Brain Activation Imaging in Emotional Decision Making and Mental Health: A Review—Part 2

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Abstract

In this report, we integrate the principles described in part 1 and describe an operational model for emotional decision making that incorporates brain activation data along with subjective experience correlates. This model takes the form of a state machine that carries out transitions between a finite set of 16 possible states of emotional and decision-making response. By considering a $4 \times 4$ grid of possible states based on left and right activation, in primary (sensation) and secondary (perception/comprehension) response, the range of responses is completely specified. The transition probabilities within this repertoire of possible response states can be used to characterize an individual (or any system) in terms of its likelihood to respond in a particular fashion. The possible value of this model in psychiatry, psychology, and counseling is introduced and discussed.

Keywords

EEG electromagnetic tomographic analysis, gamma asymmetry, response process validity, sLORETA, approach-avoidance, decision making, mental health, human performance

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Introduction

The Emotional Decision Model

Drawing from foundational models, our view of the possible brain states and responses to stimuli draws from concepts in combinatorics and group theory. One may view the emotional decision-making process as a state machine that consists of 16 possible states. State machines1 provide models for a system that can occupy a number of possible states and transition between those states based on input. The transition probability between states provides a model for the likelihood that an individual will respond in a particular manner. Figure 1 shows an example of a simple state machine that illustrates the concepts of inputs and resulting transitions applied in the present model.1

A healthy brain would contain certain strong likelihood transitions in the interest of safety and survival. For example, the response of fear and withdrawal when confronted by a bona fide threat would be a good transition to retain. Certain maladaptive transitions can be identified as well. For example, a chronic tendency to suspect and fear would reflect what is clinically identified as a paranoid or antisocial tendency.

This work is consistent with the concept of microstates reflecting momentary shifts in brain activity on the network level.2 These transitions identify shifts between different microstates. Studying transitions provides insights into the probability that a given output and state will follow, given the current state and the input, according to the rules and possibilities. In this work, we associate a particular set of activations in the brain with a defined state and look to identify and quantify brain states and transitions using selected parameters as indices.

In these models of sequential machines, the “output” is simply associated with a value, often one or zero, that indicates the result of the operation. In the current situation, the output of the system consists of a complex set of mental and physiological processes that produce the observable behaviors. And from an individual viewpoint, one’s own thoughts and feelings are observable to oneself, even if not to others. Physiologically, we are able to record and interpret, in addition to EEG signals, biological and other externally measurable phenomena that represent the output of the system. Such outputs therefore include feelings of positivity or negativity, judgments of correctness, relevance, possible value or possible danger, and decisions that can be directly monitored, such as choosing a number on a Likert-type scale or exhibiting simple approach or avoidance behaviors.

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A synthesis of literature and the application of the protocols described in part 1 of this article has resulted in the following emotional decision model. Based on these factors, the authors have chosen to focus on the medial frontal and the dorsolateral frontal areas. This includes primary emotional processing in Brodmann areas 9, 10, 11 and Brodmann areas 44, 45, and 46 as secondary combining with memory to produce perception and comprehension of emotions.

An analogy with the visual system will be helpful here. In a purely sensory system like the visual system, “primary” response refers to a sensory response that typically occurs within the first 150 ms after the presentation of the stimulus, and involves primarily Brodmann’s area 17, fed by afferents from the lateral geniculate nucleus of the thalamus. Likewise, in the visual system, “secondary” refers to the perceptual response that occurs with a longer latency, and involves Brodmann’s areas 18 and 19, which are fed by cortico-cortical projections mediating the successive stages of processing for higher levels of feature and meaning.

Thompson and Thompson³ identify 5 anatomically separate cortical–basal ganglia circuits, 2 of which are pertinent to this study. They are the “dorsolateral prefrontal” (DLPFC), focused on Brodmann’s area 44, and the orbitofrontal (OFC), centered at Brodmann’s area 11. The other 3 circuits being motor, oculomotor, and anterior cingulate. The presence of these 2 circuits lends support to the use of the associated Brodmann areas as a means to focus on their activity. They identify the DLPFC with specifically executive function related to working memory, solving complex problems, and planning, regulating actions, and shifting task gears when demanded. The OFC is identified with functions related to empathic and socially appropriate behavior and is able to “select objects and actions based on their subjective value.”³⁴

The ventromedial prefrontal cortex is associated with risk and fear and emotional decision making, owing to its connections with the amygdala. The ventrolateral prefrontal cortex is a critical foundational element of control, including inhibition and orientation, with multiple inputs serving the integrated function. This view “was articulated by Davidson and Begley⁴ who identified Brodmann’s areas 9 and 10 as primary emotional processing areas and Brodmann’s areas 44 and 45 as secondary emotional processing resources. While these areas were chosen for quantitative analysis in the work reported here, visual inspection of the resulting maps has consistently provided a validation of these principles.

While the visual analogy serves to illustrate the concepts of layered processing and a hierarchy of decision making, it is not absolute. In the visual system, primary and secondary processing is accompanied by a strict timing relationship, in that primary responses precede in time, and feed information to, secondary processing areas. In the case of frontal emotional processing, each region produces an ongoing response across time, whose content and subjective correlates reflect the primary emotional sensation (feeling a certain way), compared with the secondary emotional processing of emotional perception and even comprehension.

In the way that a circle or line has their primary sensory component, which is how they look, in broader context, the presence of a circle or line may signify something in addition, such as being an indicator of location, direction, state, and so on. In the same way that a sensory percept may be assigned further perceptual value (“valence”), a simple emotion may be assigned further perceptual value in the sense of being aware of

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**Figure 1.** Example of a simple state machine with inputs and transition table.
why the emotion is present, what it represents, what to do about it, and so on. These insights establish the theoretical underpinnings of this emotional decision-making model.

In this emotional processing model, primary emotional response is the emotional sensation that is mediated by Brodmann’s areas 9 and 10, while secondary emotional perception/comprehension is mediated by areas 44 and 45. It is important to note that these responses are not defined strictly based on time. The model does not propose that the primary response is the earliest, and that the secondary response necessarily follows it in time. Rather, both types of responses are continual, and the relative amount of activation across time determine the individual’s decision-making trajectory.

The emerging functional model reflects the processing in both left and right, as well as sensory and perceptual dimensions, is shown in Figure 2. This typical set of short-term frontal activation images are representative of the images used in this work. When the salient areas of the brain are masked off as shown in the second and third regions, the appearance of what is basically a coded version of the brain response becomes visually evident. This asymmetry model component has been discussed in detail, as well as its usefulness in showing maladaptive patterns in various mental health circumstances5) and summarized in Collura et al.6 In particular, the assignment of probabilities to the various decision-making steps provides a means of characterizing an individual in readiness to respond and to show which likely responses will lead to observed or internally perceived decisions and behaviors.

Employing the protocols of gamma asymmetry described in Bonnstetter et al,7 Figure 3 depicts the 4 corners of the model as sLORETA (standardized low-resolution brain electromagnetic tomography) images and how the upper left-hand corner with no activation can move through a continuum down to avoidance, across to approach or diagonally to full activation. Figure 3 is a simplified version of the model that provides an introduction to the 16-cell model by elaborating on the four extremes. The upper left corner shows low or no activation as represented by both right and left numeric zeros (0000). The upper right corner shows an initial primary Like (emotion) and a secondary judgment (Good) in the left hemisphere and no response in the right (0011). The lower left depicts an initial emotion of dislike and a judgment of bad as shown by the right hemisphere gamma response and the lack of left hemisphere reaction (1100). The lower right-hand corner depicts full activation (1111).

Given the presence of 16 possible states, we can immediately identify $16 \times 15 = 240$ possible transitions. Some of these would be relatively unlikely in normal circumstances, such as transitioning from a completely inactivated state to one of complete activation. The overall likelihood of various state transitions provides a set of parameters that can be quantified and is amenable to measure. The conditions and precursors to various state transitions can also be identified as shown in Figure 4 followed by a brief cell description and examples where appropriate.

As for categories or additional substates, any state that is a combination of any two states is automatically one of the 16 states, since they are inclusive as a closed set. For any state, adding the activation or deactivation of any component (“flipping a bit”) always defines one of the other possible states.
Transitions between states introduce another dimension to this analysis. To transition from one particular state to another is a specific process that has its own subjective qualities, and its unique statistical likelihood. Indeed, the likelihood of the transitions can serve to define the individual’s response patterns. This is illustrated in Figure 5, which shows that the combination of the current input and the current state leads to a set of probabilities of transition into other possible states.

The transitions from the current state are shown to depend on the current input and to lead to a set of probabilities of transitions to other possible states. These possibilities define the possible responses for the individual at that moment.

**Haidt’s Social Intuitive Model and Frontal Activation**

By combining the current $4 \times 4$ grid model with Haidt’s social intuitive model of human interaction, we can construct an interactive model. This demonstrates the responses of each individual to the other and maps each into each other in what is essentially a pair of decision-making devices operating interactively. The responses to a counselor, coworker, spouse, or other individual can be seen in this context. For example, the ways a counselor will shape responses to reframe, challenge, reflect, create an effective alliance, can be seen as the successful use of this process. Counselors commonly use techniques such as asking, “What does that emotion mean to you?,” or “Can you stay without judging?,” or other suggestions. These fall within the context of this approach, in that they help to guide the client to self-beneficial responses and behaviors, rather than repeatedly going into maladaptive patterns.

Figure 6 shows this interaction in graphical form. Two individuals produce behaviors that affect each other, resulting in a cyclic pattern of interaction.

When viewed from this perspective, the set of possible emotional decision states can be thought of as what in mathematics is called a “group,” which is a set of members with operations defined among and between them. Since we can consider the decision-making process as always being in one of the 16 defined states, it is a “closed” group so that every state leads to another state that is in the group. The inputs (experience) and rules (likelihoods of response) determine the next states. Therefore, there is a limited, albeit large, range of possible trajectories and rules that can control our group transitions.

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**Figure 3.** Simplified emotional decision model.
The top row labels represent left frontal lobe primary and left secondary brain gamma (38-42 Hz). The first column represents the right frontal lobe and again depicts the secondary and primary possible responses. Regarding the numbers: 0 = no activation and 1 = activation.
Whereas in basic group theory, the states are simply indicators, in our model, each state is accompanied by distinct emotional and decision-making experiences. Being in a particular state defines the basic components of the individual’s response but does not limit it. Each state can be thought of as a starting point, from which the intensity of the response and other factors will “color” the individual’s subjective experience and resulting thoughts and behaviors. The authors view this model as a step in the unification of cybernetic concepts such as brainwaves and self-organizing systems with the internal world of subjective personal experience. Hopefully, benefits to mental health assessment and treatment can emerge from this type of objective measure that can be scientifically correlated with experiences in the form of thoughts, feelings, and behaviors. We note that Diwadkar et al. have observed that, in the motor system, networks that are at rest are also in optimal readiness. We associate rest with being in a ground state in the transitions, potentiating transitions to states with particular areas activated to produce a defined response sequence. In a similar vein, Hesse and Gross have described the principle of self-organized criticality, which associates optimal resilience and adaptability with being in a state which is intermediate between
being excessively organized, or excessively disorganized, that is, in a state of being at rest but not frozen. From such a state, the maximum amount of transitions and adaptations are possible.

Taking concepts from game theory, the interaction can be seen as a process that seeks self-organization, stability, and minimum energy. The dominating factors determining how the system reacts to an input is related to a system seeking the most efficient, or least energetic, transition option from among a set of alternatives. Brains basically “fall” from one state to another, as perturbations introduce energy and make one or another state preferred at any given instant. The element of what we identify as “free will” can be associated with how the system chooses to react to the emotional valence of the transitions, reinforcing or inhibiting response patterns through a process of learning.

The literature reviewed and authors’ own research suggests that the resulting transitions occurring in response to environmental input are primarily automatic, in the sense of a sequential machine whose possible responses are preset with boundaries, or at least set with predetermined probabilities. Thus, immediate feelings and judgments (by virtue of millisecond execution) are not under active conscious control. It is the reactions to these that individuals can distinguish their adaptability, appropriateness, and guidance of choices and actions. The model allows the user to specifically identify each phase of sensation, perception, interpretation, and judgment, as part of a process whose function is accessible to us in the form of EEG activation to supplement personal report and observed behaviors.

Discussion

The question arises whether the particular 4 × 4 grid used here is correct, or optimal, or adequate for this domain. It is important to recognize that the model emerged from the data and, therefore, is a natural partition that suggests itself and is not dependent on any specific processing model. The 16-cell model is based on a forced-choice model in which once the regions of interest are defined and criteria for determining whether they are in a relatively active or inactive state, every possible state must fall into one of the predefined cells. There is no brain state that does not fit within the grid, based on having 4 parameters with 4 thresholds. This does not mean that the grid fully defines or limits the subjective or behavioral responses, which may be variable based on many factors. Whether the regions of interest and components are “correct” or “useful” is a matter for empirical confirmation, such as presented in this report. As one example of a possible important additional dimension, it would be possible to assign an “intensity” to any of the states, so that rather than being described by a 2-dimensional surface, the range of possible states occupies a cube that allows any state to be occupied with a range of activation from “low” to “high.”

That being said, the model does not assert that being in one of the 16 possible states completely determines the individual’s subjective and behavioral responses. In addition to occupying a particular state, perhaps at a particular intensity, the system is also retaining information related to prior states, history, biases, and additional context information. In addition, the current input enters the system, and subsequent state changes are based on both the current state and the input. In fact, the system can be thought of as characterized by a set of probabilities, so that from a given state and input, there is a range of possible next states. It is posited that having an element of choice in which states will occur, can be seen as a component of resiliency.

This suggests the possibility as suggested by one reviewer, that “decision making leads to a more complicated matrix of probabilities of response, that is, with certain initial states, is there a wider range of possible responses given an initial move mixed microstate?” The authors do believe that this range of
possible states is related to the history and the trajectory so that transitions can be conceptualized as a flow in the state space. For example, we may posit that states that incorporate both positive and negative activation, whether it is in the primary emotional or the secondary perceptual response, provide flexibility to move in one direction or the other. This would be in contrast to a response that habitually goes to one direction or the other as a matter of course, so that judgment is locked in earlier, rather than after some consideration or “pondering.” This representation is more descriptive than prescriptive, in that it is clear about what state is currently in effect, without necessarily being able to predict transitions (as of yet).

The relevance to counseling and therapy is that practitioners often reframe and use microskills such as reflecting or paraphrasing to allow a client to “hold on” to a set of feelings, as well as to be aware of multiple points of view, both pro and con, as part of developing healthy and flexible thinking and feeling habits. This approach is also consistent with concepts of emotional theory developed notably by Jaak Panskepp and described by Davis and Montag, generally labeled as “affective neuroscience,” in that his brain-based division of emotional systems is supported by the mechanisms described here, which lead to behaviors such as seeking, care, play, desire, fear, sadness, and anger, through identified neural substrates.

Interpretation of Cells in the Grid Model

The following descriptions associate an internal state of emotion and decision-making with each physiological profile. These associations have not been exhaustively studied, but their emergence is based on our experience after many sessions of self-evaluation combined with brain activation imaging. We propose that any individual is necessarily in one of these states at any time and that this grid, therefore, can be used to show tendencies, reactions, and trajectories of emotion and judgment in any circumstances. We look for real-world examples that typify each state to help to elucidate the qualities of each state. We also look to identify adaptive and maladaptive aspects of the various states to provide insight into whether emotional and decision-making tendencies are beneficial or not in individual cases. The exact constellation of thoughts, feelings, and behaviors associated with a particular state will depend on the individual, including past learning. A given state would have one intensity or “color” to one individual, and a different one to another. This model should find value in clinical evaluation and counseling, as a conceptual framework in psychology or psychiatry.

**Cell 0000 – “Off” = NOTHING.** This cell represents a minimally activated state. Neutral, no thoughts or judgments. Neither like nor dislike and judging neither good nor bad. This state may be viewed as “ready to react” and, as such, embodies the possible transitions that may occur, whether to a positive or to a negative state. If an individual is not generally in this state at rest, then some bias or predisposition may be evident, that biases possible responses, for example, “chronically negative.”

**Cell 0010 – “Like” = PLEASANT.** In this state, there is a positive primary emotional sensation but no other significant activity. This corresponds to a simple sensation that an experience or stimulus is pleasant, without further judgment. Note that in chronically depressed patients, it is often this state that cannot be accessed. That is, depression can be characterized by the inability to respond to positive stimuli, in contrast to what is truly an overtly negative state.

**Cell 0001 – “Good” = SAFE.** There is an evaluative judgment that the situation is safe, but no corresponding primary emotional responses. This is exemplified by an objective judgment that criteria have been met and that it is safe to proceed, but there is no emotional connection with that judgment. Typical situations may include financial or other objective decisions that have little or no emotional impact.

**Cell 0011 – “Like + Good” = APPROACH.** This is a positive state in which both the primary emotional tone and the judgment of positive value are present. This would be the optimal state to achieve when making a decision to proceed with some action.

**Cell 0100 – “Dislike” = UNPLEASANT.** A simply unpleasant sensation, such as “ugly,” “noisy,” “smells bad,” and so on.

**Cell 0110 – “Like + Dislike” = Suspend Feeling.** Both positive and negative primary emotional responses are experienced, but no judgments are made. A therapist may at times instruct a client to “stay with the feelings” and not act on them. This is a valuable state, if the individual can develop the ability to feel both positive and negative emotions, while avoiding making any judgments or actions based on them. This is a potential taking-off point for further processing and judgment, which can lead to an informed and considered decision, rather than acting directly on feelings, which may in fact be conflicting.

**Cell 0101 – “Dislike + Good” = (DIETING).** This exemplifies mature decisions to do something that is not pleasant. Examples include paying taxes, visiting the dentist, dieting, or other “responsible” activities that have some aspect of being unpleasant.

**Cell 0111 – “Like + Dislike + Good” = FOLLOW HEAD.** This is like going to lunch with your boss. You like the food, you may dislike the conversation, but it is good to comply, for your future benefit. It shows mixed emotions but is judged as the right thing to do.

**Cell 1000 – “Not Good” = UNSAFE.** Being unable to determine the potential danger of an action or decision, individuals are prone to dangerous or risky behavior without sufficient inhibitory influence to stifle their actions. One useful probe for clients in this state is to ask, “Do you know what it is that you are worried about?” Chronically anxious individuals may not be able to articulate these specifics. Also, manic or risk-taking patients
may be unable to access this state, lacking the normal ability to access this inhibitory process.

1010 – “Like + Not Good” = NAUGHTY. This is like buying that decadent chocolate cake when you shouldn’t.

1001 – “Safe + Not Safe” = SUSPEND JUDGMENT. In this Zen-like state, both positive and negative judgments of a situation or stimulus can be perceived, but without any emotional reaction. This is a mindful, and “nonattached” state. It provides a strong position from which to access other decision states, in a deliberate and considered manner.

1111 – “Like + Safe + Not Safe” = FOLLOW HEART and APPROACH. Examples might include purchasing an expensive or important item such as art or property. Both the positive and negative aspects of the judgment are perceived, but the individual also simply likes the proposition; or going to lunch with a coworker when your schedule is tight and your work might not get done on time. But you like going to lunch with them.

1100 – “Dislike + Bad” = AVOID. In a chronic condition, this represents an overtly avoidant or actively depressed state. It is not that the individual does not care, it is that he or she specifically dislikes and judges as bad situations or stimuli.

1110 – “Like + Dislike + Bad” = FOLLOW HEAD. A judgment is being made to avoid a situation or proposition for which both positive and negative emotions are sensed, but for which a negative judgment is perceived.

1101 – “Dislike + Bad + Good” = FOLLOW HEART and AVOID. In this state, the individual experiences both the positive and negative judgments and is, thus, aware of both pros and cons of the situation. However, on the primary emotional side, only a negative emotion is experienced. In this case, the decision is based on the feeling that “I just don’t like it.” This type of state may occur when making decisions such as purchasing an expensive item, making an expensive decision, or making a difficult career or life decision. Most of such decisions are characterized by having both “pros” and “cons” and the making of a list is a common method taught to facilitate the decision. However, in this state, the overriding decision is made by the feeling, and this overshadows the possible choices that would be made “rationally.”

1111 – “Full Activated”. In this state, the individual experiences the full spectrum of possible responses. Both positive and negative primary emotions are sensed, and both the positive and negative judgments of possible outcomes and behaviors are experienced.

Summary

The purpose of the work described here has been to use EEG technology to produce a millisecond-resolution representation of brain activity directly reflective of emotional processing. We show that it is possible to decompose emotional decision-making processes into sequential epochs that reveal the individual’s inner process and dialog underlying thoughts and behavior. The model is based on a foundation of knowledge related to the neuroscientific principles of the affective world. This is a demonstration that both objective external measurements, and internal subjective experiences, can be investigated in an objective and coupled manner, shedding light on both dimensions.

The results reported in the cited studies provided us with the motivation to produce a minimal model that could account for the emotional states and decision processes. When the transitions are viewed in a particular format that accentuates the contributions of the targeted brain locations, a sort of digital code emerges. When a left or right sensory or perceptual area becomes active, then the corresponding portions of the activation model are considered to have a role in the current processing. In addition, the spontaneous categorization of inputs that the model associates with this processing is an example of an adaptive process, as identified by Anderson and others, as an essential survival mechanism. When viewed as a comprehensive system, it provides a structure that has shown potential for applications in diagnostics, psychological assessment, individual aptitudes and differences, forensics, and related areas.

Author Contributions

TFC contributed to conception and design; contributed to acquisition, analysis, and interpretation; drafted manuscript; critically revised manuscript; gave final approval; agrees to be accountable for all aspects of work ensuring integrity and accuracy. RJB contributed to conception and design; contributed to acquisition, analysis, and interpretation; drafted manuscript; critically revised manuscript; gave final approval; agrees to be accountable for all aspects of work ensuring integrity and accuracy.

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