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Psychophysics of EEG alpha state discrimination

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ABSTRACT

Nearly all research in neurofeedback since the 1960s has focused on training voluntary control over EEG constructs. By contrast, EEG state discrimination training focuses on awareness of subjective correlates of EEG states. This study presents the first successful replication of EEG alpha state discrimination first reported by Kamiya (1962). A 150-s baseline was recorded in 106 participants. During the task, low (<30th percentile of the baseline) and high alpha events (>70th percentile) triggered a prompt. Participants indicated “high” or “low” with a keypress response and received immediate feedback. Seventy-five percent of participants achieved significant discrimination within nine sessions, with a significant learning curve effect. Performance was significantly related to physical properties of the EEG signal, including magnitude, duration, and absolute vs. relative amplitude. These results are consistent with a conceptualization of EEG state discrimination as a sensory modality, although it is also intricately related to voluntary control of these states.

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1. Introduction

The standard paradigm in neurofeedback is operant conditioning to teach people to control their EEG. In this paradigm, brainwave information is displayed in real time on a monitor and subjects are rewarded when some value, usually power or amplitude, exceeds a threshold set by the trainer.

It is often suggested that the mechanism of action of neurofeedback involves an increased awareness of the physiological states underlying the feedback (Brener, 1974; Congedo & Joffe, 2007; Olson, 1987; Plotkin, 1981). However, very few studies have tested this assumption by measuring awareness of EEG state differences in a discriminative stimulus task.

One of the earliest neurofeedback studies was a discrimination experiment by Kamiya (1962, 1968, 1969, 2011), who reported success in training human subjects to discriminate alpha (high-amplitude sinusoidal 8–12 Hz waves) from non-alpha states. Kamiya waited for distinct 2–6 s alpha or non-alpha states to appear, in random order, in an 8–12 Hz filtered EEG. Subjects were then prompted to respond “A” for alpha and “B” for non-alpha states, and were given immediate feedback whether their responses were correct. Kamiya reported that nine out of 12 subjects reached a significant proportion of correct responses within seven 1-h sessions.

In several studies, discrimination training has been shown to generalize to, or facilitate, control training and vice versa. Kamiya (1968) observed that those trained in alpha discrimination showed superior performance in an alpha production task. Facilitation of voluntary control training by prior discrimination training was also seen in peripheral biofeedback by Fudge and Adams (1985). Meanwhile, voluntary control training facilitated subsequent discrimination performance for the sensorimotor rhythm (12–15 Hz; Cinciripini, 1984) and slow cortical potentials (Kotchoubey, Kubler, Strehl, Flor, & Birbaumer, 2002).

It is assumed that standard biofeedback methods primarily teach voluntary control by rewarding desired physiological responses which are seen as behaviors in the operant conditioning scheme. Meanwhile, training the discrimination of dif-

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ferences in physiological states is assumed to involve differences in perception or awareness of discriminative stimuli. While it is possible for someone in standard neurofeedback to sit passively and pay little attention to the reward and its subjective correlates, the discrimination paradigm requires and measures conscious awareness of one's internal state. A diversity of evidence suggests that conscious awareness results in more widely distributed representations in the brain, allowing for deeper and more elaborate processing (reviewed in DeHaene & Changeux, 2011). While subliminal stimuli can produce mild emotional and priming effects, conscious awareness is necessary for strong and enduring effects on behavior (Pratkanis & Greenwald, 1988). Conscious awareness seems to be particularly important to the early stages of learning a skill (Fitts & Posner, 1967; Gentile, 2000). Therefore, it seems likely that EEG state discrimination training would facilitate learning, especially early stages of learning, if used as an adjunct to standard neurofeedback protocols.

It is an odd curiosity of history, then, that research on EEG learning since Kamiya's influential study (1962, 1968, 1969, 2011) has largely abandoned discrimination and focused on training voluntary control of EEG constructs (Evans, 2007). EEG state discrimination has been reported only in a few studies, including discrimination of stage 1 and stage 2 sleep (Antrobus & Antrobus, 1967), visual evoked potentials (in rats; 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), blood glucose levels (Cox, Carter, Gonder-Frederick, Clarke, & Pohl, 1988), heart rate (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).

Another study (Cott, Pavloski, & Black, 1981) failed to demonstrate discriminative learning of the alpha rhythm, but differed substantially from Kamiya's original study in defining an alpha state as one-half second of high absolute alpha power. Kamiya (personal communication, 2006) argued that one-half second is barely at the threshold of a subject's ability to discriminate a state. Such a threshold was also suggested by Libet (1982) who observed that a half second was the minimum stimulus for awake behaving patients to detect an electrical stimulus applied directly to the cortex. Further, Kamiya's earliest observations did not use a filter or power spectrum analysis, relying upon very clear moments of pure alpha in the raw EEG. High absolute alpha amplitude can sometimes result from generally high activity across the spectrum, rather than a distinctively alpha state – suggesting that relative alpha amplitude might provide a clearer signal. Therefore, the present study attempted to demonstrate alpha state discrimination using 1-, 2- and 4-s intervals, and compared performance between relative and absolute amplitude.

In addition to Cott et al. (1981), two additional failed replication efforts were published, although with very limited methodological detail (Legewie, 1975, 1977; Orne, Evans, Wilson, & Paskewitz, 1975, cited in Orne and Wilson (1978)). However, Orne and Wilson (1978) mentioned that one complicating factor was that the amount of alpha in most subjects increased over several sessions, to the point where it was difficult to find periods of non-alpha lasting even 1–3 s by the third session. In this situation, subjects could learn to “cheat” in the task by guessing “alpha” after short inter-trial intervals, and “non-alpha” after longer ones. Therefore, the present study avoided this complication by defining *low* alpha as events below the 30th percentile and *high* alpha as above the 70th percentile of amplitude from a sliding baseline including only the most recent 150 s. However, while addressing the problem of guessing based on inter-trial intervals, this definition creates a new potential problem, that some subjects could be in a “truly” high (or low) alpha state throughout most of the sliding baseline, and would be prompted to discriminate between states that might be perceptually the same. Therefore, it was predicted that subjects with low variance in alpha amplitude, whether always high or always low, would be less likely to achieve significant discrimination performance.

As with any perceptual process, it was predicted that correct discrimination would be associated with the magnitude of the stimulus. Thus, *very low* alpha (10th percentile or below) would be discriminated better than *moderately low* alpha (11–20th or 21–30th percentile) and *very high* alpha (91–100th percentile) would be discriminated better than *moderately high* alpha (71–80th or 81–90th percentile) events.

Preliminary observations of results from the first participants in this study showed that the sidebands (e.g., 8 and 12 Hz where the peak alpha frequency, or PAF, was 10 Hz) overlapped between high and low trials, while the difference was greatest at the PAF. Therefore, the PAF appeared to contribute the most *validity* to the signal, while the sidebands appeared to contribute noise. This observation suggested that participants might do better on *narrower* bandwidths. However, averaging over several adjacent bands contributes greater signal *redundancy* or *reliability*, which would predict that participants would do better on *wider* bandwidths. Lacking a sufficient theoretical ground to decide which effect would be more important, it was hypothesized that differences would be seen among trials with 1, 3, and 5 Hz bandwidths, without predicting the direction of the effect. However, it was predicted that individual differences in the baseline would predict the relative importance of the validity vs. redundancy effects. That is, subjects whose baseline PAF correlated with the sidebands would benefit more from redundancy, and perform better on 5 Hz bandwidths, while those whose alpha peak was more independent of the sidebands would perform better on 1 Hz bandwidths.

The central parietal location Pz was chosen because it is close to occipital sources of alpha, but farther than Oz from sources of muscle artifact. The left frontal location F3 was chosen because alpha diminishes in amplitude frontally. There are also other rhythms in the 8–12 Hz band in the frontal cortex which are not technically alpha (Shaw, 2003), so it would be of interest if performance differed between these two sites. It was assumed that for some subjects, alpha would be *too loud* most of the time and thus perceptually invariant at Pz (making F3 a more optimal site) while for others, alpha would

be *too quiet* most of the time and thus perceptually invariant at F3 (making Pz a more optimal site). It was hypothesized that subjects who achieved significant performance at Pz would have lower baseline alpha amplitude at F3, and those who achieved significant performance at F3 would have higher baseline alpha at Pz.

2. Methods

2.1. Subjects

With the approval of the Institutional Review Boards at the University of Minnesota, Temple University, the University of Tennessee, and the University of Utah, informed consent was obtained from 106 participants, age 18–59 (median 24; 50% female). Exclusion criteria were limited to the inability to understand the informed consent form or comply with task instructions. Participants were asked to abstain from alcohol or controlled substances for 24 h prior to task sessions.

2.2. Measurement and apparatus

Skin at the recording sites was prepared to bring impedance below 5 k Ω . Gold electrodes were attached to active sites including F3 (with right ear reference/left ear ground) and Pz (random left/right ear reference/ground). Early in the study, 11 participants were recorded at O2 (with a left ear reference/right ear ground) instead of Pz.

EEG was recorded with a Brainmaster 2E amplifier and Brainmaster 2.5 software using the default settings (Butterworth filter order 6; default passband 0.5–40 Hz; peak-to-peak amplitude scale; 60 Hz input notch filter; 256 samples per second). Fourier-transformed amplitudes for each 1 Hz band from 1 to 32 Hz was passed to a dynamic link library and sampled 10 times per second by custom software (*Introspect*, written in C++), which recorded both EEG and task responses. The sum of amplitudes in lodelta (0.5–2 Hz) and hibeta (23–32 Hz) were each continuously monitored as artifact channels, and recording and task were automatically suspended (and an artifact warning tone played) whenever either value exceeded a threshold (100 μ V for lodelta and 30 μ V for hibeta).

2.3. Procedure

Participants were instructed about reducing sources of muscle artifact, including eye movements, and tension in the forehead, neck and jaw. They were explained the details of the task, and asked not to get too frustrated, because the experimenter would sometimes adjust variables to make the task harder. They were told that EEG alpha usually means a relaxed but alert state with eyes closed; that alpha might be increased by clearing, emptying, or quieting the mind, or mentally disconnecting from sensation or imagination; and that alpha might be reduced by mental activity – thinking, problem solving, intending (i.e., thinking about movement), by visual imagination, or attention to phosphenes (illusory spots of light that appear with eyes closed). They were advised that drowsiness could also reduce alpha, but to try to avoid the drowsy state and cancel appointments if they had bad sleep or were unusually tired. They were told that their own experience could vary from these instructions, and what mattered most was what they experienced before each prompt and the feedback they received. They were instructed that if they did not receive a prompt for a long time (e.g., 30 s) one strategy would be to guess what state they were in and try to change to the other state to see if that change would evoke a prompt.

Participants were seated in a comfortable chair with eyes closed in a dimly lit room. A white noise recording was played at minimal volume to mask ambient noise. A 150-s eyes-closed baseline EEG was recorded each session, and was used for each of three sets of trials. The PAF was defined as the frequency from 8 to 12 Hz with greatest median amplitude in the baseline. Eight or 12 Hz were only defined as the peak if they exceeded the amplitude at seven or 13 Hz, respectively. If no peak median was observed, the same procedure was applied to the mean values. About 5% of participants (not included in the $N = 106$) were excluded from the study if they had no PAF, or if they had electrocardiogram artifact at both F3 and Pz. About 10% of subjects had a peak frequency at Pz but not F3 on their first session scheduled to run at F3. In this case, they were switched to Pz for this session. About half of these or 5% of subjects had no F3 PAF on their second F3 session. For these subjects, the Pz PAF was used for both locations. The PAF found on the previous session was sometimes used when a PAF could not be found at a given location.

Each epoch in the baseline was ranked among a percentile distribution of alpha amplitudes of the most recent 150 s initially derived from the baseline recording. The baseline was updated with each response, or whenever the experimenter pressed the pause button. The triggering of new prompts was suspended for 4 s after each prompt or after resuming from a pause. A prompt tone was sounded whenever the alpha band amplitude exceeded a critical threshold difference from the median of the baseline. Recording was then suspended until the subject responded.

The critical threshold to trigger a prompt varied randomly from 1 to 30th percentile for low alpha trials, and from 71 to 100th percentile for high alpha trials. Subjects responded “high” or “low” with a keypress response, and received immediate feedback after each trial whether the response was correct (a high pitched tone) or incorrect (a low pitched tone). Three sets of about 36 trials, or about 108 trials were administered each session, with 1- or 2-min breaks between sets while the experimenter adjusted variables for the next set. With sensor application and removal, sessions lasted about 55 min. Participants were asked to return for a total of 10 sessions (one or two sessions per week), and were paid \$10 per session.

Sensor location (F3 vs. Pz) was alternated between sessions unless a participant reached a criterion score (binomial $p < .01$), and remained at the criterion location thereafter. Trial types (high vs. low and relative vs. absolute amplitude) were randomized within each set of trials by using the rand function in C++ to generate a random number, and assigning the type of trial based upon whether the number was odd or even. Software was programmed to exclude runs of six or more of the same (high or low) trial type, although participants were not informed of this constraint. Software limitations required varying bandwidth (1, 3, or 5 Hz around each participant's PAF), and duration (or smoothing average; 1, 2, or 4 s) between sets of trials in a counterbalanced order.

3. Results

Participants were assumed to have achieved significant discrimination of their EEG states if they had one set or session where the number of correct responses exceeded a criterion of binomial $p < .01$. With three sets per session there were, thus, four opportunities to achieve criterion each session. With criterion of $p < .01$, 40 subjects ("criterion Ss") achieved 99 criterion sets and 69 criterion sessions. After a participant achieved criterion once, the "rejection region" for defining criterion for that participant was doubled to $p < .02$, increasing the criterion data set for psychophysical analysis to 126 sets and 94 sessions. There was no effect of age or gender on achieving criterion in the task.

Table 1 shows the number of subjects achieving criterion over the course of 10 sessions. The mean number of sessions to reach criterion was 4.8. The mean number of sessions completed by those 66 subjects who did not achieve criterion ("non-criterion Ss") was also by coincidence 4.8, while the 40 criterion Ss completed 8.6 sessions on average. Among the 53 subjects who completed nine or more sessions, 75% achieved criterion. Only 13/67 non-criterion Ss completed nine or more sessions.

While the binomial p -value for defining a criterion performance is an estimate of the rate of type I error, the frequency of "false positive criterion" sets or sessions from a significant number *incorrect* is an empirical check on this theoretical estimate. Therefore, the observed frequency of criterion *correct* was compared to that of "false positive criterion" *incorrect* sets and sessions.

Among 2008 sets, 99 or 4.9% had $p < .01$ *correct*. By contrast, 24 or 1.2% of sets had $p < .01$ *incorrect*. Thus, the observed frequency of $p < .01$ sets was 4.9 times greater than the binomial probability, and $99/24 = 5.2$ times the empirically observed rate of false positive error. Using the observed rate as a more conservative estimate of the type I error frequency, the binomial probability of 99 of 2008 sets when the expected rate is $24/2008$ is $p < .0001$.

Among 583 sessions, 69 or 11.8% had $p < .01$ *correct*. By contrast, 15 or 2.6% of sessions had $p < .01$ *incorrect*. Thus, the observed frequency of $p < .01$ sessions was 11.8 times greater than the binomial probability, and $69/15 = 4.6$ times the empirically observed rate of false positive error. The binomial probability of 69 of 583 criterion sessions where the expected rate is $15/583$ is $p < .0001$.

Although software prevented trials from occurring when high levels of muscle artifact (amplitude in lodelta or hibeta) was present, it is still possible that some lower levels of muscle artifact could have influenced performance in the task. However, there were no significant within-subject differences in lodelta or hibeta amplitude between successful and failed trials during criterion performances, either for high or low trials.

When the session averages were graphed with respect to session number (Fig. 1), a learning curve was evident in Criterion Ss. The sixth–tenth sessions were significantly higher than the first session (t -test $p < .05$) in Criterion Ss.

A trend suggesting a cumulative learning effect was also seen in an analysis of the effect of intersession interval. Among 35 subjects who achieved criterion after the first session, the average intersession interval leading up to the first criterion set or session was 5.4 days, while among 52 who did not achieve criterion in more than one session, the average intersession interval was 7.4 days (t -test $p = .06$).

3.1. Psychophysical comparisons

Since percentile amplitude and absolute vs. relative amplitude were varied within sets of trials, only data from criterion sets were used for these comparisons. Since bandwidth and duration were varied between sets, comparisons were made between sets of trials only if the session or at least one set reached criterion. The resulting averages for bandwidth and duration appear lower because they include below-criterion sets.

Table 1

For each of 10 sessions, the number of subjects first achieving criterion performance (N First $p < .01$); the total number of subjects having achieved criterion (N $p < .01$ cumulative); the number of subjects remaining (N sub); and the percentage of remaining subjects having achieved criterion (Pct cumulative).

Session	1	2	3	4	5	6	7	8	9	10
N First $p < .01$	5	6	1	6	5	5	4	7	1	0
N $p < .01$ cumulative	5	11	12	18	23	28	32	39	40	40
N sub	106	91	83	76	72	65	57	55	53	51
Pct cumulative (%)	5	12	14	24	32	43	56	71	75	78

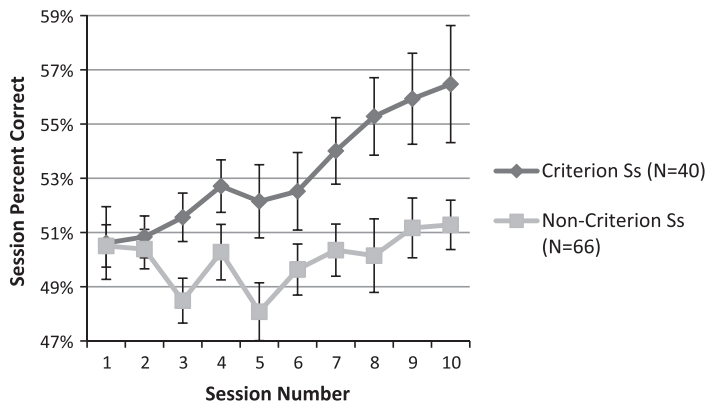


Fig. 1. Learning effect (effect of session number) on session averages in subjects who achieved criterion on the task. Bars indicate standard error.

To test the hypothesis that correct discrimination would be associated with the magnitude of the stimulus, the average percentage correct for each participant was calculated for two groups of three percentile bins: low: 1–10 (pct10), 11–20 (pct20), 21–30 (pct30); and high: 71–80 (pct80), 81–90 (pct90), and 91–100 (pct100). Repeated measures ANOVAs showed significant differences within the low ($F = 4.44$; $df = 33$; $p < .05$) and within the high ($F = 4.02$, $df = 33$, $p < .05$) groups. As predicted, the pct10 was greater than the pct30 bin (one-tailed t -test $p < .01$, $df = 33$) and the pct100 was greater than the pct80 bin ($p < .05$, $df = 34$), while the pct20 and pct90 bins were intermediate (Fig. 2).

Comparing the three high vs. the three low percentile bins in Fig. 2 suggests a superior task performance or a response bias for the high trials. Participants scored higher overall on high trials (mean 74%) than low trials (mean 69%), although the trend only bordered on significance (t -test; two-tailed $p = .053$).

The duration of the discriminative stimulus interval (or EEG smoothing average) also affected performance ($F = 11.4$, $df = 26$, $p < .001$). Compared to 1 s durations, both 2 s (t -test $p < .001$) and 4 s ($p < .01$) durations resulted in better performance (Fig. 3).

Participants performed better on absolute than relative amplitude trials (t -test $p < .05$; Fig. 4).

There was no significant effect of bandwidth ($F = 2.2$, $df = 32$), although a higher performance in the 5 Hz than 1 Hz trials trended toward significance (t -test $p = .08$; Fig. 5). However, as predicted, the correlation between the peak and the sidebands in the baseline (the first 150 s baseline recorded at the criterion location) correlated significantly with the difference between performance in the 5 Hz and 1 Hz trials ($r = .31$, $df = 31$, $p < .05$; Fig. 6). When 10% of subjects with lowest baseline peak-to-sideband correlations were removed, performance was significantly greater on 5 Hz than 1 Hz trials ($p < .05$).

A slightly higher number of participants achieved criterion at F3 (58%) than posterior locations (42%; Pz or O2) which was non-significant but trend-level (binomial $p = .08$). The average scores were the same (about 72%) and the number of sessions at criterion was the same (about 2.4) for both groups of subjects. Contrary to the prediction, the baseline PAF amplitudes were not significantly different at F3 or Pz between those who achieved criterion at F3 or Pz.

Baseline variance failed to predict criterion performance in the task. The variance in the first baseline alpha amplitudes at the criterion location (both for F3 and Pz) did not differ significantly (t -test $p > .10$) between those who achieved criterion at that location and those who achieved it at another location; or those who never achieved criterion. Differences between the average of the upper 70–100 percentile vs. the lower 1–30 percentile of the alpha amplitudes in the baselines similarly failed to predict whether a subject would achieve criterion.

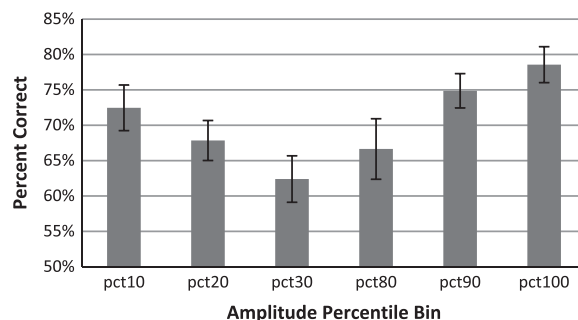


Fig. 2. Effect of percentile amplitude on discrimination task performance. Bars indicate standard error.

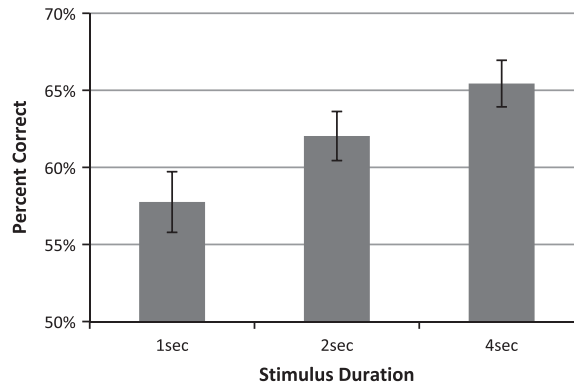


Fig. 3. Effect of stimulus duration or EEG smoothing average on discrimination task performance. Bars indicate standard error.

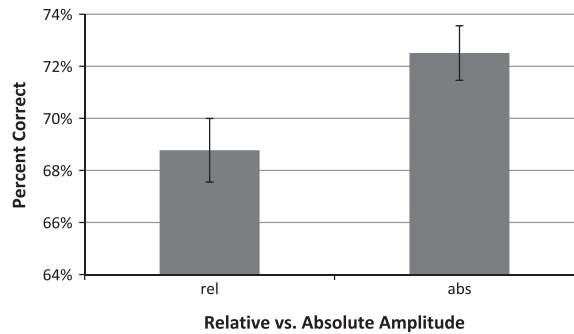


Fig. 4. Effect of relative vs. absolute amplitude on discrimination task performance. Bars indicate standard error.

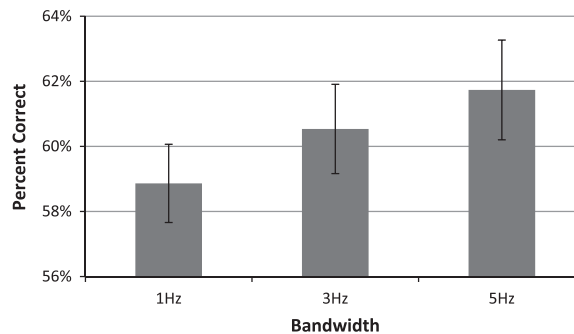


Fig. 5. Effect of bandwidth on discrimination task performance. Bars indicate standard error.

4. Discussion

The present study is the first to demonstrate that human subjects can learn to discriminate alpha activity since Kamiya (1962, 1968, 1969, 2011), despite at least three failed attempts at replicating the phenomenon (Cott et al., 1981; Legewie, 1975; Legewie, 1977; Orne & Wilson, 1978). The likelihood that true learning of an EEG state discrimination skill is taking place is supported by the significant ratio of criterion to non-criterion sets and sessions, the lack of effect of muscle artifact, and the significant learning curve effect (Fig. 1).

The finding that 75% of subjects who completed nine or more sessions achieved criterion, resembles Kamiya's finding that nine out of 12 achieved criterion in seven sessions. This observation suggests that the observed 40/106 or 38% could be an underestimate of how many would achieve criterion if given a sufficient number of sessions. It also seems likely that more subjects would achieve criterion in fewer sessions if the definition of alpha were held constant at the optimal values found by this study.

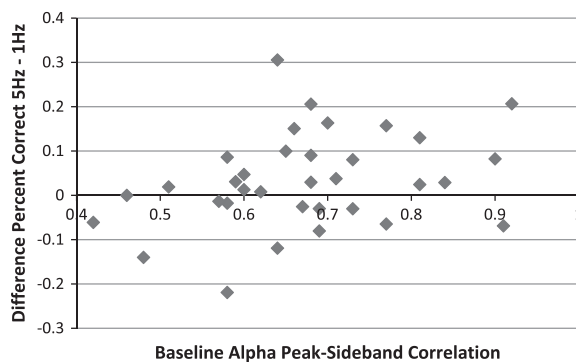


Fig. 6. Baseline correlation between alpha peak and sideband predicts effect of bandwidth on discrimination task performance between subjects.

There are at least two differences between the present paradigm and previous replication efforts which might explain the difference in results, including the use of a sliding baseline, and the use of longer stimulus durations.

The present defined study high and low alpha relative to each subject's own most recent 150-s sliding baseline. Further research is needed to directly measure the effect on performance of using sliding vs. stationary pre-task baselines. However, the successful use of a sliding baseline in this study suggests that *perceptual constancy* (Garrigan & Kellman, 2008) may apply to EEG state discrimination. That is, as with other sensory modalities, perception depends on *contrasts* more than *absolute energies*. Like a dim light being more detectable after a few minutes in a dark room, the relevant discriminable differences in alpha are those relative to one's own recent history. The observation that baseline variance in absolute alpha was not higher in those who achieved criterion than those who did not, also supports this view. If true, a future study might find that *changes* in amplitude ("increasing or decreasing?") are better discriminated than differences in amplitude ("high or low?").

A similarity with Kamiya (1962, 1968, 1969, 2011) and difference from Cott et al. (1981) was that threshold stimuli in the present study lasted 1, 2, or 4 s. Kamiya relied upon his own visual interpretation of the output of an 8–12 Hz filter, choosing events that lasted at least 1, and sometimes as long as 6 or 7 s. Cott et al. (1981) had automatic triggering of prompts after events that lasted only one half second. Psychophysical studies have shown that at near-threshold stimulus magnitudes, sensory organs act as energy integrators, where the principle of temporal summation allows small inputs to accumulate over time to produce a sensory response (Smith, 1998). Therefore, the present study's finding that discrimination of 4- and 2-s stimulus durations was better than for 1-s durations (Fig. 3) would support Kamiya's interpretation (personal communication, 2006) that stimulus durations were too brief in Cott et al. (1981).

However, the finding that discrimination performance was better for absolute than relative amplitude trials was the opposite of that predicted (Fig. 4), suggesting that dividing alpha amplitude by the wider spectrum contributed more noise than signal.

In addition to findings suggesting the importance of stimulus contrast and duration, the association of discrimination with stimulus magnitude (the superior performance in the 10th and 100th percentile bins; Fig. 2) is another property that suggests that EEG state discrimination might be conceptualized as a sensory modality. It is important to note that this study did not assume the presence of alpha was necessarily the stimulus being perceived. It is of interest that cognitive activity, the presence of thought, intention, or imagination, tends to be inversely related to alpha. The anecdotal reports of our research participants – although not systematically studied – were consistent with this general theme. The design and the results of this study leave open the possibility that the relevant discriminative stimuli or perceptual correlates are associated with either the alpha or non-alpha state, or both.

The trend toward scoring higher on high trials than low trials (74% vs. 69%) could be interpreted in at least two ways. First, the subjective correlates of high alpha states could be more salient than those of low alpha. Secondly, the trend could merely indicate a bias toward "high" responding, which gave as much advantage on high trials as it took away on low trials. Such a bias toward high alpha responding was also reported in Orne and Wilson (1978).

Although preliminary observations of a few subjects suggested that the sidebands (e.g., 8 and 12 Hz) contributed less clear signal than the peak (e.g., 10 Hz), the data actually trended toward better performance with wider bandwidths including these sidebands (Fig. 5). This observation suggests that the redundancy contributed by averaging alpha across a wider bandwidth might be more important than the greater potential validity of including only the peak. However, the relative importance of the sidebands and the peak was significantly related to individual differences in how interdependent the peaks and sidebands were during the pre-task baselines (Fig. 6). Beyond this single measure, very little is known about the influence of individual differences on EEG state discrimination. Further research is needed to assess the influence of intelligence, executive function, personality, or other EEG variables on success in this paradigm. Such study may help to indicate whether certain kinds of patients are appropriate candidates for EEG biofeedback therapy, or to identify exceptional cases for research.

It is possible that the non-significant differences between scalp locations observed in this study could be an artifact of the haphazard method of switching between locations each session and staying at the same location after criterion was reached. The purpose was more to find a location to get valid psychophysical data from than to rigorously assess the location variable. The categories of those achieving criterion at Pz or F3 are inexact because participants might have achieved criterion at the other location if given the opportunity. Similarly, the failure of pre-task baseline amplitudes to predict the optimal location might be associated with the failure to more systematically study which location was optimal.

Previous reports have raised concerns about whether subjects are truly aware of any subjective correlate of spontaneous differences in their EEG, or whether they are manipulating their alpha amplitude and reporting differences in volition (Cott et al., 1981; Orne & Wilson, 1978; Sommer & Matt, 1990). Rosenfeld and Hertzler (1973) reported direct evidence that manipulation of the EEG on correct discrimination trials was occurring in animal subjects. The present study made this variable a constant by instructing subjects to estimate their state and to intentionally change to the opposite state if a prompt was not received for a long time. Cinciripini (1984) provided instructions suggesting a similar approach. Cott et al. (1981) attempted to control for volitional control of the EEG by using only subjects naïve to neurofeedback or instructing experienced subjects not to manipulate their state. However, an examination of the demands of the EEG state discrimination tasks reveals that neither of these approaches actually controls for volitional processes in the subject. Being told sit quietly, without moving, with eyes closed, and to “do nothing” sounds a lot like being told to enter an alpha state. If subjects then perceive themselves in a quiet, relaxed but alert state, it is then a voluntary decision to either maintain that state or to activate thoughts, imagination, or intentions. Similarly, when they perceive their cognition as more activated, it is then a voluntary decision to either continue the ongoing cognitions or to “clear the mind” by some relaxation strategy. How do we know whether the maintenance of, or transitions between states of consciousness are voluntary or spontaneous?

Plotkin (1981) argued that awareness or discrimination of a physiological response was *conceptually* necessary for voluntary control over it. He reasoned that if a person is deliberately changing a physiological process, that means he or she is both motivated to change it, and has some basis for knowing that he or she is doing so. The successful manipulation of the EEG *logically entails* its successful discrimination. However, the reverse is not necessarily the case: discriminating a physiological state (e.g., knowing that one is nauseous) does not mean that one can change that state. However, when voluntary control does exist (such as knowing that clearing or activating the mind can influence one’s EEG state), it seems to be necessarily the case that every instance of discrimination entails a voluntary choice to either maintain the state or to change it. This is true regardless of whether subjects learn the difference by trial and error or by instructions.

Libet’s (1985) study of the relationship between the EEG, conscious volition, and movement suggested that the role of conscious volition is primarily inhibitory. It had long been known that a cortical potential called the readiness potential precedes voluntary movement, and Libet wanted to know when the will to act occurred in relation to the readiness potential and the movement. What he observed was that the readiness potential always preceded the will to act by about 350 ms. This experiment raised the question, what is the role of conscious volition if the brain is already making the decision before the will to act? Libet’s answer was that, consistent with the function of the frontal cortex, the role of conscious volition is largely inhibitory. “We don’t have free will, but we do have free won’t” (Gregory, 1990, personal communication cited by Blackmore, 2004).

Libet’s finding can also be interpreted to mean that the readiness potential is the discriminative stimulus of which the will to act is the perceptual correlate. Active volition of the type studied by Libet would be expected to suppress the sensorimotor rhythm, and would be analogous to the types of volition that suppress alpha. Voluntary alpha suppression may be too slow or unreliable to study by Libet’s method, but generalizing his finding would suggest that, as discriminative stimuli, alpha and its suppression may evoke volitional states among their perceptual correlates. Whether they precede or follow EEG changes, it might be that EEG state discrimination learning is a process of discerning which of a wide diversity of subtle volitional states are the right ones (as suggested by Cinciripini, 1984).

Another way of conceptualizing the relationship between awareness and control of EEG states is the difference between bottom-up (or stimulus-driven) and top-down (or expectation-driven) processing. At the onset of biofeedback training, sub-conscious physiological processes are by definition subthreshold stimuli. Psychophysical studies have demonstrated that the absolute threshold for a stimulus depends upon properties of the subject, including expectancies and motivation (Gescheider, 1976). Even in perception of superthreshold stimuli, the intention and volition of the perceiver are what orient perception toward the stimulus and block out background noise. Selective attention involves a partly voluntary, largely implicit suppression of all but a subset of the brain’s massive parallel input. From this perspective, the voluntary manipulation of mental states known to be associated with alpha states can be seen as a form of top-down processing, orienting the phenomenal spotlight to where the very subtle stimuli are expected to manifest. Anecdotally, strong performers in this study often fail to produce a prompt when willing each state and its alternate. They also often respond, based on a correct intuition, that their state is the opposite of the one intended. Even if these subjects become master manipulators of alpha, the task remains the correct detection of whether they were *successful* at that manipulation. Brener (1974) argued that voluntary control depends upon refference, or “the activation of interoceptive afferent pathways by the effectors involved in the act.” James (1890) postulated that repeated elicitation of a response results in this afferent information being stored as a *response image*, to which subsequent refference is compared. While it is possible that subjects in the present study are discriminating some non-perceptual aspect of their efferent volition (such as motivation or wanting), the findings that superior discrimination is associated with magnitude (Fig. 2), duration (Fig. 3), absolute vs. relative amplitude (Fig. 4) and bandwidth (Fig. 5) support an interpretation that EEG alpha state discrimination depends on the structure of afferent or refferent stimulation.

The relationship between discrimination training and control training may have important clinical implications. If control and discrimination skills generalize to each other, taking EEG state discrimination measurements could be a useful method of assessing client progress for neurotherapists who train control, and discrimination training could potentially improve the rate and extent of learning in control training. Learning is difficult to measure in biofeedback control training because therapists often adjust thresholds to maintain an optimum percentage of reward, and effects of training are often smaller than the baseline variation. By contrast, a direct measurement of success is intrinsic to every trial in discrimination learning, and for that reason, discrimination studies could be a more precise experimental model of control training. 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. Knowing what state one is in (for instance, discriminating states associated with the imminence of a seizure, panic attack, or a manic/depressive episode) may be of equal or greater importance than being able to control that state.

EEG state discrimination provides a novel empirical window on the relationship between the mind and the brain, and remains a vastly unexplored and promising field of inquiry. State discrimination research may produce clearer and more substantial phenomenological reports about the subjective correlates of EEG signals, because it trains recognition of contrasting poles rather than always (like standard neurofeedback) training “up” or “down.” Future studies should utilize this paradigm to characterize the phenomenology and psychophysics of other EEG constructs, including coherence, phase, peak frequency, event-related potentials, low resolution electrotopography (LORETA, Congedo & Joffe, 2007), and amplitude in frequencies other than alpha. Identifying the discriminative stimulus properties of physiological states and their relationship to control of these states, to their phenomenal correlates, and to individual differences, might contribute to the development of more specific and efficacious therapies.

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