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Program Title: Neurotechnology for Intelligence Analysts (NIA)

Join Capability Area: Battlespace Awareness

Background: DARPA neurotechnology poised to assist imagery analysts – Researchers in DARPA's Neurotechnology for Intelligence Analysts (NIA) program successfully completed Phase 1 experiments in April and May 2008. . These experiments demonstrated use of brain signals to help analysts increase search throughput, and support rapid target detection in overhead imagery. Using the brain-enabled triage search method, researchers were able to show at least a 600% increase in search throughput (measured in square kilometers per min) across multiple image analysts and target types.

Success: Continuing advancement in satellite technology has led to a significant increase in the amount of collected imagery to analyze. The current method, broad area search, is both time and labor intensive, resulting in a need for a substantial improvement over standard methods. One of the main goals of the current phase 2 NIA program is to apply the successful findings of phase 1, run in the researchers' laboratory settings, and apply them in the field.

To move toward an operational capability, researchers are currently integrating brain-assisted frameworks into standard imagery analysis platforms. In the recent tests, twelve DoD imagery analyst volunteers with varying levels of experience and expertise participated. Analysts performed a realistic manual search task as a controlled baseline as well as using the NIA platforms that have the analyst viewing rapid presentation (5-10/sec) of imagery chips while researchers recorded the analysts' brain activity. Testing was performed on imagery that ranged between 225-300 square kilometers and contained target sets consisting of Surface-to-Air Missile sites as well as urban helipads. Results indicate that independent of target density (total number of targets within the total image) analysts using the NIA platform outperformed standard search methods throughput by a minimum of 600%.

The NIA program has brought operational neuroscience into the realm of imagery analysis via advances in signal processing, human-computer interfaces, and groundbreaking neuroscience with the goal of providing new tools for warfighters in operational environments. As the current phase of the effort moves forward, researchers will begin to test increasingly complex imagery in a variety of modalities. Pilot experiments investigating differences associated with target complexity, computerized vision aiding (centering of potential targets to the users view), and alternative chip presentations are currently underway to further improve this innovative technology.

Year: 2008

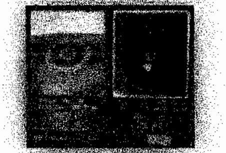
Sponsor: DARPA

# Neurotechnology for Intelligence Analysts (NIA)

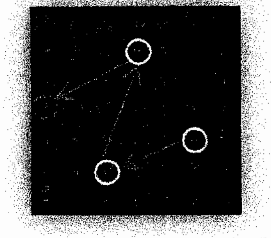
## Three teams participated in NIA Phase 2:

### Teledyne Scientific & Imaging, LLC

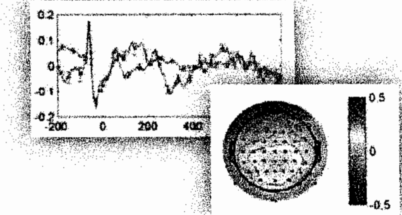
Teledyne's Phase 2 NIA system utilized an eye tracker that monitored the analyst's eye movements and gaze fixations during the viewing of imagery segments, presented at a rate of 1-2 sec./image.



The system was calibrated to individual users' brain activity by having each user search for "T"s. The resulting target-detection brain patterns were used to detect a variety of targets in multiple imagery types.



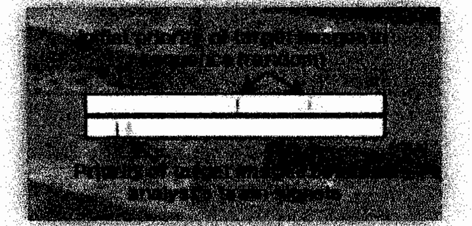
The analyst's EEG signals were time-locked to gaze fixations and used to determine probability of target detection.



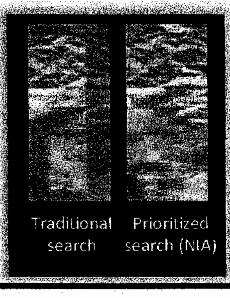
### Columbia University

Based on a set of known targets, Columbia's computer vision algorithms detected potential targets and centered imagery segments around each potential target.

As the analyst viewed rapidly presented image segments (5-10/sec.), the system identified probable targets based on the analyst's brain signals.

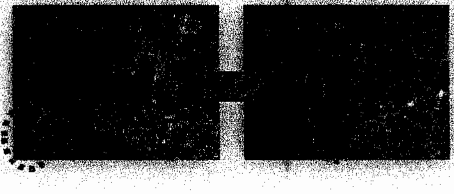


The system allowed the analyst to "jump" to regions of the imagery most likely to contain targets, based on the analyst's brain signals during previous viewing of the imagery segments.

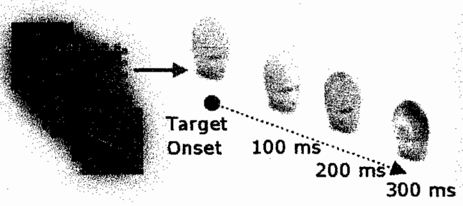


### Honeywell International, Inc.

Honeywell's Phase 2 NIA system included computer vision algorithms that automatically detected and centered potential targets within imagery segments.



The system identified targets by fusing data from the analyst's brain responses and button presses as the analyst viewed rapidly presented image segments (3-10/sec.).



Results were displayed as target probability maps overlaid on the imagery, which the analyst used to verify targets.

# Neurotechnology for Intelligence Analysts

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## ABSTRACT

Geospatial Intelligence Analysts are currently faced with an enormous volume of imagery, only a fraction of which can be processed or reviewed in a timely operational manner. Computer-based target detection efforts have failed to yield the speed, flexibility and accuracy of the human visual system. Rather than focus solely on artificial systems, we hypothesize that the human visual system is still the best target detection apparatus currently in use, and with the addition of neuroscience-based measurement capabilities it can surpass the throughput of the unaided human several-fold.

Using electroencephalography (EEG), Thorpe et al[1] described a fast signal in the brain associated with the early detection of targets in static imagery using a Rapid Serial Visual Presentation (RSVP) paradigm. This finding suggests that it may be possible to extract target detection signals from complex imagery in real time utilizing non-invasive neurophysiological assessment tools.

To transform this phenomenon into a capability for defense applications, the Defense Advanced Research Projects Agency (DARPA) currently is sponsoring an effort titled Neurotechnology for Intelligence Analysts (NIA). The vision of the NIA program is to revolutionize the way that analysts handle intelligence imagery, increasing both the throughput of imagery to the analyst and overall accuracy of the assessments.

Successful development of a neurobiologically-based image triage system will enable image analysts to train more effectively and process imagery with greater speed and precision.

**Keywords:** Neuroscience, satellite imagery, electroencephalography, near-infrared spectroscopy, independent component analysis, linear discriminant analysis, rapid serial visual presentation, classifier, change detection, expert

# 1. INTRODUCTION

The vision of the Neurotechnology for Intelligence Analysts program is to revolutionize the way in which imagery analysts (IAs) handle intelligence imagery, increasing both the throughput of imagery to the analyst and overall accuracy of the assessments. Advancing technologies now enable the collection and storage of enormous quantities of overhead imagery, a trend that promises to increase in coming years. However, the techniques for processing this information – fulfilling goals such as identifying objects in scenes, determining when changes have occurred, and marking or storing these findings in intuitive yet rapidly retrievable formats – have proven challenging. While computer vision strategies have been effective in limited contexts for automated target recognition and change detection, substantial investments from industry and government have not yet succeeded in developing technologies to keep pace with processing the increasing volume of images. This shortfall may be seen in both *triage*, the identification of images needing further analysis, as well as in *interpretation* of the significance of a scene. In the former case, consider a large geographical region surrounding a target of interest, captured in order to infer activity at the main target. In such a scenario, it is plausible that important information will be found in only a small minority of images. However, in the current operational environment, it is necessary for analysts to view an entire scene or 'deck' of images to ascertain the presence/absence of important content. This example illustrates the way in which a triage system – in the form of a tool that allows an analyst to rapidly scan many images for targets of interest – would provide a capability that streamlines one aspect of imagery analysis. The latter challenge – interpretation – suggests examples such as identification of large public gatherings. Understanding the significance of an assembly that could be either a peaceful cultural festival or a chaotic public protest in a foreign country requires the synthesis of target-specific knowledge with collateral data. While this latter task is not the specific focus of the NIA program, the current effort to create a triage capability will also facilitate interpretation by winnowing the pool of images which require additional analysis.

While technically complex, the tasks described above – in particular, rapidly identifying important objects – are ones which humans do readily and accurately numerous times each day. Humans are exceedingly effective at parsing a visual image, i.e., focusing rapidly on salient features while disregarding irrelevant ones. Modern neuroscience techniques have elucidated many of the anatomical and physiological properties which underlie this capability and the field of visual neuroscience has grown to include a wide array of experimental and analytical techniques bolstered by biologically-rigorous computational models which offer initial foundational conceptualizations for the accuracy and speed of human visual processing.

Recent research from the neuroscience community suggests that there are brain signals associated with target detection. Thorpe et al[1] described fast neural signals (150 ms) associated with the lack of a pre-defined target in complex, static natural scenes presented for 20 ms. Using electroencephalography (EEG) and Rapid Serial Visual Presentation (RSVP) -- an experimental technique which presents images briefly in quick succession -- this study demonstrated the concept that human brain activity can be used to identify targets in natural scenes. Thorpe's experiment used animals in their natural environments as targets, and pictures of forests, mountains, lakes, buildings, flowers and fruit as distractors. While this initial study was performed by averaging event-related potentials (ERPs) of numerous trials, Sajda et al[2] established the groundwork for an operational system by describing a method for detecting *single-trial* EEG signatures of natural scene target detection events. In these experiments, also using an RSVP paradigm, EEG signatures yielded both more accurate target detection results and were considerably faster than overt motor responses to the presence of targets.

Taken together, these and other converging neurophysiology, sensor and signal processing advances have given rise to the premise that the human visual system is a robust target detection apparatus whose signals may be harnessed for operational purposes. Nevertheless, the studies cited above were performed with carefully-circumscribed images of natural scenes and in the latter case included human figures, both of which may have privileged or unique status within the human visual system. Thus, in order to investigate the feasibility of transforming this phenomenon into a capability for the overhead imagery need cited above, the Defense Advanced Research Projects Agency (DARPA) is currently sponsoring an effort titled *Neurotechnology for Intelligence Analysts* (NIA). The ultimate goal of the NIA program is to utilize neural signals to improve the throughput and accuracy of overhead imagery analysis. To establish the neurophysiological framework, the program will initially focus on detecting and elucidating neural correlates of target detection in overhead imagery. In further phases, the program will expand the detection of neural signatures to other imagery types (such as streaming video) and to design and build a prototype image triage interface system which utilizes neuroscience principles in an operational environment.

## 2. TECHNICAL CHALLENGES

The technical challenges which the NIA program seeks to address range across a variety of disciplines. For this reason, teams with distinct yet complementary approaches are pursuing different aspects of the effort. Some of the key challenges and domains which will be the foci of different phases of the program include:

1. Neuroscience:
    a. Discovery and validation of neural signatures associated with target detection in overhead imagery.
    b. Determination of visual processing limitations for fast imagery viewing.
2. Hardware: Identifying the optimal sensor suite for neurosignal collection.
3. Signal Processing: Separation and classification of single trial evoked responses in real time.
4. Image Processing: Optimal imagery parameters for presentation to analysts.
5. System Integration: Recording neural signatures in an operational environment with minimally intrusive footprint/sensors.

## 3. DATA ACQUISITION APPROACHES

### 3.1 EEG

The EEG methods being implemented in the NIA program measure electrical fields at the surface of the scalp. EEG is often considered the first modern neuroimaging technology based on its initial description by Hans Berger in 1929.[3] While contemporary EEG relies on the same underlying phenomenon outlined by Berger – recording of electrical currents generated by ionic flow across neuronal membranes – modern methods have benefited greatly in recent years from miniaturized and increasingly-sensitive scalp-based detectors.

EEG data can be transformed into spectral plots (classically, by Fast Fourier Transform) with physiologically-significant correlates.[4] At the lowest frequencies, delta waves (0.5-4 Hz) are characteristic of slow-wave sleep. Theta waves (4-7 Hz) localized in medial frontal regions of the brain are correlated with focused attention, while global theta waves signify drowsiness. Some theta activity has also been correlated with pathological states. The alpha rhythm (8-12 Hz) is the prominent feature of spontaneous EEG and likely represents an idling thalamocortical state. Beta waves (14-21 Hz) generally are associated with alertness and being awake. Finally, the gamma range (25-50 Hz) -- particularly coherent activity of gamma oscillations[5] -- has been identified as a crucial component of sensory processing. Typical EEG recordings are comprised of a mix of these spectral bands. The relative intensity of each, as well as the location of their sources, are important factors in interpreting data. Shifts in the peak spectral power within these bands (calculated as the peak amplitude) may indicate cognitive shifts in load, focus, or processing strategy. As these properties indicate, EEG's major value is its high temporal resolution. However, given that tissues exterior to the brain are not electrically transparent, localization of EEG activity is intrinsically limited.

Examining the timecourse of individual trials is a crucial linchpin of the NIA strategy. The amplitude, polarity, and millisecond timing of the peaks reflect the neural basis of associated sensory or cognitive operations. Early peaks (< 100-200 ms) have been correlated with initial perceptual processing, while late peaks (> 200 ms) reflect higher-level conscious processing. For example, a feature known as P300, indicating a positive deflection in the EEG trace about 300 ms after stimulus presentation, is associated with conscious awareness of the stimulus, and is modulated by the intensity of attentional focus on the stimulus. Similarly, the N170 (negative deflection approximately 170 ms post-stimulus), has been correlated with expert (as opposed to novice) performance in a task.[6]

Since EEG signals are in the micro-volt range, they are sensitive to inductive interference, primarily from 60 Hz power lines. For optimal performance with standard electrodes and copper wires, it is preferable to perform the experiments in a shielded room. Newer EEG recording hardware has become available that amplifies the signal directly at the electrode thus minimizing inductive noise collected by conductive wires. This permits experiments to be performed outside of a shielded room while maintaining signal quality. Within the NIA program, a variety of EEG acquisition approaches are being explored. For example, these include high-density recording with as many as 256 electrodes, as well as wireless systems containing on-sensor signal processing. One advantage of increasing the spatial density of EEG data is that it enhances signal quality without the loss of temporal precision common to trial averaging in ERP studies.

### 3.2 Functional Near-Infrared Brain Imaging

In Functional Near-Infrared Brain Imaging (fNIR), an array of LED light sources is affixed to the subject's head, and near-infrared light capable of readily passing thought the skull is directed to the brain. Reflected light is then captured by silicon detectors. By assessing the differential absorption of light, inferences may be made concerning brain activation. Two primary phenomena may be measured with fNIRS: fast neuronal responses and slower hemodynamic responses. Activation of brain regions may be mapped with a spatial resolution of less than 1 cm, and temporal resolution in the millisecond range for fast neuronal responses and seconds for slower hemodynamic responses[7]. NIRS measurements are amenable to the goals of the NIA program and measurements of the fast neuronal response are being investigated for this application.

### 3.3 Pupillometry/Eye Tracking

Changes in pupil diameter have been correlated with a number of cognitive and sensory tasks. These may be measured by means of on- or off-head devices with high sampling rates, and are being explored in NIA as indications of underlying nervous system activity. In addition to their potential as signals intrinsically related to target detection, eye position, scan path and dwell time data recorded during a task can be used to provide clues to the ways in which subjects attempt to fulfill the task goals. Data of this type is highly useful for 'neuroergonomic' considerations such as optimal parameters for image size, viewing angle, and pre-processing of an image itself. The pupillometry approach is being employed in novel ways in the NIA program, both individually and in multi-modality approaches.

## 4. DATA ANALYSIS APPROACHES

Neuroimaging data has spatiotemporal properties which may be processed with a wide range of continually-evolving techniques. Within the NIA program, a number of different data analysis approaches are being explored to identify both the spatial and temporal properties of neural signals acquired using the methods outlined above. These approaches can be grouped into two categories, Localization and Spectral Analysis Strategies.

### 4.1 Localization

While temporal brain signals are obviously necessary to attain the goals of the NIA program, neural response time alone may not unequivocally indicate the presence of a target, as brain activity is an ongoing multi-spectral process in which the amplitude of numerous rhythms vary frequently. For this reason, identifying the spatial location of neural activity is a crucial step: by combining the temporal and spatial properties of a response, the NIA program is poised to create definitive spatiotemporal profiles of target-detection activity.

In the realm of neurolocalization, the classic challenge is that of an inverse problem, as there are theoretically an infinite number of current sources which could give rise to a field measured outside the head. To overcome this constraint, numerous experimental, analytical and computational strategies have been fielded.

To cite a few examples, some models use topographic approaches in which distribution of band-specific power is mapped to a surface based on the sensor configuration. Some implementations assume that there are multiple dipolar sources that maintain their position and orientation and vary their amplitude as a function of time. In this regime, dipoles can be fit by minimizing the least-square error residual over an entire response period. Alternatively, a current-source model may be computed *a priori*, with best-fit data solutions selected as the result.[8] This can be used for dipole methods or distributed current solutions. Another method used to infer the correct neuroanatomic source localization is fitting multiple dipoles over a recording epoch. Methods such as Independent Component Analysis (discussed later), which isolate signals arising from individual sources, enable multiple rounds of single dipole fitting, thus making the most of this approach.

Visualization of localized activity can also be accomplished in a variety of ways. Among the earliest approaches was that of Talairach and Tournoux, who created a scalable coordinate system which allows the comparison of data across subjects.[9] With the increasing availability of structural magnetic resonance imaging scans, data is now often presented on a three-dimensional reconstruction of the experimental subject's brain, transformed in some cases to the Talairach system.[10] Also, in recent years there have also been efforts to create canonical brain atlases based on MRI scans of large populations.[11] These provide aspects of comparability across subjects as well as relative anatomical accuracy.

### 4.2 Spectral Analysis Strategies

As noted above, the NIA program aims for rapid spatial and temporal analysis of tightly-constrained neural responses. Three computational strategies implemented in the NIA program to achieve that goal are independent component analysis, linear discriminant analysis and classifier-based methods.

### 4.2.1 Independent Component Analysis (ICA)

Independent component analysis (ICA) is a statistical technique which has been applied successfully to multichannel EEG and averaged event-related potential (ERP) data sets in both the spatial and temporal domains.[12] ICA is part of a class of computational methods designed for blind source-separation. While several underlying computational methods are currently in use, all are geared toward the same goal: separating N statistically independent inputs which have been mixed linearly in N output channels, without further knowledge about their distributions or dynamics. As an example, the InfoMax implementation of ICA decomposes signals via the maximization of mutual information in minimally- or non-Gaussian segments of the data. This creates a framework for both segregating artifactual sources which can contaminate brain imaging data as well as identifying independent features of the signal which are likely to correlate with distinct neural processes.[13]

### 4.2.2 Linear Discriminant Analysis (LDA)

Linear discriminant analysis (LDA) is a statistical approach for classifying samples of *unknown* classes, based on training samples with *known* classes. When applied to EEG, LDA is similar to ICA in that both presume that a Weight Matrix exists that will enable the linear transformation of the recorded data into useful information. One way in which LDA differs from ICA is that LDA does not attempt to recover the original signals. Instead, the goal of LDA is the discrimination of the spatially distributed recorded signals that are associated with different 'classes' of data (such as erroneous vs. error-free trials) Thus, LDA discriminates signals by using conventional logistic regression to identify the optimal spatial weight matrix for discriminating the data classes.

### 4.3 Data Classifiers

An additional signal processing approach being pursued within NIA is the use of feature-specific classifiers whose output can be used to characterize stimulus responses or even general operator state. For example, researchers in the NIA program have used support vector machines designed maximally separate EEG data points from single target and distractor trials of subjects viewing imagery.[14] Initial results suggest that supervised learning techniques may be capable of identifying features from a training data set which remain stable over multiple experiments and across individuals. This suggests the long-term possibility of a deployable triage system which can be used by multiple individuals on numerous occasions without significant subject-specific calibration.

## 5. COMPLEMENTARY RESEARCH

In addition to the acquisition and analysis methods outlined above, the NIA program also aims to account for two other fundamental aspects of target detection. First, target identification is often the underlying mechanism for detecting changes in multiple images of a given scene, so an understanding of the neural mechanisms of change detection is an important aspect of the neuroscience underlying NIA. In addition, there is well-supported evidence that novices and experts use spatiotemporally-distinct neural coding. If so, a NIA-derived triage capability is likely to be affected by the expertise of the analyst, and it is therefore imperative to consider novice and expert neural coding in the RSVP paradigm.

### 5.1 Change Detection

The comparison of a pair of images that have been collected from approximately the same georeferenced area, but at different times (e.g., before and after an event), is referred to as change detection. Under highly-controlled conditions of luminance, focus, co-registration etc., software algorithms can readily detect differences between images, though the inference of a change's *significance* is still largely a human endeavor. Nevertheless, in the absence of the constraints above, machine vision change detection algorithms are not comparable to the natural human ability to detect salient changes across images. Conversely, there is ERP evidence that attention is rapidly drawn to the novel object in an otherwise familiar display.[15]

Based on this need, one component of the NIA program is taking a novel approach to the neuroscience of change detection. This effort begins with existing software which allows the alignment and registration of two images of a particular scene (even those with different camera positions) for optimal comparison and analysis.[16] Furthermore, the software leverages the human visual system's acute sensitivity to motion by creating a synthetic movement in the changed areas between images. Against the backdrop of this interface, the combination of spatial and temporal ERP data, together with eye-tracking, will form an integrative experimental suite which is equipped to characterize the neural basis of change detection in the overhead imagery triage context.

### 5.2 The Role of Expertise in Image Triage

Imagery analysis is a highly-skilled endeavor which requires extensive training and experience until expert status is attained. Seen from a neuroscience perspective, this mandates that the unique properties of expert neurobiology must be considered as part of the NIA analysis. One neural signature – a negative EEG deflection 170 ms post-stimulus (known as the N170) – has been shown to be enhanced when subjects view objects in their domain of expertise.[6] However, previous research in this domain has largely been restricted to natural scenes or objects. Therefore, the NIA program has integrated an effort to investigate the possibility of distinct neural responses associated with expertise in overhead imagery analysis. Furthermore, beyond improved identification of targets, a related aspect of expert task execution is an understanding of the significance of an observation. NIA research will also investigate the possibility of response variability depending on the significance of changes in imagery.

## 6. FUTURE DIRECTIONS

In many realms of modern society, technological advances have created dramatic increases in data quantity which have led to the fundamental challenge of distinguishing salient from irrelevant or distracting information. Based partly on similar technologies, the field of neuroscience has begun to develop mathematically and biologically-precise models of brain function. This confluence is creating opportunities for a new field of *operational neuroscience* in which neurotechnology is applied to real-world environments. As described in this monograph, the field of satellite imagery analysis is beginning to implement this approach in DARPA's Neurotechnology for Intelligence Analysts program through the use of novel acquisition and analysis techniques. Ultimately, this effort will both serve the immediate needs of overhead imagery processing as well as present a model for other operational neuroscience implementations.

## 7. PUBLIC RELEASE

[Distribution Statement A]: This manuscript has been approved for public release; distribution unlimited.

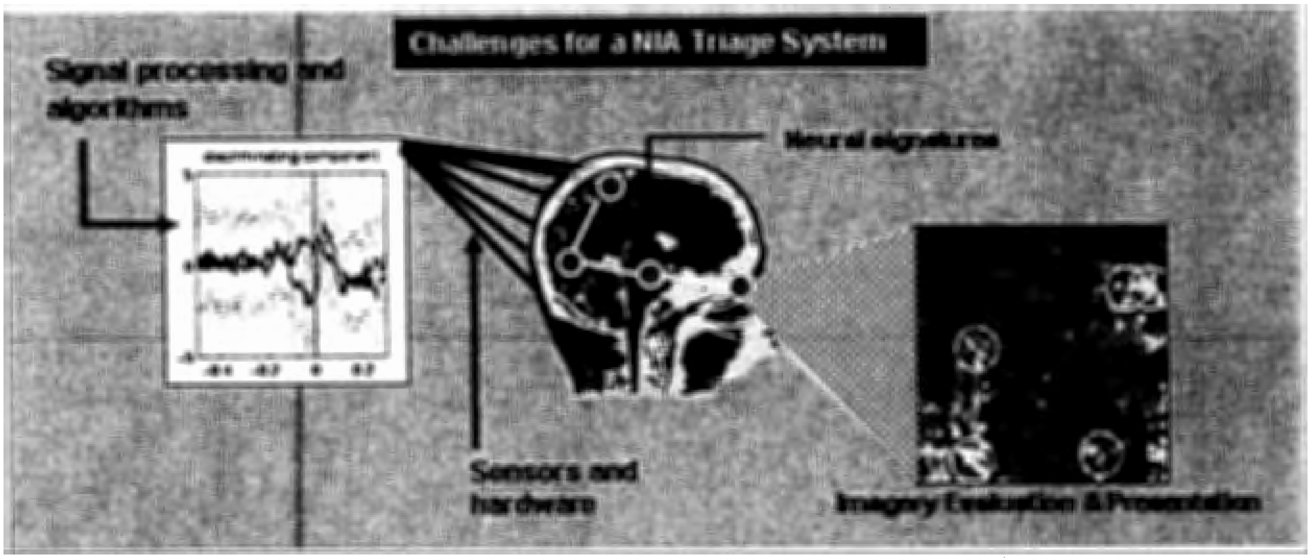

Figure 1. Challenges for a NIA Triage System. The capability for image triage being created in the NIA program will be based mechanisms for neuroergonomically optimal image presentation, hardware and sensors to record validated neural signatures, algorithms to extract these signals and overall system integration to create a deployable system.

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