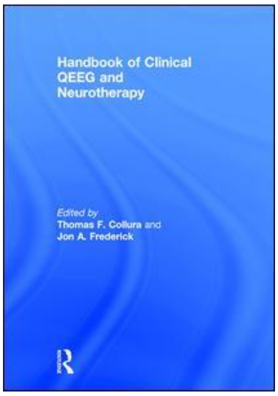

Handbook of Clinical QEEG and Neurotherapy

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PART VIII

Emerging Paradigms

25

EEG STATE DISCRIMINATION AND THE PHENOMENAL CORRELATES OF BRAINWAVE STATES

Jon A. Frederick

Abstract

While standard biofeedback training rewards the production or inhibition (or "control") of certain physiological states, state discrimination training rewards the observation and reporting (or "awareness") of these states. It is commonly argued that increasing awareness of subtle phenomenological correlates of physiological states is central to the mechanism of action of biofeedback, but the interaction between awareness and control of physiological function is vastly unexplored. Although an EEG alpha state discrimination experiment (Kamiya, 1962) was the first empirical demonstration of operant conditioning of the EEG, relatively few studies have employed this paradigm in the past 50 years. Unlike most discriminative stimulus paradigms, there is a qualitative difference between the physical dimensions of brain activity and our phenomenal experience of them. EEG state discrimination training, by repeatedly training observation of the difference between high and low magnitudes of a given brain state, may provide a novel empirical window for the systematic study of the phenomenal correlates of brainwave states and our efforts to control them. This chapter discusses the similarities and differences between operant discrimination and standard operant conditioning; the importance of observation and awareness in physiological self-regulation; the psychophysics of EEG state discrimination; EEG state discrimination as a sensorimotor process; potential clinical applications; and the possibilities of future research in this paradigm.

In 1958 at the University of Chicago, Joe Kamiya began the first experimental study to suggest the possibility of operant conditioning of the EEG (Kamiya, 1962, 1968, 1969, 2011). Kamiya had conducted experiments on the differences in the EEG between sleeping and waking states, and became fascinated with how the alpha rhythm came and went in the waking EEG. Was there a subjective correlate of this variation that people could report?

In his experiment, subjects sat quietly with eyes closed in a darkened room, while Kamiya monitored the EEG. Whenever a 2–6 second interval was seen where alpha (8–12 Hz) was clearly present or absent, based on a random order of trials, Kamiya would ring a bell. Subjects responded "A" or "B" and received immediate feedback whether they were right or wrong. Subjects were not told that "A" meant the presence and "B" meant the absence of alpha, and had to figure this out by attending to their subjective state before the prompt and whether their response was correct. Kamiya found that nine out of 12 subjects were able to discriminate their alpha states within seven sessions.

Interestingly, Kamiya also found that those subjects who could learn to discriminate their alpha state were then able to enter and sustain either the alpha or non-alpha state on command. Kamiya wondered if discrimination training was necessary to develop this ability, or if it could be trained in naive subjects by providing feedback whenever alpha waves were present. Eight of 10 subjects were able to learn to control their alpha state by this procedure, and the field of neurofeedback was born.

It is remarkable that the entire field of clinical neurofeedback has followed and emulated Kamiya's second experiment, while his first experiment, although often cited, has developed the status of a historical footnote. It is also of interest that Kamiya's pursuit of the subjective phenomenology associated with EEG alpha was partly a reaction to the oppressive orthodoxy of the behaviorism of the 1950s, and yet his approach resulted in a powerful and rigorous application of behaviorist methods for studying first person phenomenology.

Operant Conditioning and Operant Discrimination

Both standard neurofeedback and EEG discrimination training are forms of operant conditioning, although they differ in the behavior that is reinforced. Discrimination training (or operant discrimination) involves a "three-term contingency" between a discriminative stimulus, a behavior, and a reinforcer. A three-term contingency means that a behavior is rewarded only when a certain discriminative stimulus is present. For instance, answering a phone when it rings is often rewarded—except when it is someone else's phone.

Unlike standard biofeedback where the operant response is the production of some particular physiological state, in discrimination training there are actually two operant behaviors that are rewarded. One operant behavior is to press a key if the discriminative stimulus is present and not press it if absent. The other, and more interesting behavior, is called the *observing response.* Wyckoff (1952) defined the observing response (or responses; R_o) as any response which results in exposure to the discriminative stimulus (or stimuli; S_D) involved. R_o includes behaviors such as attending, orienting, or "sensory organizational activity."

For instance, if stimuli are displayed on a monitor, R_o would be turning the eyes and head toward the monitor. In EEG state discrimination training, R_o is any behavior that increases awareness of one's EEG state, such as employing or inhibiting attention, self-talk, or imagery. Observing responses are distinguished from "effective responses" (lever presses, choice selection, etc.) upon which reinforcement is based.

Most complex behaviors consist of a series of discriminative stimuli and responses linked together in a behavior chain (Cooper, Heron, & Heward, 2007). In a behavior chain, each response produces a new stimulus situation that serves both as a conditioned reinforcer for the response that produced it as well as S_D for the next response in the chain. The final response in the chain produces reinforcement that maintains the effectiveness of each conditioned reinforcer in the chain. At each step, the S_D (for the next response) acquires secondary reinforcing properties for R_o (to the previous stimulus) upon which it is contingent, based on repeated pairing with reinforcement for the final effective response.

Operating a vending machine is an common example (Shapiro & Browder, 1990). Seeing a vending machine is the S_D for the R_o of reaching into your pocket to search for coins. Feeling the coins reinforces this R_o, but it also serves as the S_D for putting the coins in the machine. Hearing the coins clink in the machine reinforces the coin insertion, but it also serves as S_D for the R_o of scanning the array of buttons to find the desired drink. Finding the correct button serves as both a reinforcer and a discriminative stimulus for the next step—leading to the primary reinforcer.

In EEG state discrimination training, having sensors attached and being told the session has started is the S_D for the R_o of attending to your internal subjective states. This R_o is reinforced by experiencing a subjective state or states associated with previous correct responses. These subjective states (plus the prompt stimulus) serve as S_D for the final effective response, the button press.

Wyckoff described how on each discrimination trial there is some probability p_o of making R_o. If p_o is small, subjects will rarely be exposed to the discriminative stimuli. In most experiments, such as the famous experiment where pigeons appeared to obey the words "TURN" and "PECK" (Reese, 1966), p_o is high and the lack of R_o may only be a temporary inconvenience in the early trials. In EEG state discrimination, an effective observing response is never made in some subjects (22%; Frederick, 2012).

With external stimuli controlled by the experimenter, there is little or no discussion of the relationship between the stimuli and the animal's internal subjective phenomenal representation of them. However, in physiological state discrimination training, this relationship is the major phenomenon of interest. The phenomenal representations of, for example, high and low alpha amplitude are very subtle. Indeed, at the onset of training they are generally below the threshold of perception. For these near- or subthreshold stimuli, it seems likely that reinforcement is acting primarily on the quality or structure of the observing response. The consequence is, at least theoretically, that the state discrimination paradigm directly trains and measures observation and awareness of the phenomenal correlates of physiological states.

The Importance of Observation and Awareness in Physiological Self-Regulation

Physiological self-regulation skills are largely a form of procedural memory, like sensorimotor skills. Unlike autobiographical or semantic memories that can be reported explicitly, they are carried out largely without attention or awareness. However, awareness does play a role in the *learning* of procedural memories. It is often argued that increasing awareness of one's physiological state is important to the mechanism of action of standard biofeedback methods (Brener, 1974; Congedo & Joffe, 2007; Olson, 1987; Plotkin, 1981). However, research on the relationship between awareness and control of physiological responses appears to have reached a peak in the mid-1970s and declined after the mid-1980s.

In addition to Kamiya's (1969) report that subjects trained in alpha discrimination showed evidence of control, facilitation of voluntary control training by prior discrimination training was also seen for heart rate (Brener, 1974, 1977; Brener, Ross, Baker, & Clemens, 1979), and for a cephalic vasomotor response (Fudge & Adams, 1985). The reverse relationship, facilitation of discrimination by voluntary control training, has been reported for the galvanic skin response (Baron, 1966; Lacroix, 1977; Stern, 1972), heart rate (Brener, 1977; Marshall & Epstein, 1978), the sensorimotor rhythm (Cinciripini, 1984), and slow cortical potentials (Kotchoubey, Kubler, Strehl, Flor, & Birbaumer, 2002). My laboratory recently reported a positive correlation between performance in EEG alpha amplitude control and discrimination tasks across seven sessions in four subjects (Frederick, Dunn, & Collura, 2015). My current research focuses on whether these two skills generalize or transfer to each other when the type of training is switched.

Black, Cott, and Pavloski (1977) and Lacroix (1981) argued that awareness is not necessary or sufficient for operant conditioning of a physiological response. Self-reported autonomic awareness appeared to correlate inversely (Blanchard, Young, & McLeod, 1972) or not at all (Young & Blanchard, 1984) with self-control of heart rate. There are also abundant examples of learning without awareness (Saltz, 1971). However, Black, Cott, and Pavloski (1977) acknowledged that awareness may *facilitate* learning even while it may not be necessary or sufficient. For instance, while subliminal stimuli can produce mild emotional and priming effects, conscious awareness is necessary for strong and enduring effects on behavior (Pratkanis & Greenwald, 1988).

Facilitation of motor learning by conscious awareness was observed by Boutin, Blandin, Massen, Heuer, and Badets (2014). In this study, participants more effectively learned a sequential finger movement when asked to make a judgment about their performance after each trial. Fitts and Posner (1967) argued that awareness is particularly important for the early stages of learning a skill. During the initial learning of a musical or athletic skill, for instance, careful attention is paid while trial and error is used to identify the correct behavior. Through extensive practice, incorrect behaviors are inhibited and ultimately the skill becomes automated. After extensive practice, awareness can actually impair highly skilled performance (Beilock & Carr, 2001; Heuer & Sülzenbrück, 2012).

Clinical Applications of EEG State Discrimination

At this stage, any clinical applications of the state discrimination paradigm are speculative and should only be interpreted as suggestions for research. However, the relationship between awareness and control in biofeedback and other forms of learning points to a prediction that supplementing standard biofeedback methods with state discrimination training, especially in the early stages of learning, could produce more effective clinical results. Taking EEG state discrimination measurements could also be a useful method of assessing client progress in standard clinical neurofeedback. A direct measurement of success is intrinsic to every trial in discrimination learning, and for that reason, discrimination studies could be a more precise and sensitive experimental model of standard neurofeedback training. The study of how individual differences in personality, intelligence, or executive function relate to performance on EEG state discrimination tasks could provide a basis for personalized medicine, suggesting what type of client is better for which type of neurotherapy. Finally, training discrimination could also have therapeutic value in its own right, just as insight-oriented psychotherapy can have value above and beyond behavior-modification psychotherapy.

A related theory of the role of awareness in learning is called chunking (Miller, 1956). Chunking is the association of individual pieces of information or motor actions into meaningful units so they occupy less working memory. Working memory famously has a finite capacity of seven plus or minus two independent items or "chunks." Chunking, the creation of a meaningful structure that integrates separate chunks, is an effortful process requiring attention and awareness, where the outcome is a structure whose connections are processed implicitly. Subjective awareness manages the relationships and transitions between chunks but not within them (Rushworth, Walton, Kennerley, & Bannerman, 2004). A possible exception may be when it is necessary to unlearn maladaptive associations.

Conscious awareness of a stimulus facilitates learning by activating more widely distributed representations in the brain (DeHaene & Changeux, 2011), and mobilizing and integrating brain processes that are otherwise independent (Baars, 2002). These processes include problem solving, decision making, and action planning (Boutin et al., 2014), which allow the solution of conflicts between competing motor plans (Morsella, 2005).

In standard biofeedback, a client has the option of not paying attention to the subjective correlates of the physiological signals displayed. Furthermore, the rewarded state differs from the unrewarded state only by an infinitesimal difference at the reward threshold. By contrast, every trial in discrimination training directly measures and trains observation and awareness of differences between extremes of the physiological state.

Given the diverse evidence on the importance of awareness for learning, it is remarkable how few physiological state discrimination studies exist in the literature, especially in the past 25 years. EEG state discrimination has been reported for stage 1 and stage 2 sleep (Antrobus & Antrobus, 1967), visual evoked potentials (Rosenfeld & Hetzler, 1973), the sensorimotor rhythm (Cinciripini, 1984), P300 amplitude (Sommer & Matt, 1990), and slow cortical potentials (Kotchoubey et al., 2002). Physiological state discrimination has also been demonstrated outside the central nervous system, for finger temperature (Lombardo & Violani, 1994), galvanic skin response (Dickoff, 1976; Stern, 1972), blood glucose levels (Cox, Carter, Gonder-Frederick, Clarke, & Pohl, 1988), heart rate (Brener & Jones, 1974; Grigg & Ashton, 1986), blood pressure (Greenstadt, Shapiro, & Whitehead, 1986), cardiac R-waves (Violani, Lombardo, de Gennaro, & Devoto, 1996), pulse transit time (Martin, Epstein, & Cinciripini, 1980), and cephalic vasomotor activity (Fudge & Adams, 1985).

However, there were at least three studies in the 1970s that failed to replicate alpha state discrimination (Cott, Pavloski, & Black, 1981; Legewie, 1975, 1977; Orne, Evans, Wilson, & Paskewitz, 1975, cited in Orne & Wilson, 1978). Although most were published with very limited methodological detail, Cott et al. (1981) defined an alpha state as lasting only half a second, where Kamiya had used a much longer interval. In my alpha state discrimination study (Frederick, 2006, 2007, 2012; Viebrock and Frederick, 2006), I compared performance on 1-, 2-, and 4-second intervals.

Psychophysics of EEG Alpha State Discrimination

One hundred and six subjects completed 583 sessions consisting of three sets of about 36 trials. A 150-second eyes-closed baseline EEG was recorded at F3 or Pz. Each epoch was ranked among a percentile distribution of alpha amplitudes of the most recent 150 seconds initially derived from the baseline recording. A tone sounded whenever the alpha band power exceeded a critical difference from the median of the baseline. Alpha amplitudes in the first to 30th percentile were defined as "low," and the 70–99th percentile were defined as "high." Participants responded "high" or "low," and received feedback about whether the response was correct or incorrect after each trial. Each session, trials were presented with the following in random order: high vs. low amplitude; 1-, 2-, or 4-second discriminative stimulus durations; and absolute vs. relative amplitude.

A successful criterion performance was defined as binomial $p < 0.01$ for percentage correct. I found that 40/106 participants reached criterion within a median of five sessions. Seventy-six percent of those who completed nine or more sessions achieved criterion, which is very similar to Kamiya's results. On average, those who achieved criterion did so in 4.8 sessions.

Subjects who achieved criterion tended to do significantly better in later sessions than earlier sessions (Figure 25.1). Thus, learning appeared to be cumulative.

I observed that very high alpha amplitudes (above the 90th percentile) were discriminated better than moderately high (between the 70th and 80th percentile), and very low (below the 10th percentile) were discriminated better than moderately low (between the 20th and 30th percentile; Figure 25.2).

I found that longer (2- and 4-sec) stimulus durations were discriminated better than shorter (1-sec) ones (Figure 25.3).

I also found that participants scored significantly higher on absolute rather than relative amplitude trials (Figure 25.4).

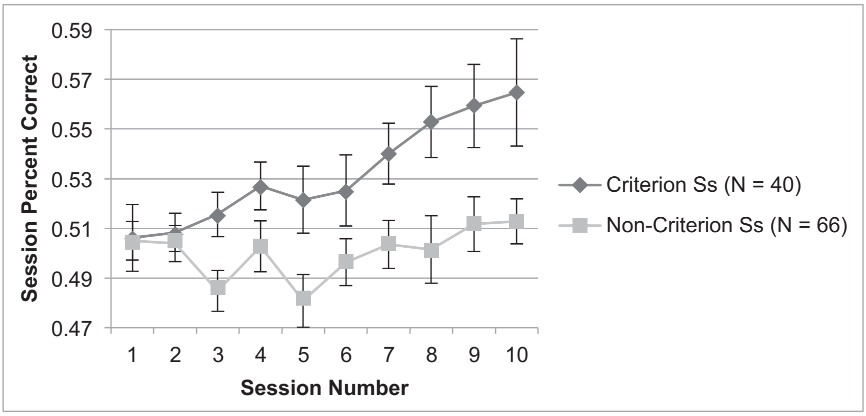

Figure 25.1 Learning effect (effect of session number) on session averages in subjects who achieved criterion on the task. Bars indicate standard error.

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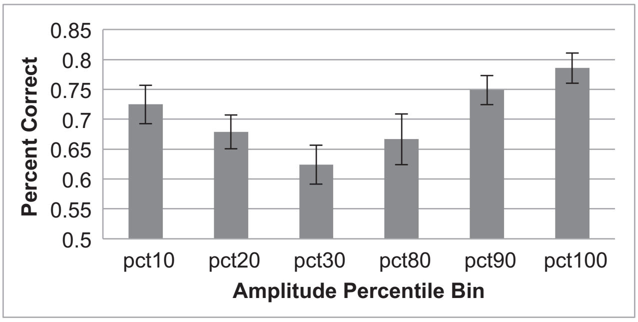

Figure 25.2 Effect of percentile amplitude on discrimination task performance. Bars indicate standard error.

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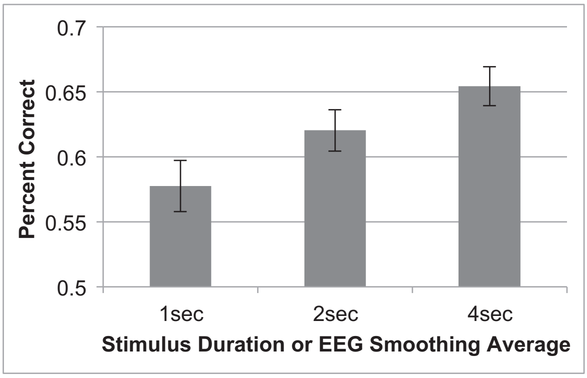

Figure 25.3 Effect of stimulus duration or EEG smoothing average on discrimination task performance. Bars indicate standard error.

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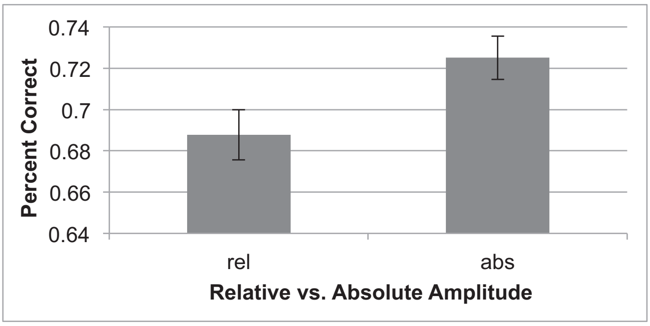

Figure 25.4 Effect of relative versus absolute amplitude on discrimination task performance. Bars indicate standard error.

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EEG State Discrimination as a Sensorimotor Process

The greater performance seen at extremes of signal intensity, and with longer stimulus durations, is consistent with a signal detection interpretation, or with the conceptualization of EEG state discrimination as a sensory modality.

This raises two important questions: what are they sensing, and how are they sensing it?

In fact, the alpha state has multiple correlates. We know that it correlates with a relatively quiet and empty state of mind and, in subjects who are good at it, it probably also correlates with the efforts to achieve this state. Kamiya (1968) said subjects in the non-alpha state reported "seeing with the mind's eye," where the alpha state was commonly reported as "not thinking," "letting the mind wander," or "feeling the heart beat."

My participants were informed prior to the task that alpha involved being alert and relaxed but not drowsy; mentally disconnecting from sensation or imagination; and that it is reduced by mental activity—thinking, problem solving, intending (i.e. thinking about movement), by visual imagination. They were encouraged to guess what state they were in and if they didn't receive a prompt, see if changing to a different state evoked the prompt.

Previous studies raised concerns that subjects may merely be controlling alpha and may not be truly aware of any subjective correlate of spontaneous changes in alpha (Cott et al., 1981; Orne & Wilson, 1978). However, I argue that both perceptual and volitional processes can serve as discriminative stimuli, and that at the level of perceiving cortical activity, it is not entirely clear that there is a difference between the two.

This may be easier to understand if we consider the example of EMG biofeedback to train relaxation first. All voluntary muscle activity in the body is accompanied by what is called sensory reafference: kinesthetic and proprioceptive receptors in our muscles and joints give us feedback about their position, tension, and movement.

Are people who have chronic muscle tension deficient in their *sensory awareness* of that muscle tension? Probably. But there is another possibility. The other possibility is that they lack a fine-grained awareness of their own *volitional* states. So, as a client receives feedback about their muscle tension, they might think, "Am I doing that? Let me try something else. Hey, that worked!"

Then, if they go home and they successfully practice their new physiological self-regulation skill without the equipment—are they practicing new sensory skills, or new motor skills?

My best guess is that they are doing both.

The same question applies to EEG biofeedback, except in the CNS the reafferent loop is much shorter. And if the sensor is right over the premotor cortex, the distinction between sensory and motor, between awareness and volition, may start to lose meaning.

Benjamin Libet's (1985) experiment on the timing of conscious volition illustrates this point. Libet recorded the EMG from a voluntary movement, the premotor potential, and asked subjects to report when they willed the voluntary movement. He reported the surprising finding that the premotor potential occurred about 350 milliseconds before the will to act. This had all sorts of controversial implications for the concept of free will but, for our purposes, it had another important implication. That is, experience of volition in Libet's experiment is undeniably the subjective correlate of which the premotor potential is the discriminative stimulus.

Could alpha be the discriminative stimulus of which the will to produce alpha is the subjective correlate? Possibly. Libet's finding is one of many in the area of perceptual motor control that suggest the experience of volition is not related in a straightforward way to the voluntary actions themselves (e.g. Castiello, Paulignan, & Jeannerod, 1991; Milner & Goodale, 1995). If a subject becomes aware that he might be in an alpha or non-alpha state, both changing or not changing the state are voluntary choices. It is, thus, not entirely clear whether the maintenance of, or transitions between, these states are voluntary or spontaneous.

It is likely that the will to produce alpha and whatever neurologically precedes it is part of a chain of conditioned responses that includes both the effort and the "reafferent" consequences of that effort. Each effort may be different both in terms of its specific intent ("these thoughts are interesting, but I am going to try to quiet them by focusing on my breathing") and their relative success.

In addition to subtle and variable qualities of volition being a phenomenal correlate, it is also likely that an effort to produce or suppress alpha serves as an observing response that makes the perception the phenomenal correlate(s) possible. For instance, if I attempt to create a state of mental quiet, I will not necessarily succeed, but this effort results in attention to how I may have succeeded or failed.

The Human Phenome Project

Kamiya proposed that discrimination training could provide the basis of a first person science, for bridging the gap between physiological measurements and first person phenomenological reports (Kamiya, 2011; Kamiya & Collura, 2011). Even as a graduate student in the 1950s, Kamiya believed that a science of psychology could not be complete without including these essential features of human life: our private thoughts, feelings, images, and dreams (Kamiya, 2011). While the prevailing viewpoint was that introspective reports were an unreliable dead-end for research (Boring, 1953), Stoyva and Kamiya (1968) made a compelling argument that physiological measures provided a renewed validity for hypothesized mental states. For instance, the duration of rapid eye movements (REMs) was observed to correlate with the verbally reported duration of dreams upon awakening (Dement & Kleitman, 1957), and the density of REMs preceding an awakening was related to the amount of physical activity reported in the dream (Berger & Oswald, 1962). In this view, both verbal reports and physiological measures are imperfect operational definitions of subjective experience, which then has the same status as other hypothetical constructs in science like extraversion, genes, and electrons.

Kamiya's initial interest in the operant discrimination of EEG alpha was to determine if transient fluctuations in alpha were associated with changes in subjective experience. I have always argued (1992, 2007, 2012) that neurofeedback is not just a clinical therapy, but a novel empirical method for studying mind–brain interactions.

Several recent European studies have agreed with this premise (Bagdasaryan & Le Van Quyen, 2013; Micoulaud-Franchi, Quiles, Fond, Cermolacce, & Vion-Dury, 2014; Petitmengin & LaChaux, 2013). Micoulaud-Franchi et al. contrasted neurofeedback with neuropsychological approaches—which manipulate brain function as an independent variable (IV) and measure cognitive processes as a dependent variable (DV)—and with psychophysiological approaches—which manipulate cognitive processes (IV) and measure brain function (DV). They noted how in neurofeedback, the cognitive and brain processes interact recursively, repeatedly trading places as IV and DV. As a result, the hypothesized relationship between these two variables—rather than being externally specified by the experimenter and tested once per experiment—is internally specified by the subject and can be varied and tested dozens or perhaps hundreds of times per session, until the subject arrives at an optimal solution. State discrimination approaches may leverage this property of neurofeedback with the additional advantage of repeatedly focusing attention on the difference between high and low states rather than always training up or down. Meanwhile, advances in phenomenological interviewing methods (Petitmengin, Remillieux, Cahour, & Carter-Thomas, 2013) have shown that it is possible to elicit more valid, reliable, and precise reports of our cognitive processes than previously thought possible (Nisbett & Wilson, 1977).

Kamiya proposed a study (Kamiya & Collura, 2011) where subjects would be extensively trained in the discrimination and control of a large variety of physiological measures, then asked to provide paired comparison ratings on the degree of subjective similarity between physiological states (1 = not similar; 5 = very similar). A principal components analysis could then identify the major dimensions of the subjective space associated with all of the measures.

I proposed doing stimulus generalization studies of how much learning of one psychophysiological modality transfers to another (Frederick, 2007). It would be very interesting to see how the clusters of psychophysiological variables from Kamiya's proposed study would overlap with the clusters found from mine.

If we take the 52 Brodmann areas as the estimate of the number of distinct functional regions of the cortex, across all frequency bands and including coherence measures, not to mention fMRI measures, finding the discriminable phenomenological correlates of all of these variables is enough to keep hundreds of scientists busy for dozens of years. My best guess is that the scientific revolution needed to make this project happen is unlikely to happen in my lifetime. So my second best effort will be for those few of us doing the studies to aim carefully and hope that we get lucky.

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