.

Brain fingerprinting exceeds this standard. In all laboratory and field research and field applications to date, brain fingerprinting has had an error rate of less than 1%. In each individual study, brain fingerprinting has also had an error rate of less than 1%. In fact, to date brain fingerprinting has never produced an error, neither a false positive nor a false negative, in any research or field applications.

Accuracy is 100% minus the error rate. In reporting results, it is important to report the error rate directly, or to report the accuracy rate in such a way that the true

[1] Note that an indeterminate outcome is neither a false positive nor a false negative error. Rather, it is a determination that there was insufficient data to draw a conclusion with a high statistical confidence in either direction. False negatives and false positives are errors that provide false evidence, to the detriment of the judicial process. An indeterminate provides no evidence, and has no legal impact.

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error rate can be computed.[2] (See the section entitled "Is Brain Fingerprinting 100% Accurate?")

Brain fingerprinting in criminal cases and in court

In addition to laboratory and field studies conducted by the author at the CIA, the FBI, the US Navy, and elsewhere as well as replications in independent laboratories, brain fingerprinting has been applied in real-world criminal cases and has been ruled admissible in court. According to courtroom testimony by expert witnesses on both sides of the issue, the fundamental science underlying brain fingerprinting testing has been established by hundreds of studies published in the peer-reviewed scientific literature and is well accepted in the relevant scientific community (Farwell and Makeig 2005; Harrington v. State 2001; Iacono 2008).

The James B. Grinder case

Fig. 3 Brain fingerprinting test on a serial killer. Dr. Lawrence Farwell conducts a brain fingerprinting test on serial killer J. B. Grinder, then a suspect in the murder of Julie Helton. The test showed that Grinder's brain contained a record of certain salient features of the crime. He then pled guilty and was sentenced to life in prison (Photo: Brain Fingerprinting Laboratories, Inc.)

On August 5, 1999, Dr. Lawrence Farwell administered a brain fingerprinting test to murder suspect J. B. Grinder (Figure 3). The test was designed to determine if Grinder's brain contained specific details of the rape and murder of Julie Helton. Drew Richardson, then a scientist in the FBI Laboratory, was the criminal investigator who developed the probe stimuli.

The brain fingerprinting test found that the specific details of the crime were recorded in Grinder's brain (Figure 4). The result was "information present," with a statistical confidence of 99.9%.

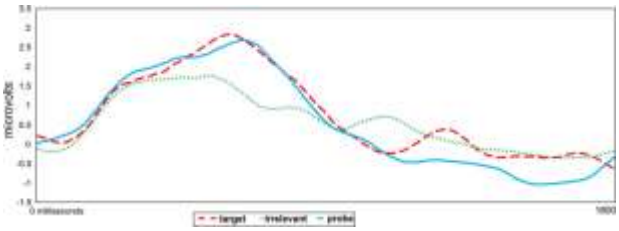

Fig. 4 ''Information present'' brain response of a serial killer. Brain response of serial killer J. B. Grinder to information relevant to the murder of Julie Helton. There is a clear P300-MERMER in response to the known targets. The P300 is the positive voltage peak at the upper left. The P300-MERMER contains both the P300 peak and the late negative potential (LNP) at the lower right. There is no P300-MERMER in response to the irrelevants. Grinder's brain response to the crime-relevant probes clearly contains a P300-MERMER. This shows that the record in the brain of J. B. Grinder contains salient details of the murder. Determination: ''information present.'' Statistical confidence: 99.9%

Considering the brain fingerprinting test results and other evidence, Grinder faced an almost certain conviction and highly probable death sentence. One week after the brain fingerprinting test, Grinder pled guilty to the rape and murder of Julie Helton in exchange for a sentence of life in prison without the possibility of being released. He is currently serving that sentence. In addition, Grinder confessed and later pled guilty to the murders of three other young women.

The Terry Harrington case

In 1977 John Schweer, a retired police captain, was murdered near the car dealership in Council Bluffs, Iowa where he was working as a security guard. Terry Harrington was arrested for the murder. An alleged witness claimed that he had accompanied Harrington to the crime scene and witnessed Harrington committing the crime.

A jury found Harrington guilty in Iowa District Court in 1978. He was sentenced to life in prison without the possibility of being released. On April 18 and 25, 2000, Dr. Lawrence Farwell administered a brain fingerprinting test to Harrington. The test results demonstrated that Harrington's brain did not have a record of certain specific salient features of the crime. Another test showed that he did recognize salient details of his alibi. The result was "information absent" with respect to the crime, and "information present" with respect to the alibi. In both cases the statistical confidence was over 99%.

When Farwell confronted the only alleged witness to the crime with the brain fingerprinting test results, he recanted his testimony. He admitted that he had lied in

[2] Accuracy is correctly reported as 100% minus the error rate. This allows the reader to compute the true error rate. Reports of "accuracy" that confound false positive and false negative errors with indeterminate outcomes have the effect of hiding the true error rate, and thus make comparison with correctly reported studies problematic.

the original trial, falsely accusing Harrington to avoid being prosecuted for the murder himself.

In *Harrington v. State* (2001), Terry Harrington sought to overturn his murder conviction on several grounds, including an allegation that newly discovered evidence in the form of brain fingerprinting entitled him to a new trial (Erickson 2007; Farwell and Makeig 2005; Roberts 2007).

Standard of review

To obtain relief, the petitioner Harrington had to show that the newly discovered evidence was unavailable at the original trial, and that the new evidence, if introduced at the trial, would probably change the verdict. Additionally, in view of the fact that the proffered evidence consisted of a novel forensic application of psychophysiological techniques, the court was required to determine whether this scientific evidence was sufficiently reliable to merit admission into evidence and, if admitted, whether the weight of the scientific evidence was sufficiently compelling to change the verdict.

In the Daubert case (Daubert v. Merrell Dow Pharmaceuticals, Inc. 1993; Erickson 2007) the U.S. Supreme Court has held that the standard for admissibility of novel scientific evidence is a showing of reliability based on (1) whether a theory or technique can be (and has been) tested; (2) whether it has been subjected to peer review and publication; (3) whether, in respect to a particular technique, there is a known or potential rate of error, and whether there are standards controlling the technique's operation; and (4) whether the theory or technique enjoys general acceptance within a relevant scientific community. The Iowa Supreme Court has not formally endorsed this federal evidentiary standard, but in *Leaf v. Goodyear Tire & Rubber Co*. (1999) it announced that the Iowa courts may use the Daubert factors in assessing the admissibility of novel scientific evidence.

Moenssens (2002), Erickson (2007), and Roberts (2007) discuss the issues involved in admissibility of brain fingerprinting in some detail.

The brain fingerprinting assessment of Harrington.

In the Harrington case, Farwell developed a series of probes for the crime scene, and a separate series of probes for the petitioner's alibi, from investigations, witness interviews, and previously undisclosed police files. Farwell administered the test to Harrington in May 2000. In October 2000, he rendered a report to the Iowa District Court analyzing the P300-MERMER responses. He supplemented the report with a separate analysis based solely on P300 responses on November 10, 2000. Both analyses produced a result of "information absent" regarding the crime scene probes and "information present" regarding the alibi probes, with a high degree of statistical confidence (over 99%). Figure 5 presents Harrington's brain responses to specific crime-relevant information to which he had not been exposed prior to the test.

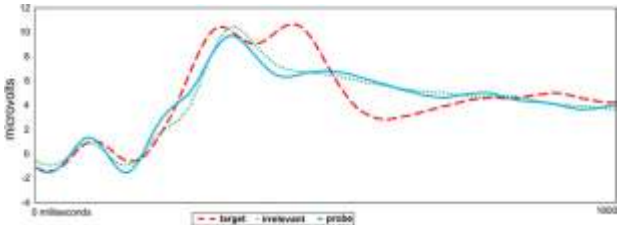

Fig. 5 ''Information absent'' brain response of an innocent convict. Brain response of Terry Harrington to information relevant to the murder of which he had been convicted. There is a clear P300-MERMER in response to the known targets. P300 is the positive peak in the top center. The P300-MERMER is the P300 plus the late negative potential (LNP) in the lower right. The response to irrelevant stimuli lacks a P300-MERMER. There is no P300-MERMER in response to the crime-relevant probes. This shows that Harrington's brain does not have a record of these specific features of the crime. He was exonerated and released. Determination: ''information absent.'' Statistical confidence: 99.9%

Proceedings in the Iowa District Court.

The District Court held a one-day hearing on the brain fingerprinting evidence on November 14, 2000. The court took preliminary testimony on Farwell's credentials, the efficacy of the test, and the reliability of the underlying science. The court also examined the test results, subject to a later determination whether this scientific evidence was sufficiently reliable to be admissible.

At the November 14 session, Dr. Farwell testified and was cross-examined on the basis of his test reports. Additionally, two other psychophysiologists with EEG expertise, Dr. William Iacono of the University of Minnesota and Dr. Emanuel Donchin of the University of Illinois at Champaign/Urbana, testified on Dr. Farwell's credentials, his test reports and the science underlying the brain fingerprinting test. Iacono testified at Harrington's request, and Donchin was called by the state.

Both experts validated the science underlying brain fingerprinting and acknowledged Dr. Farwell's credentials. However, while Iacono validated the forensic application of P300 science based on his own research, Donchin asserted that the tester's selection and presentation of the specific probes is the point at which science ends and art begins.

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The investigative phase of preparing the brain fingerprinting test discovers the salient features of the crime that are used as probe stimuli. It depends on the skill and judgment of the criminal investigator. This is not a scientific process.

The scientific phase of brain fingerprinting testing begins after the investigation has identified appropriate probes. The science of brain fingerprinting testing determines how the subject's brain responded to the probes, providing an objective result: "information present" or "information absent." This result does not depend on the subjective judgment of the scientist conducting the test. The test result is then presented to the trier of fact to assist in the determination of guilt and innocence. The brain fingerprinting scientist does not opine on guilt or innocence, or whether the suspect committed the crime, but only on the presence or absence in the brain of the suspect of a record of the specific crime-relevant information contained in the probe stimuli.

Donchin contended that the selection of probes in brain fingerprinting is the end of science and the beginning of art. Farwell noted that the selection of probes is a feature of the skilled investigation and not of the scientific brain fingerprinting testing. Farwell agreed that the selection of probes is a subjective element depending on the skill and judgment of the criminal investigator. He asserted, however, that this subjective element is the kind of evidence that judges and juries are competent to evaluate. A non-scientist is well equipped with common sense and life experience to evaluate all the facts and circumstances of the case and determine whether a finding that the specific probes in question returned a scientific result of "information present" or "information absent" helps to establish the subject's guilt.

Farwell, Iacono, and Donchin agreed that brain fingerprinting as practiced using the P300 and published by Farwell and Donchin (1991) in both the laboratory and the real-life cases was generally accepted in the relevant scientific community (Harrington v. State 2001). They also agreed that the additional analysis using the MERMER did not yet have the same level of acceptance, and was not necessary to reach the scientific conclusions relevant to the case.

The District Court's ruling.

The court determined that brain fingerprinting was new evidence not available at the original trial, and that it was sufficiently reliable to merit admission of the evidence (Erickson 2007; Farwell and Makeig 2005; Harrington v. State 2001; Roberts 2007). However, the court did not regard its weight as sufficiently compelling in light of the record as a whole as meeting its exacting standard, and thus it denied a new trial on this and the other grounds asserted by Harrington.

The court stated the following:

> "In the spring of 2000, Harrington was given a test by Dr. Lawrence Farwell. The test is based on a 'P300 effect'."
>
> "The P-300 effect has been recognized for nearly twenty years."
>
> "The P-300 effect has been subject to testing and peer review in the scientific community."
>
> "The consensus in the community of psycho-physiologists is that the P300 effect is valid."
>
> "The evidence resulting from Harrington's 'brain fingerprinting' test was discovered after the verdict. It is newly discovered."

The court admitted only the brain fingerprinting evidence using the P300. The additional analysis using the P300-MERMER was superfluous, and not necessary to establish the brain fingerprinting results. It reached the same statistical and scientific conclusions as the P300 analysis, with essentially the same extremely high statistical confidence. At that time, Farwell had not yet published the P300-MERMER in peer-reviewed journals. It has now been peer reviewed and published.

Appeal

The Iowa Supreme Court reversed the trial court and granted Harrington a new trial (Harrington v. State, 2003). The Supreme Court did not reach the brain fingerprinting issue, and decided the case on other grounds. Due to a constitutional rights violation, Harrington was accorded a new trial. The only alleged witness to the crime, Kevin Hughes, had recanted when Farwell confronted him with the "information absent" results of the brain fingerprinting test on Harrington. Without its star witness, the state subsequently dismissed the murder prosecution without prejudice for lack of evidence due to witness recantations and the passage of time.

Resolution and vindication of Harrington.

In his recantation, Hughes stated under oath under questioning by Farwell that the detectives and prosecutors had told him he would go to prison for life if he didn't implicate Harrington. He stated that when he

agreed to falsely accuse Harrington of the murder, they coached him in fabricating the story to which he later testified in the trial. He stated that when he said something that contradicted known facts – such as identifying the wrong murder weapon – they corrected him, and he changed his story accordingly.

Harrington sued the prosecutors and the State of Iowa for framing him. The prosecutors did not deny the accusations brought by Hughes and Harrington. Their defense was that they enjoyed absolute immunity due to their professional position. The US Supreme Court agreed to hear the case. Before the Supreme Court heard the case, however, the State of Iowa settled with Harrington and another man falsely convicted of the same crime. The state paid them a $12 million settlement.

The Jimmy Ray Slaughter case

In 2004, brain fingerprinting testing was offered in support of the Oklahoma petition for post-conviction relief filed by death-row inmate Jimmy Ray Slaughter (Slaughter v. State 2004). The Oklahoma court of final resort in post-conviction matters declined to order an evidentiary hearing on numerous issues raised by the petitioner. These included not only an "information-absent" result for crime-scene items returned by a brain fingerprinting test, but also exculpatory DNA evidence; the sworn testimony of the original lead investigator on the case in which he stated that he had come to believe that Slaughter was innocent, and that others involved in the investigation had falsified reports and fabricated evidence against Slaughter; and other exculpatory evidence. Slaughter was subsequently executed.

The Oklahoma court declined to return the case to the trial court where it could reach the merits of the brain fingerprinting challenge, based on procedural grounds and on the appeal court's view that the petitioner's brief affidavit contained insufficient evidence of the efficacy of the test and salience of the probes, and that the newly discovered evidence was presented in an untimely manner. "[B]ased on the evidence presented, we find the brain fingerprinting evidence is procedurally barred," "What we have are some interesting, indeed startling, claims that are not backed up with enough information for us to act on them."

Published research on brain fingerprinting science and technology

Overview of scientific research

Farwell and colleagues have tested brain fingerprinting technology in over 200 cases, including over a dozen scientific studies as well as individual forensic cases involving real-life crimes and other events. Numerous other scientists have conducted similar research on the P300 brain response and have replicated Farwell's brain fingerprinting research.

The scientific studies conducted on brain fingerprinting testing have included both field/real-life and laboratory studies. Real-life studies involve using brain fingerprinting technology to detect information stored in the brain regarding real-life events that took place in the course of actual life experience. Laboratory studies involve detecting information that was acquired by subjects in the course of a knowledge-imparting procedure such as a mock crime. Of the approximately 200 cases where the author has tested brain fingerprinting technology, about half were real-life situations and half were laboratory experiments.

Brain fingerprinting testing has been used to detect information stored in the brain regarding two different types of situation:

1. Specific issue tests detect information regarding a specific incident or a particular crime.

2. Specific screening or focused screening tests detect information relevant to a specific type of training or inside knowledge of a specific field or organization, such as FBI agent training or knowledge of bomb making.

Brain fingerprinting technology detects information stored in the brain. Therefore brain fingerprinting testing is not applicable for general screening or interrogation where the investigators do not know what specific information they seek to detect. General screening includes most pre-employment screening and periodic general security screening of employees.

Federal Bureau of Investigation (FBI) studies

Farwell conducted FBI Experiment 1, the "FBI agent study," (Farwell and Richardson 2006a; Farwell, Richardson, and Richardson 2011) with Drew Richardson, then a scientist at the FBI Laboratory. Brain fingerprinting produced 100% accurate results in detecting FBI-relevant knowledge in 17 FBI agents and lack of this knowledge in four non-FBI agents.

In this experiment, the information detected was specific knowledge that is known to FBI agents and not to the public. The detection of FBI agents indicates that the system could detect knowledge specific to members of specific organization such as a terrorist, criminal, or intelligence organization as well as perpetrators of a specific crime. For example, members of a particular

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terrorist organization or terrorist cell share a particular body of knowledge that is unknown to the public, and the detection of such knowledge could assist in the identification of a suspect as a member of such an organization.

Stimuli were words, phrases, and acronyms presented on a computer screen. Analysis using the P300-MERMER resulted in correct determinations in every case, with a high statistical confidence in every case. There were no false positives, no false negatives, and no indeterminates. Analysis using the P300 alone resulted in the same determinations, with somewhat lower statistical confidence in some cases.

The FBI agent study included the following innovation that proved useful in making more accurate determinations in future studies. The scientists used the usual probe and irrelevant stimuli. Probes consisted of FBI-relevant knowledge. Irrelevants consisted of irrelevant, unknown items. In initial pilot studies, they used targets consisting of irrelevant items that had been disclosed to the subjects. Some of the stimuli were acronyms wherein the probes were known to the subjects, and both targets and irrelevants were random strings of letters.

For an FBI-knowledgeable subject, the probes were easily recognizable combinations of letters, and both targets and irrelevants were nonsense letter strings. The subjects recognized the probes more quickly than targets and irrelevants, resulting in shorter latency P300-MERMER responses only to the probes. (See Figure 6; contrast this with Figure 4, wherein probe and target brain responses have identical time course.) When computing correlations, this discrepancy in latency between targets and probes reduced the correlations between these response types. This resulted in decreased statistical confidence in detection of information-present pilot subjects.

To correct this, the authors used targets that were FBI-relevant acronyms (like the probes) in the blocks where stimuli were acronyms. The only difference between targets and probes was that the targets had been disclosed to the subjects immediately before the test. Subjects were instructed to push a different button for targets. With this algorithm, targets were more similar to probes for FBI-knowledgeable subjects. Both were quickly recognizable as known acronyms. Both resulted in short-latency P300-MERMER responses. The probe-target correlations were higher, resulting in higher statistical confidence. (For non-FBI-knowledgeable subjects, all three types of stimuli were random letter strings, so using FBI-relevant targets made no difference in latency or correlations.)

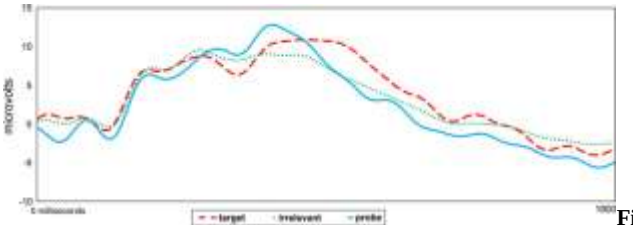

Fig. 6. FBI agent brain response to FBI-relevant acronyms. Brain response of an FBI agent to acronyms known to FBI agents and random letter sequences. There is a clear P300-MERMER in response to the known targets. The P300 is the positive voltage peak at the upper left. The P300-MERMER contains both the P300 peak and the late negative potential (LNP) at the lower right. There is no P300-MERMER in response to the irrelevants. The FBI agent's brain response to the FBI-relevant probes, like the target response, clearly contains a P300-MERMER. This shows that FBI agent knows the FBI-relevant acronyms. Note, however, that the response to the probes has a shorter latency than the response to the targets and irrelevants. This is because only probes, and not targets, were FBI-relevant acronyms. Subsequent research uses targets that are relevant to the investigated situation, like probes. Subjects are informed of the targets, but are not told which stimuli are probes.

Farwell and colleagues generalized the procedure of using situation-relevant targets in this and subsequent studies. Brain fingerprinting targets now consist of features of the crime or investigated situation, like probes. For a knowledgeable subject, this makes the targets more similar to the probes than targets that are not relevant to the investigated situation. The only difference is that targets have been disclosed to the subject, and the subject pushes a special button only for targets. This tends to increase the accuracy of the algorithm for classifying the probes as being more similar to targets for a knowledgeable subject.

Farwell conducted FBI Experiment 2, the "real-life FBI study," (Farwell and Smith 2001) at the FBI with Sharon Smith of the FBI Laboratory. Brain fingerprinting technology correctly detected whether or not subjects who were FBI agents had participated in specific, real-life events. All determinations were correct, with a high statistical confidence in every case.

Central Intelligence Agency (CIA) and US Navy studies

Farwell and colleagues' studies at the CIA and the US Navy (Farwell and Richardson 2006a, 2006b; Farwell et al. 2011) showed that brain fingerprinting could accurately and reliably detect individuals possessing information regarding both mock crimes and real-life activities, including some actual major crimes.

In CIA Experiment 1, the "picture study," (Farwell and Richardson 2006a) the information detected was relevant to a mock espionage scenario enacted by some of the subjects. The stimuli that elicited the brain responses

were relevant pictures presented on a computer screen. Fifteen subjects were correctly determined to be "information present," and 13 were correctly determined to be "information absent." An example of the stimuli was a picture of the subject's contact person in the mock espionage scenario.

CIA Experiment 2 was a collaboration between the CIA and the US Navy (Farwell and Richardson 2006b). In this experiment words and phrases relevant to knowledge of military medicine were presented on a computer screen, and subjects were determined to be "information present" or "information absent" with respect to knowledge of military medicine. Brain fingerprinting technology resulted in the correct determination in every case. Sixteen subjects were correctly classified as "information present," and 14 subjects were correctly classified as "information absent."

In CIA Experiment 3, the "real-life CIA study," (Farwell and Richardson 2006b; Farwell et al. 2011) the information detected was relevant to real-life events, including a number of felony crimes. This study used visually presented words and phrases as stimuli. Seventeen subjects were correctly classified as "information present," and three control subjects were correctly classified as "information absent." An example of the stimuli was the type of automatic pistol used in one of the crimes.

In the CIA and Navy studies there were no false negatives, no false positives, and no indeterminates. All determinations were correct, with a high statistical confidence in every case. Two separate analyses were conducted, one using the P300-MERMER and one using only the P300. Both analyses resulted in the same correct determinations. The analysis using the P300-MERMER produced a somewhat higher statistical confidence for some of the determinations than the analysis using only the P300 (Farwell et al. 2011).

In the three CIA and Navy experiments, the statistical confidence for the "information present" results was 99.9% for each of 44 of the 48 individual determinations. The lowest confidence for any ''information present'' determination was 98.8%, well above the 90% criterion for ''information present'' determinations. ''Information absent'' determinations for the real-life experiment were also at least 99.9% in every case. ''Information absent'' determinations for the Navy and picture studies were lower on average, but all met the criterion of 70% necessary for an ''information absent'' determination.

Other studies by Farwell and colleagues

Farwell and colleagues' more recent studies have focused on real-life/field applications. One study successfully detected knowledge of improvised explosive devices in bomb makers (Farwell 2009; Farwell et al. 2011).

In other field studies, Farwell and colleagues (Farwell 2008; Farwell et al. 2011) detected information regarding real crimes. To ensure that the brain fingerprinting tests potentially had a major, life-changing impact on subjects regardless of judicial consequences, they offered a $100,000 cash reward to any subject who could beat the test. They also taught subjects countermeasures that been effective in defeating alternative, non-brain fingerprinting tests (Mertens and Allen 2008; Rosenfeld et al. 2004). Brain fingerprinting correctly detected all subjects, with no false positives, no false negatives, and no indeterminates.

Summary of results of research and field applications by Farwell and colleagues

In over 200 test cases by Farwell and colleagues, brain fingerprinting resulted on no false positives and no false negatives. Accuracy rate for determinations made was 100%; error rate was 0%. Determinations made were "information present" or "information absent" with a criterion statistical confidence for each individual determination.

Since the introduction of the P300-MERMER in the data analysis algorithm, there have been no indeterminates.

In 3% of cases, all of them using the P300 alone prior to the discovery of the P300-MERMER, the data analysis algorithm returned a result that insufficient data were available to make a determination with a strong statistical confidence in either direction. No determination was made: the result was "indeterminate." All of the indeterminates were in one study (Farwell and Donchin 1991), wherein they comprised 12.5% or results.

For all brain fingerprinting studies by Farwell and colleagues, Grier A' (Grier 1971) values are 1.0.

Table 2 outlines the laboratory studies on brain fingerprinting testing conducted by Farwell and colleagues.

Table 3 outlines the field / real-life studies on brain fingerprinting testing conducted by Farwell and colleagues.

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Table 2. Brain fingerprinting laboratory studies by Farwell and colleagues

Study Authors (year)	Type of Information Detected	Type of Study	Number of Subjects	Accuracy Rate (%) [a]	Indeter-minates [b]
Bootstrapping Study Farwell and Donchin (1988b)	mock crime; bootstrapping analysis	specific issue	4	100	0
Mock Espionage Study "Experiment 1" Farwell and Donchin (1991); Farwell (1992a)	mock crime / espionage; word stimuli	specific issue	40	100	5
CIA Study 1 Farwell and Richardson (2006a)	mock espionage; picture stimuli	specific issue	29	100	0

[a] Percent correct in all cases wherein a determination was made.
[b] Number of cases where no determination was made. In all indeterminate cases, analysis was with P300 alone, not P300-MERMER.

Table 3. Brain fingerprinting field / real-life studies by Farwell and colleagues

Study Authors (year)	Type of Information Detected	Type of Study	Subjects	Accuracy Rate (%) [a]	Indeter-minates [b]
Crime detection Farwell & Donchin (1986)	real-life minor crimes	specific issue	8	100	0
Real-life "Experiment 2" Farwell & Donchin (1986; 1991); Farwell (1992a)	real-life minor crimes	specific issue	8	100	1
Occupation Study Farwell (1992b)	occupation-specific knowledge	specific screening	4	100	0
FBI Study 1 – FBI Agents Farwell & Richardson (2006b; Farwell et al. (2011)	FBI-relevant knowledge, FBI agents	specific screening	21	100	0
CIA/US Navy Study 2 Farwell & Richardson (2006b); Farwell et al. (2011)	expertise in military medicine	specific screening	30	10	0
CIA Study 3: Real-life CIA study Farwell & Richardson (2006b); Farwell et al. (2011)	real-life events (some crimes)	specific issue	20	10	0
FBI Study 2: Real-life Farwell and Smith (2001)	real-life events in FBI agents' lives	specific issue	6	10	0
Field Tests on Suspects Farwell & Richardson (2006b; Farwell et al. 2011)	information on crimes in brains of suspects	specific issue	7	100	0
Brain Fingerprinting in Counterterrorism Farwell (2009); Farwell et al. (2011)	bomb-making knowledge	specific screening	20	100	0
Real Crime $100,000 Reward Test Farwell (2008); Farwell et al. (2011)	knowledge of actual crimes; $100k reward for beating test	specific issue	8	100	0

[a] Percent correct in all cases wherein a determination was made.
[b] Number of cases where no determination was made. In all indeterminate cases, analysis was with P300 alone, not P300-MERMER.

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Replications of brain fingerprinting science in other, independent laboratories

Others who have followed similar or comparable scientific procedures to those of Farwell and colleagues have published similar accuracy results in the peer-reviewed literature. For example, Iacono and colleagues have published studies reporting similar procedures and similar results to those achieved by Farwell and colleagues.

Iacono and colleagues (Allen, Iacono, and Danielson 1992) used P300 event-related potentials to detect learned information in a three-stimulus experimental design similar to Farwell's technique. The authors achieved 94% accuracy in detecting learned material as learned, and 96% accuracy in identifying unknown material as unknown. Like Farwell and colleagues, the authors used an algorithm that included a method for arriving at one of two different determinations, a determination that the subject knew the information or a determination that the subject did not. Also like Farwell and colleagues, they computed a statistical confidence for whichever determination was achieved for each individual subject. The authors used a Bayesian algorithm for computing a determination and statistical confidence for each individual subject. Although the mathematical algorithm was not identical to the bootstrapping algorithm used by Farwell and colleagues, the results showed a relatively high level of accuracy.

In another study, they (Allen and Iacono 1997) replicated Farwell and colleagues' brain fingerprinting technique, and compared their Bayesian algorithm with the bootstrapping of the brain fingerprinting technique and with a simplified application of bootstrapping. The authors replicated the high accuracy of the brain fingerprinting technique. Like Farwell and colleagues, they reported no false positives using this method. They also found that increased motivation to beat the test increased the accuracy of Farwell's brain fingerprinting technique. This may be one of the reasons for the extremely high accuracy achieved by Farwell and colleagues using brain fingerprinting in field situations. The authors theorized that the basis of this difference was cognitive rather than emotional: that the difference resulted from increased cognitive salience of stimuli in the more motivated condition.

As reported in Iacono and colleagues' previous study (Allen et al. 1992) the Bayesian procedure achieved an accuracy rate nearly as high as that achieved by Farwell and colleagues using the brain fingerprinting technique, although unlike brain fingerprinting the Bayesian procedure returned some false positive/negative errors. The accuracy rate achieved by the authors using Farwell and colleagues' bootstrapping technique was comparable. The alternative, simplified bootstrapping procedure achieved a slightly lower accuracy rate.

Other experimenters detected concealed information with event-related brain potentials by applying methods that are in some ways similar to, and in some ways different from, brain fingerprinting. Some studies have used mock crimes or virtual mock crimes (Abootalebi, Moradi, and Khalilzadeh 2006; Hahm et al. 2009). Some have applied various other knowledge-imparting procedures (Gamer and Berti 2009; Lefebvre, Marchand, Smith, and Connolly 2007; 2009; Meijer, Smulders, Merckelbach, and Wolf 2007). Some have detected recognition of well-known personal information such as pictures of known individuals (Meijer et al. 2007; 2009). These studies have met some but not all of the brain fingerprinting scientific standards. Accuracy rates have in some cases been quite high. Accuracy has varied considerably based on the methods used.

A number of researchers in Japan (Hira and Furumitsu 2002; Miyake et al. 1993; Neshige et al. 1991) used a variety of procedures applying event-related brain potentials in the detection of concealed information. Results varied considerably according to the methods applied. Kakigi and colleagues (Neshige et al. 1991) achieved similar results to Farwell's CIA picture study (Farwell and Richardson 2006a).

All of these studies serve to further establish the validity, reliability, and general acceptance in the scientific community of the fundamental science on which brain fingerprinting is based.

A number of studies have been conducted attempting to detect simulated malingering relevant to brain injury and memory loss. These studies are not directly comparable to brain fingerprinting, and are not reviewed herein.

Limitations of brain fingerprinting

Is brain fingerprinting "100% accurate"?

As described in detail above, brain fingerprinting technique using the P300-MERMER has resulted in no false positives, no false negatives, and no indeterminates. All of the determinations have been correct. Overall including studies using the P300 alone, there have been 3% indeterminates. Whether using the P300 alone or the P300-MERMER, 100% of determinations in brain fingerprinting tests by Farwell and colleagues have been correct. Error rate to date has been 0%.

Does this mean that "brain fingerprinting is 100% accurate"? No. In science, there is no such thing as "100% accurate." There is always a margin of uncertainty, a margin of error. In reporting on a specific series of laboratory or real-life cases wherein there were no errors, however, it is correct to say (and incorrect not to say), "In these specific cases, brain fingerprinting testing produced 100% accurate results." This is simply a statement of the observed facts.

To state that "brain fingerprinting (or any science) is 100% accurate," without qualification or reference to a specific, existing data set, however, would never be correct. Such a statement contains an implicit prediction about the future. A technology that is "100% accurate" never makes an error, now or ever. There is no guarantee that any technology ever can meet that standard throughout all future applications. A technology may have produced 100% accurate results in a particular set of tests already completed, as brain fingerprinting has. Nevertheless, even a technology such as brain fingerprinting technology that has achieved this standard in the past cannot be characterized as "100% accurate" without qualification.

In short, neither brain fingerprinting nor any other science or technology can be unqualifiedly characterized as "100% accurate."

Limits to the applicability of brain fingerprinting testing

The brain of the perpetrator plays a prominent role in every crime. Perpetrators virtually always know of their participation in the crime, and often know the features of the crime in considerable detail.

Nevertheless, brain fingerprinting is not applicable in every case for every suspect. Probes must contain information that, in the judgment of the criminal investigators, was experienced by the perpetrator in the course of committing the crime. Probes must contain information that the subject claims not to know. Consequently, there are some circumstances where no probes can be developed for a particular crime for a particular subject. Obviously, in such cases a brain fingerprinting test cannot be conducted.

If the investigators have no idea what took place in the perpetration of a crime, for example, when a person simply disappears and foul play is suspected, they cannot develop any probes. No brain fingerprinting test can be conducted. A subject may claim that he was at the crime scene as a witness and not a perpetrator. In such a case, there would be no information that the subject claimed not to know. Thus there could be no probes, and a brain fingerprinting test could not be structured. Similarly, a brain fingerprinting test is not applicable when the subject knows absolutely everything about the crime that investigators know because he has been told this information after the crime. This may occur when a subject has already gone through a trial and has been convicted of the crime. If there is no information known to investigators that the subject claims not to know, there is no material for probe stimuli, and one cannot structure a brain fingerprinting test.

In some cases, however, such as the Terry Harrington case (Harrington v. State 2001), it is possible to find salient features of the crime to which the subject was never exposed in the trial or investigation, and which he claims not to know. Under these circumstances, a brain fingerprinting test can be conducted using these salient features of the crime as probe stimuli.

Brain fingerprinting and the limitations of human memory

Human memory is not perfect. It is affected by myriad factors, including mental and physical illness, trauma, injury, drugs, aging, passage of time, and many other well known factors.

The limitations on human memory already figure prominently in all judicial proceedings that include testimony by witnesses or suspects, whether they involve brain fingerprinting evidence or not. A witness, even if he is truthful, does not testify to the absolute truth. He testifies only to the contents of his memory.

To perform their evaluation of witness testimony adequately, judges and juries must already be aware of the well established limitations on human memory and take them into account. Judges and juries must apply these exact same considerations and standards when weighing brain fingerprinting evidence.

The argument that brain fingerprinting evidence should not be admitted or considered due to the limitations of human memory is without merit in any forum that admits witness testimony of any kind. Witness testimony constitutes a subjective report of the contents of memory. Brain fingerprinting constitutes objective, scientific evidence of the contents of memory. In any forum where subjective reports of the contents of memory are considered, objective evidence of the contents of human memory warrant at least the same treatment. For brain fingerprinting, witness testimony, and confessions, the well-known limitations of human memory go to the weight of the evidence, not to admissibility or applicability.

When the brain fingerprinting determination is "information present," the limitations of human memory play a minor role. Despite these limitations, the technology has shown that the suspect knows details about a crime that he has previously claimed not to know and has no reasonable explanation for knowing other than having participated in the crime.

With brain fingerprinting science, as with all science, negative findings must be interpreted with caution. When the brain fingerprinting determination is "information absent," then the judge and jury must take into account the limitations on human memory in the same way as they do when weighing witness testimony. Conducting a brain fingerprinting test on the alibi as well as the crime can help to minimize the possibility that the subject's lack of knowledge of the crime was due to a catastrophic memory failure. (Note, however, that an "information present" determination with respect to the alibi does not prove that the alibi is true, only that the subject's memory of the alibi is intact.)

The effect of the imperfections of human memory and perception on brain fingerprinting evidence is identical to the effect of these factors on the testimony of a witness.

The evidence provided by a brain fingerprinting test is limited to a specific determination as to whether certain information is stored in the subject's brain or not. (See above discussion of brain fingerprinting scientific standard 18.) The brain fingerprinting determination is "information present" or "information absent" with respect to the specific probe stimuli provided by the criminal investigators, which in the criminal investigators' judgment are salient features of the crime.

Neither brain fingerprinting science nor any other science tells us directly what took place at the crime scene, or whether a particular individual is guilty of a particular crime. Like DNA, fingerprints, and every other forensic science, brain fingerprinting science does not provide a determination of "guilty" or "innocent," or a determination that this suspect did or did not do specific actions. The value of brain fingerprinting science is that it can provide evidence that the triers of fact use in their decisions regarding what took place and who was involved. Brain fingerprinting science does not determine what the facts are, other than the one fact of presence or absence of specific information stored in a specific brain. Brain fingerprinting expert witnesses testify only to this fact and to the validity and reliability of the science that establishes this fact. They do not opine regarding whether or not the suspect committed the crime; this is to be decided by the judge and jury.

The role of brain fingerprinting science in judicial proceedings is to provide evidence that the judge and jury can utilize in reaching their verdict. This evidence must be considered along with all other available evidence. Like other evidence and witness testimony, it must be considered in light of the known limitations on human memory.

For a forensic scientist, the import of all discussions about human memory is simply the following: Draw scientific conclusions only regarding what the subject knows at the time of the brain fingerprinting test. This is one of the brain fingerprinting scientific standards discussed above (standard 18).

For the trier of fact, memory considerations can be summarized as follows. The contents of human memory are revealed subjectively (and not always truthfully) by witness testimony, and objectively by brain fingerprinting. In weighing the evidence and extrapolating from facts regarding the contents of human memory to facts regarding crimes or guilt, use common sense and take into account the well known limitations of human memory.

Countermeasures

Brain fingerprinting has proven to be highly resistant to countermeasures. No one has ever beaten a brain fingerprinting test with countermeasures. Farwell (2008; Farwell et al. 2011) tested countermeasures in a series of brain fingerprinting tests on actual crimes. In order to produce life-changing effects regardless of judicial outcomes, Farwell offered perpetrators of actual crimes a $100,000 cash reward for beating the brain fingerprinting test. The perpetrators were trained in countermeasures that had previously reduced the accuracy of other techniques, but not of brain fingerprinting (Rosenfeld et al. 2004; Mertens and Allen 2008). No one succeeded in beating the brain fingerprinting test. Brain fingerprinting accurately detected the crime-relevant knowledge in all such subjects, with no false positives, no false negatives, and no indeterminates.

Other countermeasure experiments (Sasaki, Hira, and Matsuda 2002) found a simple mental-task distraction countermeasure to be ineffective.

Rosenfeld et al. (2004) report several different countermeasure experiments and several different data analysis and statistical methods. In every case, they used fundamentally different subject instructions, subject tasks, statistics, data acquisition procedures, and methods (or lack thereof) for establishing ground truth

than those of brain fingerprinting. Their methods failed to meet 15 of the 20 brain fingerprinting scientific standards.

As a result of the fundamental differences between their methods and those of brain fingerprinting, Rosenfeld et al. did not achieve accuracy rates as high as the accuracy rates consistently achieved by brain fingerprinting. For some of Rosenfeld's methods in some studies, accuracy was as low as 54%, no better than chance. All of their methods are very different from brain fingerprinting. Even their one method that they correctly characterize as most similar to brain fingerprinting lacks some of the most essential features of brain fingerprinting methods. All of Rosenfeld's (2004) alternative, non-brain fingerprinting methods were found to be susceptible to countermeasures.

The countermeasure taught in Rosenfeld et al. (2004) was to perform covert actions such as wiggling the toe in response to each irrelevant stimulus. This was predicted to increase the P300 amplitude to irrelevants, thus lessening the difference between probe and irrelevant brainwave responses.

Some of the same subjects had slower reaction times to the stimuli. Reaction times, however, are easily manipulated and therefore not suitable for detection in real-life situations with real consequences.

Rosenfeld et al. (2008) conducted a second series of studies that showed that their non-brain fingerprinting "complex trial protocol" method is susceptible to countermeasures. Accuracy was 92% without countermeasures and 83% when subjects practiced Rosenfeld et al.'s (2004) countermeasure described above. As discussed below, the complex trial protocol has three fundamental characteristics that render it unusable in the field: high and variable error rates, failure to isolate the critical variable along with invalid statistics, and procedures that are ineffective when used with motivated subjects.

Another non-brain fingerprinting study, Mertens and Allen (2008), found similar countermeasures to be effective against their procedure. As discussed below, that procedure failed to meet the brain fingerprinting scientific standards, resulting not only in susceptibility to countermeasures but also in very low accuracy even without countermeasures.

In discussing countermeasures, it is important to avoid over generalizing the susceptibility to countermeasures of non-brain fingerprinting techniques that fail to meet even the most essential of the brain fingerprinting standards. Some authors (e.g., Rosenfeld 2005, Rosenfeld et al. 2004, Mertens and Allen 2008) have mistakenly generalized the inaccuracy and susceptibility to countermeasures of the non-brain fingerprinting techniques they studied to apply to brain fingerprinting, whereas the actual data on studies that meet the brain fingerprinting scientific standards demonstrate definitively that this generalization does not apply. All available actual data have shown that although these other, non-brain fingerprinting techniques are inaccurate and susceptible to countermeasures, brain fingerprinting is highly accurate and highly resistant to countermeasures.

Criticisms of brain fingerprinting

Critics have advanced the following criticisms of brain fingerprinting.

1. Criticism: "Brain fingerprinting is inaccurate."

The relevant facts: Purported support for this criticism comes solely from citing the inaccuracy of non-brain fingerprinting studies that used alternative techniques and did not meet the brain fingerprinting scientific standards outlined above. All studies that have met these scientific standards have had extremely high accuracy. Brain fingerprinting has never produced a false positive or false negative error.

2. Criticism: "Brain fingerprinting could be used to detect knowledge that was acquired innocently."

The relevant facts: Any forensic science could be used to detect evidence that arose through innocent means. For example, a suspect may have left fingerprints at a crime scene innocently before the crime. Observing common sense, and specifically observing the brain fingerprinting standards summarized above, will ensure that innocently acquired information is eliminated in advance from the test (Farwell 1994; Iacono 2008). The standards require the experimenter to establish in advance that the probes contain only information that the subject has no known way of knowing, that the subject denies knowing, and that the subject states are not significant to him and are indistinguishable from the irrelevant stimuli.

This criticism does not apply to brain fingerprinting, but only to non-brain fingerprinting methods that fail to meet the brain fingerprinting scientific standards, particularly standards 4 and 7 - 10.

3. Criticism: "Brain fingerprinting detects the contents of human memory, and human memory is imperfect."

The relevant facts: Human memory is indeed imperfect. Brain fingerprinting is not the only evidence commonly admitted in court that depends on human memory,

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however. All witness testimony depends critically on human memory. In every trial involving witness testimony, judges and juries must already be aware of and take into account the limitations of human memory. Witness testimony constitutes a subjective report of the contents of human memory. Brain fingerprinting is an objective account of the contents of human memory. In both cases, the trier of fact must evaluate the facts in light of common sense, life experience, and the known limitations of human memory. Such considerations go the weight of the evidence, not to admissibility. This is discussed in more detail above in the section entitled "Brain fingerprinting and the limitations of human memory."

For a forensic scientist, the import of all discussions about human memory can be stated in its entirety in one sentence, as follows. Observe brain fingerprinting scientific standard # 18: draw scientific conclusions only regarding what the subject knows at the time of the brain fingerprinting test.

Critiques of human memory in the context of a discussion of brain fingerprinting (Allen 2008; Allen and Mertens 2009; Meegan 2008) amount to a criticism not of brain fingerprinting but rather of any non-brain fingerprinting technique that fails to follow brain fingerprinting scientific standard #18.

4. Criticism: "Brain fingerprinting is art not science, subjective not objective."

The relevant facts: There are three different processes involved in the application of brain fingerprinting science in a judicial case. These are 1) the investigation that precedes the science; 2) the objective, scientific procedure of brain fingerprinting; and 3) the legal interpretation that may follow later.

Before a brain fingerprinting test, a criminal investigator investigates the crime. He formulates an account of the features of the crime. These are the probe stimuli to be tested (and the targets). This criminal investigation is outside the realm of science. This process is based on the skill, expertise, and subjective judgment of the criminal investigator. The criminal investigator provides the scientist with the probe stimuli that in the criminal investigator's judgment represent the actual events at the time of the crime.

The scientist applies the scientific procedure of brain fingerprinting to determine objectively whether or not the subject knows the crime-relevant information contained in the probes. Brain fingerprinting determines only the presence or absence of this information stored in the subject's brain. The brain fingerprinting scientist opines only on the presence or absence in the subject's brain of the specific knowledge embodied in the probes that were provided by the criminal investigator. Here the science ends. The science and the scientist do not address the question of whether the results are probative of the subject's guilt or innocence. The science does not even address whether the probes provided by the investigator have anything to do with the crime, or whether a crime took place.

The judge and/or jury weigh the brain fingerprinting evidence along with other evidence to reach a non-scientific, common-sense judgment regarding the suspect's participation in the crime. This process is outside the realm of science. They may reach a legal determination of guilty or not guilty. The role of the scientifically produced brain fingerprinting evidence is only to inform the trier of fact, not to render a scientific conclusion regarding guilt or innocence.

In short, brain fingerprinting is an objective, scientific process that is preceded by a process outside the realm of science and followed by another process outside the realm of science.

Criticisms of brain fingerprinting as being unscientific result from mistakenly lumping brain fingerprinting with the preceding and/or subsequent non-scientific processes. In effect, all such criticisms amount to a criticism not of brain fingerprinting but of any non-brain fingerprinting technique that fails to observe brain fingerprinting scientific standards, particularly standards 4 and 18.

5. Criticism: "Brain fingerprinting does not prove that a subject is innocent or guilty, and it would go beyond the science for a brain fingerprinting expert to opine on the guilt or innocence of a subject based on test results."

The relevant facts: This is a limitation that brain fingerprinting shares with all other forensic sciences. As described with reference to the preceding criticism, brain fingerprinting accurately and objectively detects whether certain specific information is or is not stored in a subject's brain. Brain fingerprinting standard procedures do not allow a brain fingerprinting expert to draw any conclusions beyond the presence or absence of specific information stored in the brain. It is up to the court to weigh the probative value of these scientifically established findings (Erickson 2007; Harrington v. State 2001; Iacono 2008; Roberts 2007).

DNA, fingerprints, and all other forensic sciences also do not prove a subject guilty or innocent. Like brain fingerprinting experts, experts in these other forensic sciences testify only to what the science actually shows.

For example, an expert may testify that DNA putatively from the crime scene matches DNA putatively from the subject.

As discussed above, it is up to the judge and jury, not the scientist, to decide if brain fingerprinting evidence, taken along with all the other evidence, warrants a legal determination of guilty or not.

This criticism amounts to a criticism not of brain fingerprinting but rather of any non-brain fingerprinting technique that fails to observe brain fingerprinting scientific standard 18.

6. Criticism: "Brain fingerprinting is subject to countermeasures."

The relevant facts: All evidence cited in support of this contention arises solely from research showing only that non-brain fingerprinting studies that did not meet the scientific standards for brain fingerprinting were susceptible to countermeasures. The one study cited as evidence for this contention (Rosenfeld et al. 2004) purported to be a replication of Farwell and Donchin (1991), but in fact failed to meet over half of the brain fingerprinting standards that were met in the original Farwell and Donchin brain fingerprinting research and all other brain fingerprinting research.

Farwell (Farwell and Richardson 2006b) offered a $100,000 reward to any subject who could beat a brain fingerprinting field test using the countermeasures that proved effective against non-brain fingerprinting tests. Brain fingerprinting correctly detected all subjects practicing countermeasures. This is discussed in more detail above in the section entitled "Countermeasures."

7. Criticism: A brain fingerprinting test requires that the investigators have specific information regarding the features of the investigated situation. Therefore it is not applicable for general screening when the investigators have no idea what undesirable activities the subject may have undertaken.

The relevant facts: This is a limitation that brain fingerprinting shares with other evidentiary forensic sciences. To use evidence to connect a suspect to a crime, there must be evidence of the crime. Brain fingerprinting is indeed inapplicable for general screening purposes such as pre-employment screening wherein the investigators have no knowledge of what information they are seeking. Brain fingerprinting can be applied, however, in specific or focused screening for a specific type of knowledge. For example, brain fingerprinting has been successfully used to detect knowledge unique to FBI agents, to US Navy military medical experts, and to bomb experts (Farwell and Richardson 2006b, Farwell 2009; Farwell et al. 2011).

8. Criticism: A 2001 report by the US General Accounting Office (GAO) quoted representatives of several federal agencies as stating that they did not see a role for brain fingerprinting in their current operations at that time.

The relevant facts: The GAO report was entitled "Federal Agency Views on the Potential Application of 'Brain Fingerprinting.'" It was essentially a sampling of opinions of individuals associated with the polygraphy in the federal government prior to 9-11. (It was completed before 9-11-2001 and issued shortly thereafter.) It reported that most such individuals did not see the need for brain fingerprinting in their pre-9-11 operations over a decade ago. The report stated:

> Officials representing CIA, DOD, Secret Service, and FBI do not foresee using the brain fingerprinting technique for their operations because of its limited application. For example, CIA and DOD officials indicated that their counterintelligence operations and criminal investigations do not usually lend themselves to a technique such as brain fingerprinting because use of the technique requires a unique level of detail and information that would be known only to the perpetrator and the investigators. These officials indicated that they need a tool to screen current and prospective employees, which as indicated above, involves questioning a subject about events unknown to the investigator. Further, a Secret Service official indicated that the agency has had a high success rate with the polygraph as an interrogative and screening tool and therefore saw limited use for brain fingerprinting.

The report noted, however, that the only two US government scientists interviewed who had conducted research on brain fingerprinting both were convinced that it would be useful in FBI investigations.

The report did not include an account of the peer-reviewed scientific research on brain fingerprinting or its successful use as scientific evidence in court. The report did not discuss the value of brain fingerprinting for other applications other than general screening, for which it does not apply as discussed above. The GAO did not evaluate or opine on the effectiveness, accuracy, or validity of brain fingerprinting. The report stated:

> …we did not independently assess the hardware, software, or other components of the technology

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nor did we attempt to determine independently whether brain fingerprinting is a valid technique.

The report concluded that a number of federal officials did not see an immediate application for brain fingerprinting in their general screening operations before 9-11. The report constituted a reasonably accurate opinion poll of federal employees associated with the polygraph a decade ago, before the 9-11 terrorist attacks. This is not relevant to the validity, value, accuracy, or current applicability of brain fingerprinting.

Consequently Senator Grassley, who commissioned the original GAO report, has asked the GAO to develop a new report. He asked the GAO to discuss the potential applications of brain fingerprinting in criminal investigations and counterterrorism in the post-9-11 world. He also asked the GAO to include the views of experts well versed in brain fingerprinting and MERMER technology, and to include the successful brain fingerprinting research at the FBI, CIA, and US Navy. The new report is currently being prepared.

Non-brain fingerprinting research on brainwave-based concealed information tests

Common errors in research on brainwave-based concealed information tests

The seminal papers on brain fingerprinting, Farwell and Donchin (1991), Farwell (1992a; 1994; 1995a; 1995b), and Farwell and Smith (2001) described the scientific standards for brain fingerprinting outlined herein. By meeting these standards, the authors achieved error rates of less than 1% in every study. In our view, this is the level of accuracy that is required for field use. Subsequent experimenters whose research met the brain fingerprinting standards, such as the replication of Farwell and Donchin's (1991) seminal brain fingerprinting research by Iacono and colleagues (e.g., Allen and Iacono, 1997), achieved similar accuracy levels to those of brain fingerprinting.

Virtually all subsequent researchers adopted some of the original experimental design introduced in the original brain fingerprinting studies. Many of the subsequent experimenters, however, did not follow the scientific standards for brain fingerprinting, and consequently did not achieve results comparable to those of brain fingerprinting. Methods that failed to meet the brain fingerprinting standards have generally produced error rates at least ten times higher than the error rates necessary for field use – error rates of over 10%, and in some cases as high as 50%, no better than chance.

In their seminal research and publications on the subject, Farwell and Donchin (1986; 1991) made it clear that brain fingerprinting detects information, not lies, guilt, or actions. Unfortunately, some commentators and even some subsequent researchers have mistakenly considered brain fingerprinting to be a method to detect lies, guilt, or past actions, rather than information stored in the brain. Many errors by subsequent commentators and researchers have resulted from this fundamental misunderstanding. Most of the criticisms of brain fingerprinting (see above) have arisen from the mistaken understanding that brain fingerprinting is supposed to detect truthfulness/lies or past actions, rather than information stored in the brain.

The following is a summary of the most common errors and the errors that have produced the greatest decrements in accuracy or validity.

A. Failure to recognize that brain fingerprinting detects only the presence or absence of certain specific knowledge stored in the brain. This fundamental misunderstanding or misrepresentation of what is detected by the brainwave measurements is expressed in several ways: Failure to distinguish between what the experimenter knows, or thinks the subject should know, and what the subject actually knows; confounding the knowledge-imparting procedure with the knowledge-detection procedure; failure to establish ground truth; failure to distinguish between subject's actions and knowledge; drawing conclusions that are not warranted by the data, such as that the subject is "innocent" or "guilty," rather than that the subject does or does not possess the specific knowledge tested. (Brain Fingerprinting standards 18 and 19. This error is often combined with failure to meet other standards, particularly 4, 7, 8, and 9.)

In several studies that reported low accuracy rates, for example, Rosenfeld, Shue, and Singer (2007), the experimenters confounded the knowledge-imparting procedure with the knowledge-detection procedure. This study failed to meet 13 of the 20 brain fingerprinting standards, numbers 4, 5, 7, 8, 9, 10, 12, 13, 14, 15, 17, 18, and 19. This resulted in failure to establish valid ground truth, failure to distinguish between knowledge and actions, and unwarranted conclusions. The result was very low accuracy rates, ranging from 33% to 62% in different conditions and averaging 51% (no better than chance) overall.

The experimenters implemented a knowledge-imparting procedure consisting of a mock crime. They tested the subjects on probe stimuli that the *experimenter* (but not necessarily the subject) knew were associated with the

mock crime. They did not conduct post-test interviews to determine whether or not the knowledge-imparting procedure had been effective in imparting the relevant knowledge to the subjects.

They interpreted the lack of a large P300 to the probes to indicate that the test had failed to detect information possessed by the subjects. This result may, however, have been simply a failure of the knowledge-imparting procedure to impart the relevant knowledge. No knowledge-detection procedure, no matter how perfect, can detect knowledge that the subject does not have. The knowledge-detection procedure may have correctly detected that the subjects lacked the relevant knowledge, because the knowledge-imparting procedure had failed to impart it.

Since ground truth was unknown, true accuracy was unknown. Confounding the knowledge-imparting procedure with the knowledge-detection procedure produces results that cannot be meaningfully interpreted.

One study that obtained very low accuracy rates, Mertens et al. (2003), combined this fundamental error with several other errors. This study failed to meet 10 of the 20 Brain Fingerprinting standards, numbers 4, 5, 8, 9, 10, 11, 12, 13, 18, and 19.

B. Confounding or confusing "lying" with knowing the relevant information. Instructing laboratory subjects to "lie" by pushing a specific button. (Brain Fingerprinting standard #12.) This is generally done in the laboratory without any real intent or attempt to deceive. Brain fingerprinting includes no such instruction. Subjects neither lie nor tell the truth in a brain fingerprinting test; they simply observe stimuli and push buttons as instructed.

One fundamental error that Rosenfeld and a number of other researchers have made is to instruct subjects to "lie" in response to probe items in a laboratory experiment (see Farwell 2011a; 2011b; 2012; Rosenfeld et al. 1987; 1988; 2004; Rosenfeld 2002). Recall that in brain fingerprinting the subject is instructed to press one button in response to targets, and another button in response to all other stimuli. Rosenfeld et al. also instructed their subjects to press one button for targets and another for all other stimuli. They told the subjects, however, that their instructed button presses meant "yes, I recognize the stimulus" and "no, I don't recognize the stimulus" respectively. They told the subjects they would be "lying" when they pressed the "no" button as instructed for probes.

Telling subjects to press a button and then telling them that pressing that button constitutes a lie, however, does not create a lie. The Rosenfeld studies and other similar laboratory studies involved no intent to deceive and no attempt to deceive. Subjects did not seriously intend to deceive the experimenter into believing they did not recognize well known information by simply pressing the "no" button as instructed by the same experimenter. The P300 obviously is not a lie response. If a large P300 in response to probes is interpreted as indicating a lie, then a large P300 to targets logically would indicate the same thing.

In one study Rosenfeld and colleagues (Verschuere, Rosenfeld, Winograd, Labkovksy, and Wiersema 2009) attempted to validate the procedure wherein subjects are told they will be "lying" when they press the instructed button in response to probes. The experimental instructions emphasized the salience of the probes in the "lie" condition, and not in the control condition. The large P300 to the probes in the "lie" condition was predictably produced by the experimental instructions emphasizing their salience, rather than by the act of pretending to lie. (The "lie" was pushing a "no" button as instructed in response to the subject's own name – clearly subjects did not actually intend to deceive the experimenter into believing they did not recognize their own name.)

Kubo and Nittono (2009) showed that enhanced P300s in "deception" conditions are caused not by a deception-specific process but by increased significance due to additional processing.

One reason that there is no "lie response" is that lying is not a unitary phenomenon. Many different cognitive and emotional processes can be involved in a lie. No one set of cognitive and emotional processes uniquely defines a lie. Instructing subjects to "lie" and interpreting a large P300-MERMER as being due in part to a "lie response" is contrary not only to brain fingerprinting standards but also to logic and common sense. Such a fiction unnecessarily confounds and complicates the phenomenon being measured and makes the interpretation of results problematic.

C. Failure to inform subjects of the significance of the probes and to describe the significance of the probes and targets that will appear in each block immediately before the block (brain fingerprinting standard 8).

Some experimenters failed to describe the significance of the probes in the context of the crime to the subjects.

The brainwave responses depend on the subject recognizing the significance of the probe stimuli in the context of the crime. Simply presenting "probe" stimuli that the *experimenter* interprets as being meaningful in

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the context of the crime is insufficient to ensure an appropriate brain response from the subject. For example, Rosenfeld et al. (2007) had subjects pretend to steal an item from a desk drawer lined with blue paper. Then they used "blue" as a probe, with no indication to the subjects why that might be significant. They failed to describe the significance of the probes in the context of the crime to the subjects, and also failed to determine ground truth through post-test interviews. The consequence of this and the dozen or so other errors common to all the Rosenfeld studies was detection rates that were extremely low (33% to 62%, averaging no better than chance) for this study (see Farwell 2011a; 2011b; 2012).

To ensure that a knowledgeable subject recognizes the probes as significant in the context of the investigated situation, the experimental instructions must explicitly inform the subject of this significance. Of course, the instructions must not inform the subject which is the probe and which are the similar irrelevants constituting incorrect details with the same possible significance.

Failure to follow this procedure tends to markedly decrease accuracy (Meijer, Smulders, and Wolf 2009).

D. Failure to run a sufficient number of trials for adequate signal-to-noise enhancement, or failure to apply adequate signal-processing and noise-reduction techniques such as digital filters and artifact detection algorithms (brain fingerprinting standard #13). This is a very common error.

All studies with extremely low accuracy rates have failed to meet this standard, including Mertens and Allen (2008), Mertens et al. (2003), Miyake et al. (1993), Rosenfeld et al. (2007), and some conditions of Rosenfeld et al. (2006) and Rosenfeld et al. (2004). (For discussion see also Roberts 2007). Each of these studies also failed to meet at least several other standards, as discussed above.

E. Teaching subjects "countermeasures" or instructions that transparently accentuate the probe stimuli, or that require the subject to read and attend to the probe stimuli when motivated subjects otherwise would not do so. (Rosenfeld et al. 1987; 2008 and subsequent "complex trial protocol" studies; see discussion below). Such "countermeasures" actually increase the salience of the probes and enhance the responses to the probes, making the test appear to be more effective and/or resistant to countermeasures. Motivated subjects who understand how the test works would not be coerced or tricked into following such instructions. (See Farwell, 2012 for a review.)

F. Failure to require an overt behavioral task that requires the subject to recognize and process every stimulus, specifically including the probe stimuli (brain fingerprinting standard 11). Studies that fail to meet this standard are unusable in the field, where there is no guarantee that the subject can be trusted to do what the experimenter would like him to do except insofar as required by overt actions.

Rosenfeld and colleagues have published several studies using a "complex trial protocol" that fails to meet this and other standards and consequently is unusable in the field (Meixner, Haynes, Winograd, Brown, and Rosenfeld 2009; Meixner and Rosenfeld 2010; Meixner and Rosenfeld in press; Rosenfeld and Labkovsky in press; Rosenfeld, Labkovsky, Lui, Winograd, Vandenboom, and Chedid 2008; Rosenfeld, Tang, Meixner, Winograd, and Labkovsky 2009; Winograd and Rosenfeld in press; for a review, see Farwell 2011a; 2011b; 2012). In addition, all of these studies failed to meet 17 of the 20 Brain Fingerprinting standards. This is further discussed below.

G. Failure to isolate the critical variable, generally combined with improper and invalid use of statistics. Failure to establish separate determinations and reasonable statistical confidence criteria for both information-present and information-absent results. Failure to include an indeterminate category. Classifying some results in a category where there is up to an 89% probability that the classification is an error. (Brain fingerprinting standards 4 – 7, 14, 15, and 17.)

This error and its consequences are illustrated by a series of experiments conducted by Rosenfeld and colleagues (see Farwell 2011a; 2011b; 2012; Lui and Rosenfeld 2008; Johnson and Rosenfeld 1992; Rosenfeld, Angell, Johnson, and Qian 1991; Rosenfeld, Biroschak, and Furedy 2006; Rosenfeld, Cantwell, Nasman, Wojdac, Ivanov, and Mazzeri 1988; Rosenfeld et al. 2004; Rosenfeld, Nasman, Whalen, Cantwell, and Mazzeri 1987). All of Rosenfeld and colleagues' studies failed to meet 12 to 17 of the 20 brain fingerprinting standards, including standards 14, 15, and 17 in every case (see Farwell 2011a; 2011b; 2012). Although they used some of the major features of the probe-target-irrelevant stimulus design introduced by Farwell and Donchin, their methods were significantly different (Farwell 2011a; 2011b; 2012; Farwell and Smith 2001; Rosenfeld 2002). Their subject instructions, subject tasks, data acquisition procedures, data analysis procedures, and even stimulus types all failed to meet the brain fingerprinting standards outlined above. They conducted a fundamentally different procedure from

brain fingerprinting, and not surprisingly obtained different and less accurate results. Their methods and results varied in their various attempts (see Farwell 2011a; 2011b; 2012). In some cases results were over 80% or 90% accurate (Johnson and Rosenfeld 1992; Lui and Rosenfeld 2008; Rosenfeld et al. 1991; 2004; 2006). In some cases Rosenfeld et al.'s results were no better than chance or less than chance (Rosenfeld et al. 2004; 2006; 2007). None of their techniques approached the requirement of less than 1% error rate across all studies and less than 5% error rate in every individual study that is necessary in our view for a technique to be viable for field use.

These studies generally failed to meet the same 14 brain fingerprinting scientific standards, 3 - 6, 8 - 10, 12 - 15, and 17 – 19. In some cases they also failed to meet additional standards. For example, in their first attempt Rosenfeld et al. (1987) also measured P300 from the wrong location on the head (standard #2) and did not require any overt responses (standard #11). They made their determinations on the basis of subjective judgment based on looking at the plots of the waveforms, and did not compute any statistics on individual subjects (standards 14 - 17) (see Bashore and Rapp 1993; Rosenfeld, 1995). Moreover, they included instructions to the subject to engage in covert behavior that introduced a confound that made results uninterpretable. In their second attempt Rosenfeld et al. (1988) corrected the confound and the scalp location, but repeated all of the other same errors.

In all of Rosenfeld et al.'s subsequent studies (e.g., Rosenfeld et al. 2004) they failed to isolate the critical variable, and failed to properly use the bootstrapping algorithm introduced by Farwell and Donchin (1988b; 1991). They ignored target responses, and simply attempted to determine if probe responses were "larger" than irrelevant responses. This resulted in invalid statistical procedures that classified subjects in a category where the statistics computed had determined that there was up to an 89% probability that the classification was incorrect. This is discussed below in reference to the "complex trial protocol," which combines this error with numerous others.

Failure to establish separate, reasonable criteria for both information-present and information-absent determinations virtually guarantees classification errors. This obviously reduces accuracy. It also makes results uninterpretable and difficult to compare to results obtained in studies that have used statistics properly and reasonably.

The "complex trial protocol" (Rosenfeld et al. 2008 and subsequent studies cited above) fails to isolate the critical variable; it lacks the necessary standard to do so. The statistical procedures based on (and necessitated by) this failure are not valid or viable for field use. In addition, it fails to meet 17 of the 20 brain fingerprinting scientific standards, specifically standards 3 – 6 and 8 – 20. It has not been used in the field or in any real-world situation with non-trivial consequences, and is not viable for such use. The following three fundamental characteristics make the complex trial protocol fundamentally unusable in the field (for details see Farwell 2011a; 2011b; 2012).

First, complex trial protocol published error rates are far too high for field use. In our view, to be viable for field use a technique must have false positive/negative error rates of less than 1% overall and less than 5% in each and every individual study. Complex trial protocol error rates in published studies average over ten times higher than these criteria. Even in highly contrived laboratory conditions with accommodating subjects and no real consequences to the outcome, published accuracy in some studies is as low as 53%, no better than chance. Error rates in all published studies average 15% without countermeasures and 29% with countermeasures.

Second, the complex trial protocol does not isolate the critical variable. It lacks a standard for an information-present response. Without a standard for comparison, it is impossible to compute valid and meaningful statistics. The statistics applied are invalid and result in extremely low statistical confidences, on average no better than chance for information-absent determinations. Targets are simply meaningless number strings. They are not comparable to probes and do not provide a standard for an information-present response. Data analysis ignores target responses, and simply seeks to determine whether the probe responses are "larger" than the irrelevant responses (with "larger" variously defined). Bootstrapping computes the probability that the probe responses are "larger" than the irrelevant responses[3]. It classifies subjects as information present (or "guilty") if this probability is 90% or greater, and otherwise classifies them as "innocent." Thus, the statistics applied classify subjects as "innocent" when there is up to an 89% probability that they are in fact "guilty," that

[3] Note that in brain fingerprinting, both targets and irrelevants provide standards. Bootstrapping computes the probability that the probe responses are more similar to the target responses, or more similar to the irrelevant responses. This results in high statistical confidences for both information-present and information-absent determinations.

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is, an 11% probability that the determination is correct. In published research subjects have been classified as "innocent" when the statistics used returned as high as an 86% probability that the opposite classification would be correct[4], or 14% probability that the classification returned by the procedure is correct. Moreover, in the published data, the average statistical confidence for an "innocent" classification is 50%, no better than a coin flip. This is in accord with the predictions of the statistical model used. This is a fundamental flaw in the statistical procedures, due to the lack of a standard for an information-present response, that cannot be corrected by simply changing the criterion. Setting a higher statistical confidence criterion for an "innocent" determination will simply increase the already unacceptably high error rate. (See Farwell 2011a; 2011b; 2012 for a detailed explanation.) For example, a criterion could be established that subjects are classified as "innocent" when there is a 50% or greater probability that the probe response is larger than the irrelevant response (that is, a higher than chance probability that this classification is correct). Applying this criterion to the actual reported data results in an error rate of 50% or more (less than chance accuracy) in the published studies. In other words, according to both published data and the predictions of the statistical model used, any criterion that results in greater than chance statistical confidence results in lower than chance accuracy. Obviously, the procedures that produce such low statistical confidences and high error rates are unsuitable for field use, where high statistical confidence is a necessity and errors have real consequences for life and freedom.

Third, on the stimulus presentations that are included in the data analysis (probes and irrelevants), the subjects are not required to distinguish behaviorally between stimulus types. They simply push a button indicating that something appeared in a general area on the screen. Probes/irrelevants occur at totally predictable times that are known to the subjects. Thus, subjects are not required to read and process probe and irrelevant stimuli and prove behaviorally that they have done so on each trial. Motivated subjects with something to hide do not read and process these stimuli, and consequently their brain responses do not reveal their concealed knowledge. The accuracy of the complex trial protocol in detecting real-world information in motivated subjects is 0% (Farwell, Richardson, and Richardson, 2011). A suggested means to coerce a subject into accommodatingly revealing her concealed knowledge (Rosenfeld et al. 2008) was to periodically ask the subject to recall what stimuli she had seen, and threaten to file a false report that the subject had "failed" the brainwave test if she did not recall the stimuli accurately. Such a report would be false, since in truth she had passed the brainwave test: her brain responses contained no evidence of any relevant knowledge. Clearly, this would be both unethical and ineffective in any real-world situation with motivated subjects and real consequences. Subjects could easily discern that neither their brain responses nor such a false report would provide any scientific evidence of their knowledge of the relevant information, and the false report would carry no weight in any real-world judicial proceeding.

This method differs from brain fingerprinting in several other ways. The complex trial protocol has never been independently replicated. It has never been applied in the field or in any real-world situation with non-trivial consequences. It has never been ruled admissible in court, and in light of the above it appears extremely unlikely that it ever will be in the future. In our view, any attempt to apply it in the real world would be scientifically, ethically, and legally untenable.

Reports in the popular press have sometimes mistakenly considered another method, the brain electrical oscillation system (BEOS) developed in India by Chanpadi Raman Mukundan, to be based on the author's original brain fingerprinting research. Unlike brain fingerprinting, however, it is not based on established scientific phenomena and published data. Like the complex trial protocol, it has not been independently replicated or published in the peer-reviewed literature. It purports to distinguish between knowledge gained while committing a crime and knowledge learned after the fact by an innocent person. No known mechanism or psychophysiological phenomenon has been proposed on the basis of which to make this distinction. Initially it was used in some criminal cases in India, but it later was ruled inadmissible in court there.

In addition to the complex trial protocol and the BEOS system, three studies, Miyake et al. (1993), Rosenfeld et al. (2004), and Mertens and Allen (2008) warrant particular mention in the context of scientific and methodological errors. This is because 1) the errors resulted in exceptionally low accuracy rates; and 2)

[4] For example, in Meixner et al. (2009, p. 215, Table 2, "innocent" subject 11) the subject was determined to be ''innocent'' when the computed probability was 85% that ''guilty'' was the correct determination (i.e., that the probe P300 was larger than the irrelevant P300, which is the definition of "guilty" in the "Iall" condition). Statistical confidence for this (correct) determination was 15%, far less than chance.

although the methods are fundamentally different from brain fingerprinting and fail to meet the brain fingerprinting standards, the studies have been mistakenly considered to reflect negatively on brain fingerprinting (Harrington v. State 2001; Rosenfeld 2005; Mertens and Allen 2008). In fact, the studies show only that these alternative, non-brain fingerprinting methods, which fall far short of the brain fingerprinting standards in fundamental ways, are inaccurate and susceptible to countermeasures.

A study in Japan by Miyake et al. (1993) failed to meet 18 of the 20 brain fingerprinting scientific standards (all but numbers 3 and 20). Moreover, the experimenters failed to implement data collection, artifact rejection, and data analysis procedures that meet the universal standards met by other laboratories in the field of event-related brain potential research. They measured responses from the wrong scalp location. These errors resulted in an exceptionally low accuracy rate. Only 65% of their determinations were correct.

In a study that has been mistakenly (Rosenfeld 2005, Mertens and Allen 2008) considered to be similar to brain fingerprinting, and even purported to be a replication of the original Farwell and Donchin brain fingerprinting research, Rosenfeld et al. (2004) failed to meet 15 of the 20 brain fingerprinting scientific standards, specifically numbers 3 - 6, 8 - 10, 12 – 15, and 17 - 20. They reported a variety of accuracy rates for different methods and analysis procedures. None of the accuracy rates were as high as the accuracy rates of brain fingerprinting, and some were as low as chance (54%) even without countermeasures (see Farwell 2011a; 2011b; 2012). This study also showed that Rosenfeld's techniques (but not brain fingerprinting) are susceptible to countermeasures.

In a third study that has been mistakenly considered to be similar to brain fingerprinting, Mertens and Allen (2008) failed to meet standards 8, 13, 18, and 19 and consequently achieved very low accuracy rates as well as susceptibility to countermeasures. They used valid statistical procedures and met several other standards that were not met by the Rosenfeld et al. (2004) and Miyake et al. (1993) studies. Nevertheless, failure to meet several vital scientific standards resulted in a major decrement in accuracy and also in susceptibility to countermeasures.

The above studies serve to demonstrate that meeting the scientific standards for brain fingerprinting research outlined herein is important in order to obtain valid, accurate, reliable, and interpretable results. Meeting certain standards is also necessary for establishing procedures that can be applied in field settings. These studies also highlight the fact that the proven inaccuracy and susceptibility to countermeasures of other, non-brain fingerprinting techniques does not imply that brain fingerprinting shares these same shortcomings.

Summary

The role of brain fingerprinting in forensic science is to bring within the realm of scientific scrutiny the record of a crime, terrorist act, terrorist training, specific crime- or terrorism-related knowledge or expertise, or other relevant information stored in the brain of a suspect or other person of interest, and to develop reliable forensic science evidence based on the accurate detection of such information.

Brain fingerprinting is a scientific technique to detect concealed information stored in the brain by measuring event-related potential (ERP) brainwave responses. Brain fingerprinting laboratory and field tests at the CIA, the FBI, the US Navy, and elsewhere have detected the presence or absence of information regarding the following:

- real-life events including felony crimes;
- real crimes with substantial consequences, including judicial outcomes such as the death penalty or life in prison;
- concealed information in real-world cases where subjects were offered a $100,000 reward for beating the test;
- knowledge unique to FBI agents;
- knowledge unique to explosives (EOD / IED) experts;
- knowledge unique to US Navy medical military personnel;
- pictorially represented knowledge;
- mock crimes and mock espionage scenarios;
- other laboratory tests and real-world applications.

Brain fingerprinting has been successfully applied in field settings, including actual criminal cases wherein the brain fingerprinting test was ruled admissible in court and/or contributed to bringing the perpetrator to justice or exonerating the innocent. Brain fingerprinting helped to bring a serial killer to justice and to exonerate an innocent man falsely convicted and imprisoned for murder.

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A brain fingerprinting test measures the subject's brain responses to specific information. The information is embodied in stimuli consisting of words, phrases, or pictures presented on a computer screen. Some of the stimuli are probe stimuli. Probes contain information that is relevant to the crime or situation under investigation and that the subject has no way of knowing outside of having participated in the crime. When the subject recognizes the relevant information contained in the probes as significant in the context of the crime, the brain emits an "Aha!" response. Brain fingerprinting measures and analyses the brainwaves and detects the corresponding P300-MERMER brain response.

Brain fingerprinting computes a determination of "information present" (the subject possesses the specific information tested) or "information absent" (he does not) for each individual subject. The brain fingerprinting bootstrapping algorithm also computes a statistical confidence for each individual determination.

In data analysis, responses to probes are compared with two standards. Target stimuli provide a standard for the subject's brain response to known crime-relevant information, information which is provided to all subjects. Irrelevant stimuli provide a standard for the subject's response to irrelevant information consisting of plausible but incorrect features of the crime. Data analysis determines whether the response to the probes is more similar to the response to the targets or to the response to the irrelevants, and provides a statistical confidence for this determination.

In our view, in order to be viable for field use, a technique must have less than 1% error rate overall, and less than 5% error rate in every individual study. Brain fingerprinting exceeds this standard. In over 200 cases including all field and laboratory research so far, brain fingerprinting has not produced a single error, neither a false negative nor a false positive. Error rate has been 0%. 100% of determinations have been correct. (Note, however, that this is simply a report of the actual data to date; no science can be generally characterized as "100% accurate" without qualification or reference to a specific data set.) In brain fingerprinting using the P300-MERMER, all tests have resulted in a definite determination with a high statistical confidence. There have been no indeterminates. In brain fingerprinting using the P300 alone, in less than 3% of cases, the data analysis algorithm has concluded that insufficient information is available to make a determination in either direction with a high statistical confidence, resulting in an indeterminate outcome (not an error).

Brain fingerprinting specific issue tests detect information regarding a specific event at a particular time and place, such as a crime or terrorist act. Brain fingerprinting specific screening tests detect a specific type of knowledge or expertise, such as knowledge unique to FBI agents, bomb makers, or Al-Qaeda-trained terrorists. Brain fingerprinting is not applicable for general screening, when the investigators have no idea what information is being sought.

Brain fingerprinting is highly resistant to countermeasures. Subjects have been taught the same countermeasures that have proven effective against other, non-brain fingerprinting techniques. Countermeasures had no effect on brain fingerprinting, despite the $100,000 reward offered for beating the test with countermeasures and the motivation to beat the test inherent in real-world applications. All subjects, whether practicing countermeasures or not, have been correctly detected.

The results of original research by the author and independent replications in other laboratories show that accuracy and validity can be reliably attained by following the established brain fingerprinting scientific standards outlined herein. Studies that have failed to meet the brain fingerprinting scientific standards show that such failure can result in low accuracy, susceptibility to countermeasures, and in some cases unreliable results and invalid procedures.

Studies in the original laboratory and independent replications elsewhere that meet the brain fingerprinting scientific standards consistently report extremely accurate results. Studies that fail to meet the brain fingerprinting standards, particularly certain critical standards, have resulted in inconsistent and lower accuracy rates, in some cases no better than chance. In some cases such failure also produced results that are uninterpretable and/or invalid. We have outlined herein the most common errors in brainwave-based concealed information tests, and the errors that have produced the greatest decrements in accuracy, reliability, and validity.

This paper reviews all relevant research previously published in English. In view of the published data, some caveats are necessary with respect to reliability, accuracy, practical usefulness in the field, and generalizations regarding results. The published results indicate that following the established brain fingerprinting scientific standards outlined herein is sufficient to ensure accurate, reliable, and valid results in laboratory studies and field applications. However, the available evidence does not support the notion that any attempt that fails to meet the established brain

fingerprinting scientific standards could be expected to obtain accurate, reliable, or valid results. Techniques that fail to meet at least the most essential of the brain fingerprinting scientific standards have generally produced error rates at least ten times higher than the error rates that in our view are necessary for viable field use. To be meaningful and practically useful, generalizations about brainwave-based concealed information tests must distinguish between the studies that meet the brain fingerprinting standards and those that fail to meet the standards. Generalizations that fail to recognize this distinction are inadequate to present a meaningful interpretation of the available data, and can result in drawing erroneous conclusions about brain fingerprinting that in fact apply only to non-brain fingerprinting tests that fail to meet the standards. For example, the low accuracy and susceptibility to countermeasures characteristic of several non-brain fingerprinting techniques has sometimes been erroneously generalized to apply to brain fingerprinting, whereas in fact the actual data directly contradict this generalization.

In addition to conducting the science according to established brain fingerprinting standards, it is also vitally important to restrict the interpretation of brain fingerprinting results to what the science actually shows. Brain fingerprinting detects the presence or absence of specific information stored in the brain. It does not detect guilt, lies, emotions, intentions, or any action, including participation in a crime.

Prior to a brain fingerprinting test, a criminal investigator develops his account of the crime, based not on science but on his skill and judgment as an investigator. He determines that, in his non-scientific judgment, information contained in specific probe stimuli is relevant to the crime.

The brain fingerprinting scientist tests scientifically whether or not this specific information is stored in a specific subject's brain. Scientific reports of brain fingerprinting results, and testimony by brain fingerprinting expert witnesses in court, must be confined to an explanation of the science and a report of what the science actually shows. The only legitimate scientific conclusion to be reported is that the brain fingerprinting evidence shows, with a particular statistical confidence, that the subject either does or does not know the information contained in the probe stimuli in the context of the crime. Any interpretation of the results in terms of the subject's guilt or innocence goes beyond the science and is outside the legitimate purview of testimony by a brain fingerprinting scientist. Brain fingerprinting scientists whose testimony on brain fingerprinting has been admitted as scientific evidence in court have adhered closely to this requirement.

As discussed herein, brain fingerprinting science does not evaluate whether the criminal investigator's account of the crime, and the probe stimuli included therein, accurately represent the crime, or whether the suspect committed the crime. Brain fingerprinting, and a brain fingerprinting scientist's testimony, do not address what the suspect *should know, could know*, or *would know* about a crime under what circumstances (e.g., if he is innocent or guilty). Brain fingerprinting only detects what the subject *actually does know* about the crime. It is up to the criminal investigator to come up with an account of the crime and the knowledge relevant thereto (the probe stimuli). It is up to the prosecuting and defense attorneys to debate, and the judge and jury to decide, what all the evidence, including the brain fingerprinting evidence, means with respect to what happened, whether a crime was committed, and if so what was the crime, who committed it, and who is guilty or not.

Brain fingerprinting is similar to other forensic sciences in this regard. DNA testing, for example, concludes only that Sample A (ostensibly from the crime scene) matches sample B (ostensibly from the subject). DNA science and DNA expert witnesses do not determine or opine on whether the subject is guilty of a murder. That is up to the judge and jury to decide based on all the evidence. Brain fingerprinting does not present a conclusion regarding the subject's guilt or innocence of the crime. Like other forensic sciences, it simply provides evidence that is useful for the judge and jury in their determinations regarding what took place and who is guilty or not.

In weighing the evidence and extrapolating from witness testimony and scientific evidence to the question of whether a suspect committed a crime, judges and juries must use common sense and take into account the well known limitations of human memory. This consideration applies equally to witness testimony, which is a subjective (and not always truthful) account of the contents of memory, and to brain fingerprinting, which provides an objective, scientific account of the contents of human memory. Such considerations are evaluated by the judge and jury on the basis of their common sense and life experience, and are outside the realm of the scientific testimony of a brain fingerprinting scientist.

The results of published laboratory research and field applications indicate that brain fingerprinting testing

consistently provides accurate, reliable, and valid scientific evidence in the detection of concealed information, provided that the science is conducted strictly according to the established brain fingerprinting scientific standards and interpreted according to these same standards such that the scientific interpretation stays strictly within the boundaries of what the science actually demonstrates. Brain fingerprinting evidence, when based on science so conducted and interpreted, has proven to be of value in real-world criminal justice and national security applications.

Brain fingerprinting has been successfully applied in real-world cases and ruled admissible as scientific evidence in court. Scientists in the United States currently continue to apply it successfully in the field. The results reviewed herein suggest that brain fingerprinting provides a new scientific method to accurately and reliably detect the presence or absence of concealed information that can generate useful forensic evidence in real-world applications in criminal justice and national security.

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References

Abootalebi, V, Moradi, MH, Khalilzadeh, MA (2006). A comparison of methods for ERP assessment in a P300-based GKT. International Journal of Psychophysiology 62(2), 309–320

Allen, J (2008). Not devoid of forensic potential, but... The American Journal of Bioethics 8(1), 27-28

Allen, J, Iacono, WG (1997) A comparison of methods for the analysis of event-related potentials in deception detection. Psychophysiology 34, 234 - 240.

Allen, J, Iacono, WG, Danielson, KD (1992). The identification of concealed memories using the event-related potential and implicit behavioral measures: a methodology for prediction in the face of individual differences. Psychophysiology 29, 504–522

Allen, JJ, Mertens, R (2009) Limitations to the detection of deception: true and false recollections are poorly distinguished using an event-related potential procedure. Social Neuroscience 4(6), 473-90

Başar-Eroglu C, Başar E, Demiralp T, Schürmann M (1992) P300-response: possible psychophysiological correlates in delta and theta frequency channels. A review. International Journal of Psychophysiology, 13, 2, 161-79.

Bashore, T, Rapp, P (1993) Are there alternatives to traditional polygraph procedures? Psychological Bulletin 113, 3-22

Baudena P, Halgren E, Heit G, Clarke JM (1995) Intracerebral potentials to rare target and distractor auditory and visual stimuli. III. Frontal cortex. Electroencephalogr Clin Neurophysiol 94:251–64.

Daubert v. Merrell Dow Pharmaceuticals, Inc. 509 U.S. 579, 594 (1993)

Donchin, E, Miller, GA, Farwell, LA (1986) The endogenous components of the event-related potential - a diagnostic tool? In: DF Swaab, E Fliers, M Mirmiran, WA Van Gool,, F Van Haaren (eds) Progress in Brain Research. Elsevier, Amsterdam, Vol. 70: Aging of the Brain and Alzheimer's Disease, p. 87-102

Donchin, E, Ritter, W, McCallum, WC (1978) Cognitive psychophysiology: the endogenous components of the ERP. In: E Callaway, P Teuting, and S Koslow (eds) Brain Event-related Potentials in Man, Academic Press, New York, p. 349 - 441

Erickson, M J (2007) Daubert's Bipolar Treatment of Scientific Expert Testimony -- From Frye's Polygraph to Farwell's Brain Fingerprinting. Drake Law Review 55, 763-812

Fabiani, M, Gratton, G, Karis, D, Donchin, E (1987) The definition, identification and reliability of measurement of the P300 component of the event-related brain potential. In: P K Ackles, JR Jennings, MGH Coles (eds) Advances in Psychophysiology, JAI Press, Greenwich, CT, Vol. 2, p. 1 - 78

Farwell, L A (1992a) The Brain-Wave Information Detection (BID) System: A New Paradigm for Psychophysiological Detection of Information. Doctoral Dissertation, University of Illinois at Urbana-Champaign p. 1-165

Farwell, L A (1992b) Two new twists on the truth detector: brain-wave detection of occupational information. Psychophysiology 29(s4A), S3

Farwell, LA (1994) Method and Apparatus for Multifaceted Electroencephalographic Response Analysis (MERA). U.S. Patent #5,363,858

Farwell, LA (1995a) Method and Apparatus for Truth Detection. U.S. Patent #5,406,956

Farwell, LA (1995b) Method for Electroencephalographic Information Detection. U.S. Patent #5,467,777

Farwell, LA (1999) How consciousness commands matter: The new scientific revolution and the evidence that anything is possible. Sunstar. Fairfield, IA

Farwell, LA (2008) Brain fingerprinting detects real crimes in the field despite one-hundred-thousand-dollar reward for beating it. Psychophysiology 45(s1), S1

Farwell, LA (2009) Brain fingerprinting in global security. Presented at the Global Security Challenge Security Summit, November 2009, London Business School, London, UK

Farwell, LA (2010) Method and Apparatus for Brain Fingerprinting, Measurement, Assessment and Analysis of Brain Function. U.S. Patent # 7,689,272

Farwell, LA (2011a) Brain fingerprinting: Corrections to Rosenfeld. *Scientific Review of Mental Health Practice*, *8*(2), 56-68. http://www.brainwavescience.com/Farwell_Brain_Fingerprinting_Corrections_to_Rosenfeld_Scientific_Review_of_Mental_Health_Practice.pdf

Farwell LA (2011b) Brain Fingerprinting: Comprehensive Corrections to Rosenfeld in Scientific Review of Mental Health Practice. http://www.brainwavescience.com/Scientific_Review_of_Mental_Health_Practice_Farwell_Corrections_to_Rosenfeld.pdf . Seattle: Excalibur Scientific Press.

Farwell, L.A. (2013). Lie Detection. In: Saukko P (ed) *Encyclopedia of Forensic Sciences, 2nd Edition.* Oxford: Elsevier.

Farwell, LA (2012). Brain Fingerprinting: A Tutorial Review of Laboratory Research and Field Applications. Seattle: Evergreen Press. Available at: http://www.brainwavescience.com/Farwell_Brain_Fingerprinting_Tutorial_Review

Farwell, LA, Donchin, E (1986) The "brain detector": P300 in the detection of deception. Psychophysiology 23(4), 434

Farwell, LA, Donchin, E (1988a) Talking off the top of your head: toward a mental prosthesis utilizing event-related brain potentials. Electroencephalography and Clinical Neurophysiology 70, 510-523

Farwell, LA, Donchin, E (1988b) Event-related brain potentials in interrogative polygraphy: analysis using bootstrapping. Psychophysiology 25(4), 445

Farwell, LA, Donchin, E (1991) The truth will out: interrogative polygraphy (‘‘lie detection’’) with event-related potentials. Psychophysiology 28(5), 531–547. http://www.Brainwavescience.com/Farwell_Donchin_1991_Psychophysiology_Brain_Fingerprinting_The_Truth_Will_Out.pdf

Farwell, LA Farwell, GW (1995) Quantum-mechanical processes and consciousness. *Bulletin of the American Physical Society, 40*, 2, 956-57.

Farwell, LA, Makeig, TH (2005) Farwell brain fingerprinting in the case of Harrington v. State. Open Court X [10]:3, 7-10 Indiana State Bar Assoc. Available at: http://www.brainwavescience.com/Farwell_Brain_Fingerprinting_in_Harrington_v_State

Farwell, LA, Martinerie, JM, Bashore, TR, Rapp, PE, Goddard, PH (1993) Optimal digital filters for long-latency components of the event-related brain potential. Psychophysiology 30(3), 306-315

Farwell, LA, Richardson, DC (2006a) Brain fingerprinting in laboratory conditions. Psychophysiology 43(s1), S37-S38

Farwell, LA, Richardson, DC (2006b) Brain fingerprinting in field conditions. Psychophysiology 43(s1), S38

Farwell L.A., Richardson D.C., Richardson G. (2011) Brain Fingerprinting Field Studies Comparing P300-MERMER and P300 ERPs in the Detection of Concealed Information. *Psychophysiology 48*: S95-96 (abstract). Available at: http://www.brainwavescience.com/Farwell_Richardson_Richardson_2011_Brain_Fingerprinting_Field_Studies_Comparing_P300MERMER_and_P300_in_the_Detection_of_Concealed_Information.pdf

Farwell LA, Richardson DC, Richardson GM (in press) Brain Fingerprinting Field Studies Comparing P300-MERMER and P300 Brainwave Responses in the Detection of Concealed Information.

http://www.brainwavescience.com/Farwell_Richardson_Richardson_Brain_Fingerprinting_Field_Studies_Comparing_P300-MERMER_and_P300_Brainwave_Responses_in_the_Detection_of_Concealed_Information

Evergreen Press.

Farwell, LA, Smith, SS (2001) Using brain MERMER testing to detect concealed knowledge despite efforts to conceal. Journal of Forensic Sciences 46(1),135-143. Available at: http://www.Brainwavescience.com/Farwell_Smith_Journal_of_Forensic_Sciences_Brain_Fingerprinting.pdf

Gaillard, AKW, Ritter, W (1983) Tutorials in Event-related Potential Research: Endogenous Components. North-Holland, Amsterdam

Gamer, M, Berti, S (2009) Task relevance and recognition of concealed information have different influences on electrodermal activity and event-related brain potentials. Psychophysiology 47(2), 355-364

Grier, JB (1971) Non-parametric indexes for sensitivity and bias: computing formulas. Psychology Bulletin 75, 424–429

Güntekin, B, Başar, E (2010) A new interpretation of P300 responses upon analysis of coherences. Cognitive Neurodynamics, 4, 2, 107-18.

Hahm, J, Ji, HK, Jeong, JY, Oh, DH, Kim, SH, Sim, KB, Lee, JH (2009) Detection of concealed information: combining a virtual mock crime with a P300-based Guilty Knowledge Test. Cyberpsychology and Behavior 12(3), 269-275

Halgren E, Baudena P, Clarke JM, Heit G, Liegois C, Chauvel P, et al. (1995) Intracerebral potentials to rare target and distractor auditory and visual stimuli. I. Superior temporal plane and parietal lobe. Electroencephalogr Clin Neurophysiol 94:191–220.

Halgren E, Marinkovic K, Chauvel P (1998). Generators of the late cognitive potentials in auditory and visual oddball tasks. Electroencephalogr Clin Neurophysiol 106:156–64.

Halgren E, Stapleton JM, Smith ME, Altafullah I (1986). Generators of the human scalp P3(s). In: Cracco RQ, Bodis-Wollner I, editors. Evoked potentials, frontiers of clinical neuroscience (vol. 3). New York: Alan R. Liss

Harrington v. State. Case No. PCCV 073247(Iowa District Court for Pottawattamie County, March 5 2001)

Harrington v. State. 659 N.W.2d 509 (Iowa 2003)

Werner Heisenberg, W (1958). Physics and Philosophy, the Revolution in Modern Science. New York: Harper

Hira, S, Furumitsu, I (2002) Polygraphic examinations in Japan: applications of the guilty knowledge test in forensic investigations. International Journal of Police Science and Management 4,16 -27

Huster RJ. Pantev C, Konrad C, Westerhausen R (2010). The role of the cingulate cortex as neural generator of the N200 and P300 in a tactile response inhibition task. Human Brain Mapping, 31, 8, 1260-1271

Iacono, W G (2007) Detection of deception. In: J Cacioppo, L Tassinary, G Berntson (eds) Handbook of Psychophysiology, Cambridge University Press, New York, p. 688-703

Iacono, WG (2008) The forensic application of "Brain Fingerprinting:" why scientists should encourage the use of P300 memory detection methods. The American Journal of Bioethics 8(1), 30-32

Iacono, WG, Lykken, DT (1997) The validity of the lie detector: two surveys of scientific opinion. Journal of Applied Psychology 82, 426–433

Iacono, W G, C J Patrick, CJ (2006) Polygraph ("lie detector") testing: current status and emerging trends. In: IB Weiner, AK Hess (eds) The Handbook of Forensic Psychology, Wiley, New York, p. 552–588

Johnson, R (1988) The amplitude of the P300 component of the event-related potential: review and synthesis. In: P Ackles, JR Jennings, MGH Coles (eds) Advances in Psychophysiology: A Research Annual, JAI Press, Greenwich, CT, Vol. 3, p. 69-137

Johnson, RJ (1989) Auditory and visual P300s in temporal lobectomy patients: evidence for modality-dependent generators. Psychophysiology, 26, 6, 633-50.

Johnson RJ (1993). On the neural generators of the P300 component of the event-related potential. Psychophysiology, 30, 1, 90-7

Johnson, MM, Rosenfeld, JP (1992) Oddball-evoked P300-based method of deception detection in the laboratory II: utilization of non-selective activation of relevant knowledge. International Journal of Psychophysiology 12(3), 289-306

Kiss I, Dashieff RM, LordeonP (1989) A parieto-occipital generator for P300: evidence from human intracranial recordings. The International Journal of Neuroscience, 49, 1-2

Kubo, K, Nittono, H (2009) The role of intention to conceal in the P300-based concealed information test. Applied Psychophysiology and Biofeedback 34(3), 227-235

Leaf v. Goodyear Tire & Rubber Co., 590 N.W.2d 525, 533 (Iowa 1999)

Lefebvre, CD, Marchand, Y, Smith, SM, Connolly, JF (2007) Determining eyewitness identification accuracy using event-related brain potentials (ERPs). Psychophysiology 44(6), 894–904

Lefebvre, CD, Marchand, Y, Smith, SM, Connolly, JF (2009) Use of event-related brain potentials (ERPs) to assess eyewitness accuracy and deception. International Journal of Psychophysiology 73(3), 218-225

Linden, D (2005). The P300: Where in the Brain Is It Produced and What Does It Tell Us? The Neuroscientist, 11, 6, 563-576

Li, Y, Hu, Y, Liu, T, Wu, D (2011) Dipole source analysis of auditory P300 response in depressive and anxiety disorders. Cognitive Neurodynamics, 5, 2, 221-229.

Long, J, Gu, Z, Li, Y, Yu, T, Li, F, Fu, M (Janua2011) Semi-supervised joint spatio-temporal feature selection for P300-based BCI speller. Cognitive Neurodynamics, 5, 4, 387-398.

Lui, M, Rosenfeld, JP (2008) Detection of deception about multiple, concealed, mock crime items, based on a spatial-temporal analysis of ERP amplitude and scalp distribution, Psychophysiology 45(5), 721-730

Lykken, DT (1959) The GSR in the detection of guilt. Journal of Applied Psychology 43, 385–388

Lykken, DT (1960) The validity of the guilty knowledge technique: the effects of faking. Journal of Applied Psychology 44, 258–262

Meegan, DV (2008) Neuroimaging techniques for memory detection: scientific, ethical and legal issues. The American Journal of Bioethics 8, 9-20

Meijer, EH, Smulders, FTY, Merckelbach, H L G J, Wolf, A G (2007) The P300 is sensitive to face recognition. International Journal of Psychophysiology 66(3), 231–237

Meijer, EH, Smulders, FTY, Wolf, A (2009) The contribution of mere recognition to the P300 effect in a concealed information test. Applied Psychophysiology and Biofeedback 34(3), 221-226

Meixner, JB, Haynes, A, Winograd, MR, Brown, J, Rosenfeld, PJ (2009) Assigned versus random, countermeasure-like responses in the p300 based complex trial protocol for detection of deception: task demand effects. Applied Psychophysiology and Biofeedback 34(3), 209-220

Meixner, JB, Rosenfeld, PJ (2010) Countermeasure mechanisms in a P300-based concealed information test. Psychophysiology 47(1), 57-65

Meixner, JB, Rosenfeld, PJ (in press) A mock terrorism application of the P300-based concealed information test, Psychophysiology

Mertens, R, Allen, J, Culp, N, Crawford, L (2003) The detection of deception using event-related potentials in a highly realistic mock crime scenario. Psychophysiology 40, S60

Mertens, R, Allen, JJB (2008) The role of psychophysiology in forensic assessments: deception detection, ERPs, and virtual reality mock crime scenarios. Psychophysiology 45(2), 286–298

Miller, GA, Bashore, TR, Farwell, LA, Donchin, E (1987) Research in Geriatric Psychophysiology. In: Schaie KW, Eisdorfer C (eds), Annual Review of Gerontology and Geriatrics, Springer, New York, Vol 7, 1-27

Miyake, Y, Mizutanti, M, Yamahura, T (1993) Event related potentials as an indicator of detecting information in field polygraph examinations. Polygraph 22, 131–149

Moenssens, AA, (2002) Brain Fingerprinting—Can It Be Used to Detect the Innocence of Persons Charged with a Crime? UMKC L. Rev. 70, 891-920

Murphy PR, Robertson IH, Balsters JH, O'Connell RG (2011) Pupillometry and P3 index the locus coeruleus–noradrenergic arousal function in humans. Psychophysiology, 48 1531–1542.

National Research Council (2003) The Polygraph and Lie Detection. National Academies Press, Washington, DC

Neshige, R, Kuroda, Y, Kakigi, R, Fujiyama, F, Matoba, R, Yarita, M, Luders, H, Shibasaki, H (1991) Event-related brain potentials as indicators of visual recognition and detection of criminals by their use. Forensic Science Int 51(1), 95-103

Nieuwenhuis S, Aston-Jones G, Cohen, JD (2005) Decision making, the P3, and the locus coeruleus--norepinephrine system. Psychological Bulletin, 131, 4, 510-532. .

Picton, TW (1988) Handbook of Electroencephalography and Clinical Neurophysiology: Human Event-related Potentials. Vol. 3, Elsevier, Amsterdam

Pineda, JA, Foote, SL, Neville, HJ (1989). Effects of locus coeruleus lesions on auditory, long-latency, event-

related potentials in monkey. Journal of Neuroscience, 9, 81–93.

Rapp, PE, Albano, AM, Schmah, TI, Farwell, LA (1993) Filtered noise can mimic low dimensional chaotic attractors. Physical Review E 47(4), 2289-2297

Roberts, A J (2007) Everything New Is Old Again: Brain Fingerprinting and Evidentiary Analogy. Yale J L, Tech 9, 234-270. Available at: http://www.brainwavescience.com/roberts-9-YJOLT-234.pdf

Rosenfeld, JP (1995) Alternative views of Bashore and Rapp's (1993) alternatives to traditional polygraphy: a critique. Psychological Bulletin 117(1),159-166

Rosenfeld, JP (2002) Event-related potentials in the detection of deception, malingering, and false memories. In: M Kleiner (ed) Handbook of Polygraph Testing, Academic Press, New York, p. 265–286

Rosenfeld, JP (2005) ''Brain fingerprinting:'' a critical analysis. Scientific Review of Mental Health Practice 4, 20–37

Rosenfeld, JP, Angell, A, Johnson, M, Qian, J (1991) An ERP-based, control-question lie detector analog: algorithms for discriminating effects within individuals' average waveforms. Psychophysiology 28, 319-335

Rosenfeld, JP, Biroschak, JR, Furedy, JJ (2006) P-300-based detection of concealed autobiographical versus incidentally acquired information target and non-target paradigms, International Journal of Psychophysiology 60(3), 251-259

Rosenfeld, JP, Cantwell, G, Nasman, VT, Wojdac, V, Ivanov, S, Mazzeri, L (1988) A modified, event-related potential-based guilty knowledge test. International Journal of Neuroscience 42,157–161

Rosenfeld, JP, Labkovsky, E (in press) New P300-based protocol to detect concealed information: Resistance to mental countermeasures against only half the irrelevant stimuli and a possible ERP indicator of countermeasures. Psychophysiology

Rosenfeld, JP, Labkovsky, E, Lui, MA, Winograd, M, Vandenboom, C, Chedid, K (2008) The Complex Trial Protocol (CTP): A new, countermeasure-resistant, accurate P300-based method for detection of concealed information. Psychophysiology 45, 906–919

Rosenfeld, JP, Nasman, VT, Whalen, R, Cantwell, B, Mazzeri, L (1987) Late vertex positivity in event-related potentials as a guilty knowledge indicator: a new method of lie detection. International Journal of Neuroscience 34, 125-129

Rosenfeld, JP, Shue, E, Singer, E (2007) Single versus multiple probe blocks of P300-based concealed information tests for autobiographical versus incidentally learned information. Biological Psychology 74, 396–404

Rosenfeld, JP, Soskins, M, Bosh, G, Ryan, A (2004) Simple effective countermeasures to P300-based tests of detection of concealed information. Psychophysiology 41(2), 205–219

Rosenfeld, JP, Tang, M, Meixner, JB, Winograd, M, Labkovsky, E (2009) The effects of asymmetric vs. symmetric probability of targets following probe and irrelevant stimuli in the complex trial protocol for detection of concealed information with P300. Physiology and Behavior 98(1-2), 10-16

Sabeti M, Moradi E, Katebi, S (2011) Analysis of neural sources of p300 event-related potential in normal and schizophrenic participants. Advances in Experimental Medicine and Biology, 696, 589-97.

Sasaki, M, Hira, H, Matsuda, T (2002) Effects of a mental countermeasure on the physiological detection of deception using P3. Studies in the Humanities and Sciences 42, 73–84

Slaughter v. State, No. PCD-2004-277 (Okla. Ct. of Crim. App., April 16 2004)

Smith ME, Halgren E, Sokolik M, Baudena P, Musolino A, Liegois-Chauvel C, et al. (1990) The intracranial topography of the P3 event-related potential elicited during auditory oddball. Electroencephalogr Clin Neurophysiol 76:235–48.

Sochurková D, Brázdil M, Jurák P, Rektor I (2006). P3 and ERD/ERS in a visual oddball paradigm: A depth EEG study from the mesial temporal structures. Journal of Psychophysiology, 20, 1, 32-39

Soskins, M, Rosenfeld, JP, Niendam, T (2001) The case for peak to peak measurement of P300 recorded at .3 Hz high pass filter settings in detection of deception. International Journal of Psychophysiology 40, 173–180

Spencer, KM, Dien, J, Donchin, E (2001) Spatiotemporal analysis of the late ERP responses to deviant stimuli. Psychophysiology 38, 343–358

Stapleton JM, Halgren E (1987). Endogenous potentials evoked in simple cognitive tasks: depth components and task correlates. Electroencephalogr Clin Neurophysiol 67:44–52.

Sutton, S, Braren, M, Zubin, J, John, ER (1965) Evoked potential correlates of stimulus uncertainty. Science 150, 1187–1188

Verschuere B, Ben-Shakhar G, Meijer E (2011) Memory Detection: Theory and Application of the Concealed Information Test. Cambridge: Cambridge University Press; 1 edition.

Verschuere, B, Rosenfeld, JP, Winograd, M, Labkovksy, E, Wiersema, JR (2009) The role of deception in P300 memory detection. Legal and Criminological Psychology 14(2), 253-262

Vrij, A (2008). Detecting lies and deceit: Pitfalls and Opportunities, 2nd Ed. Chichester, England: Wiley.

Wang C, Ulbert I, Schomer DL, Marinkovic K, Halgren E (2005) Responses of human anterior cingulate cortex microdomains to error detection, conflict monitoring, stimulus-response mapping, familiarity, and orienting. J Neurosci 25:604–13.

Wasserman, S, Bockenholt, U (1989) Bootstrapping: applications to psychophysiology. Psychophysiology 26, 208-221

Winograd, MR, Rosenfeld, P (in press) Mock crime application of the Complex Trial Protocol (CTP) P300-based concealed information test. Psychophysiology