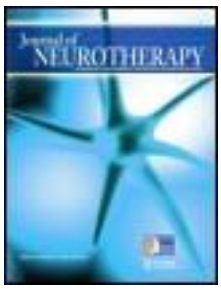

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Application of Repetitive Visual Stimulation to EEG Neurofeedback Protocols

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Application of Repetitive Visual Stimulation to EEG Neurofeedback Protocols

Thomas F. Collura, PhD

ABSTRACT. *Introduction.* This report describes an approach for using repetitive visual stimulation in the context of electroencephalographic (EEG) neurofeedback protocols. The EEG response to repetitive stimulation can be described as a series of successive evoked potentials (EPs), giving rise to a periodic response in the cortex, the *steady-state visual evoked potential* (SSVEP). Experimental data and signal analyses are presented to support this view. This approach is useful because evoked potential signals reflect sensory and perceptual processes, are sensitive to short-term shifts in attention, and also show important differences between normal and ADD/ADHD groups for example. Methods can be developed to provide real-time measurement and feedback of important variables related to the evoked response.

Method. Computerized averaged EP data are compared with filtered EEG "photic driving" responses measured in real time. Synchronous comb-filtering is used to extract real-time SSVEP data which are plotted along with conventional EPs and EEGs. Results are plotted as a time-series and short-term variations are visible.

Results. Results of pilot studies are shown, illustrating the ability to record real-time SSVEP's, and to provide information suitable for neurofeedback. The correspondence with averaged evoked potential traces is shown. These data support the concept that EEG responses to repetitive light flashes may be described as a superposition of successive evoked responses, and do not have to appeal to an "entrainment" model. Short-term variations in signal amplitude are shown to be sensitive to attentive state, and to reveal moment-to-moment changes in brain responsiveness.

Discussion. A basic understanding of the brain's response to repetitive stimuli can be used to develop a variety of feedback methods. Some

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of these are identified. The concept of entrainment is discussed and it is shown that neurofeedback with repetitive photic stimulation may be approached without appealing to the notion of a nonlinear response to repetitive stimulation. In our studies the EEG reveals only the expected periodic evoked responses, indicating that the brain is following the stimulus, but not that any lasting or "entrained" frequencies are introduced. Methods that do not rely on the concept of entrainment, but that depend solely on monitoring and feedback of the brain evoked response, provide promising avenues for neurofeedback.

Conclusions. This study provides experimental data and a supporting rationale for the use of photic stimulation in EEG neurofeedback. Our approach is based upon an understanding and use of the fact that the EEG response is comprised of a succession of sensory evoked potentials. This is in contrast to methods and models based upon the concept of nonlinear entrainment. A variety of methods for creating neurofeedback protocols are presented and discussed.

KEYWORDS. EEG, photic stimulation, visual evoked potential, steady-state visual evoked potential, entrainment

INTRODUCTION

The purpose of this report is to explore and analyze some methods for using repetitive visual stimulation in the context of EEG neurofeedback protocols. Basic principles and examples using event-related potentials as biofeedback signals have been described by Rosenfeld, Stamm, Elbert, Rockstroh, Birbaumer, and Roger (1984). A key issue is the real-time extraction and feedback of relevant evoked potential information. There are many ways to introduce such stimulation into a neurofeedback setting, and different approaches have different effects on the training, the subject, and the outcome. We will show results of pilot studies using flickering (pulsed) light stimulation to produce an EEG response. The focus is on instrumentation, methods, and underlying physiological concepts. While the literature contains a variety of clinical reports on therapeutic effects (for example, Patrick, 1996), the purpose here is to identify key methodologies and review their applicability from a basic point of view.

Whenever a brief stimulus is presented to a trainee, there is a tran-

sient brain response due to that stimulation (Ciganek, 1961). The signal produced in the EEG is generally very small, but it can be detected. In cases where it is possible to discern the EEG changes, either in the raw EEG or in a processed form, then there is said to be an *event-related potential* (ERP), particularly a *sensory evoked potential*. The evoked potential provides an indication of the effect of the stimulus on the brain, and it has been established that the EP is sensitive to changes in sensory and perceptual processes (Schechter & Buchsbaum, 1973; Naatanen, 1975).

Stimulation may be repetitive, or it may be non-repetitive. By repetitive, we mean that successive stimuli occur within a relatively short interval of time (well below one second), they occur at regular intervals, and that they are sustained throughout the stimulation period, which can be anywhere from under a second to many minutes, or more. When the stimulation is not repetitive, then it is said that there is a single EEG brain evoked potential response that is embedded in the ongoing EEG activity. If the stimuli are provided in a successive manner so that a computer can analyze more than one of them, it is possible to extract an estimate of the averaged evoked potential, which represents a canonical, or standard, response of the brain to the stimuli. When the stimulation is repetitive in nature, each stimulus follows the previous one by a short period of time (less than 500 milliseconds), and the successive evoked responses in the brain are found to overlap in time, so that the trailing end of one response is superimposed upon the beginning of the next.

When repetitive stimulation is applied, there is a small periodic signal introduced in the EEG. This phenomenon was first reported by Walter and Walter (1949). Studies by Van Der Tweel and Lunel (1965) and Regan (1966) further clarified this effect. In general, a repetitive flash produces an EEG response at the same frequency as the stimulation, and harmonics may be present. When sinusoidal light is applied, there is a stabilizing effect, and an interaction with intrinsic rhythms (Townsend, Lubin, & Naitoh, 1975). This effect is not seen in the case of flickering or square-wave light, which produces a simple train of stimulus-induced visual evoked potential waves (Sato, Kitajima, Mimura, Hirota, Tagawa, & Ochi, 1971; Kinney, McKay, Mensch, & Luria, 1973). Van Hof (1960) analyzed averaged visual evoked responses to a flash stimulus, and compared the waveform produced by repetitive flashes to that predicted by arithmetically combining the response to flashes at 1 per second. The linearity of overlap was confirmed by showing this equivalence for the entire range of flash rate studied, with flash rates of 2 per

second to 18 per second. Childers and Perry (1971) presented averaged visual evoked response elicited by spot flashes from 0.5 per second to 15 per second. Visual inspection of their waveforms confirms that the size and latency of evoked potential components is preserved across frequencies, and that the successive responses overlap, producing the observed response. Furthermore, the synchronous component response shown in their report is identical in shape to the frequency spectrum of single evoked responses presented by McGillem and Aunon (1977). This similarity in spectral energy distribution is what would be expected from a linear overlap model (Collura, 1987; 1990). In particular, a low-frequency band from 4 to 10 Hz is evident, and a higher-frequency band from 12 to 20 Hz is also evident. From these results, it is clear that repetitive visual stimulation produces a periodic evoked potential in the EEG, and that the frequency characteristics of this periodic wave can be predicted by using simple linear superposition.

Flickering and square-wave light are understood to produce results by similar mechanisms, although square-wave stimulation produces separate "on" and "off" responses, which are combined in the case of a single momentary "on/off" response to a brief light flash. Despite this difference, observations with both flicker and square-wave evoked potentials can be entirely explained by the assumption that evoked responses are being elicited in a repetitive manner, based upon linear superposition of the responses. This includes the presence of harmonics, which are a simple consequence of the complex wave shape of the individual evoked responses, and the resulting Fourier Series that describes the frequency spectrum (Collura, 1978a; 1990). This point of view is further supported by work reported by Saltzberg (1976) which shows that transient wavelets in the EEG produce measurable peaks in EEG spectral power, which can be observed in the frequency spectrum. Based upon this understanding, our laboratory works exclusively with flicker and square-wave stimuli, and analyzes the EEG in narrow frequency bands. It follows from the mathematics of linear superposition that slow EP components will be manifested in the lowest (fundamental) response, while faster components will be reflected in higher (second and higher harmonic) frequencies.

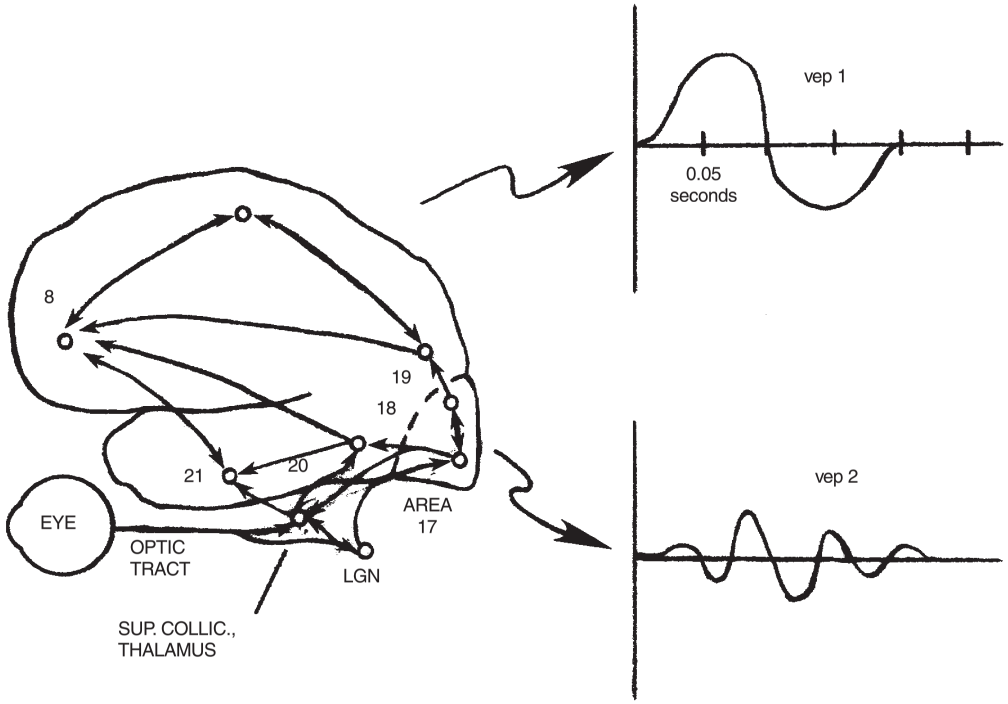
Further rationale for using this approach in neurofeedback includes the observation that transient evoked potentials exhibit correlations with attention and mental task (Spong, Haider, & Lindsley, 1969). Evoked potentials also show systematic differences in clinical populations, particularly with regard to ADD and ADHD. Linden, Gevirtz, Isenhart, and Fisher (1996) showed that an ADHD group had abnormal

high amplitude early components of the VEP, and that a mixed group (ADD and ADD/ADHD) had slow latency late components (N2, P3). Lubar (1991) reported similar findings in the 300 to 500 msec post-stimulus responses for LD children compared to normals. Further results were reported by Barabasz, Stevens, and Genthe (1999), who saw delayed P300's in children with ADD as well as ADHD. These findings are consistent with the high theta-low beta/smr profile of such children, based the understanding that the speed of cortical response is one factor that determines the frequency distribution of an EEG rhythm. This suggests that SSVEP latencies and amplitudes can be important indicators for assessment, as well as for training. In the interest of pursuing real-time feedback of SSVEP information, we recorded EEG and SSVEP traces under different attentive tasks, hoping to demonstrate systematic differences.

The relationship between late ERP components and endogenous rhythms becomes clear if one considers the commonalities, as well as the differences, between evoked and intrinsically generated cortical activity. In the case of endogenous rhythms, interaction between the cortical centers and the thalamic nuclei produce interactive sequences of afferent and efferent bursts, which are accompanied by sequences of cortical responses. In essence, an endogenous rhythm consists of a train of "intrinsic evoked potentials," which are elicited by thalamocortical interaction, rather than by sensory stimulation. A sensory evoked potential, on the other hand, consists of the cortical response to a particular sensory input that is specified in time. In both cases, the frequency characteristics of the individual cortical responses become manifested in the power spectral density of the resulting EEG wave (Collura, 1987). Since later components of individual cortical responses produce lower frequencies in the composite power spectrum, it is reasonable to expect a cortex that produces increased or delayed late components in a sensory evoked potential to also show increased energy in low frequencies in endogenous EEG activity.

To further understand the origin of the SSVEP waves, refer to Figure 1. This shows the anatomic pathways involved in the processing of visual information (Brodal, 1969; Regan, 1989). Note in particular that afferent neural signals originating in the retina of the eye are first sent to thalamic nuclei where they are preprocessed, and then forwarded to the occipital and infero-temporal cortexes, before being sent to other cortical locations. The initial processing in Brodman's areas 17 and 18 leads to the early components of the evoked response (less than 150 milliseconds), and further processing in other cortical locations produces the

FIGURE 1. Neuroanatomical pathways involved in the response of the human brain to a light flash. When the neural activity first reaches the visual cortex, Brodman areas 17 and 18, the early components of the visual evoked potential are produced. As activity diffuses in the cortex and reaches the association areas, the later components of the evoked potential are produced.

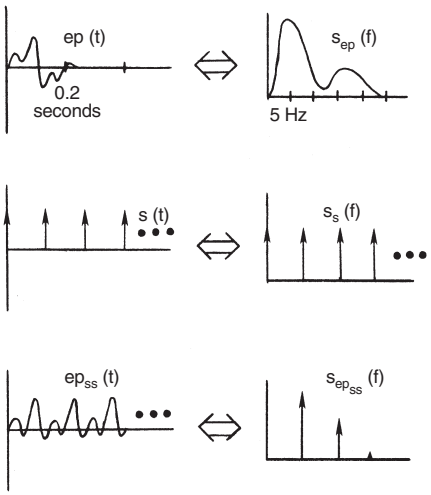


later components (200 to 400 milliseconds). This was illustrated, for example, in trauma studies by Greenberg, Mayer, Becker, and Miller (1977), in which loss of primary visual areas resulted in decreased or extinguished fast EP components, while loss of secondary areas resulted in decreased or extinguished slower components. In terms of the SSVEP, it can be shown that the early components will lead to higher frequency terms in the SSVEP (above 12 Hz), and the later components will lead to lower frequency terms (10 Hz and below) (McGillem & Aunon, 1977; Collura, 1987). These components are thus visible in the filter outputs of a system that stimulates at a predetermined repetitive rate (e.g., 7 Hz) and filters at both the fundamental, and the harmonic of that rate (e.g., 14 Hz).

In addition to clarifying the anatomical sources of the EP waves, this analysis helps to distinguish "driven" rhythms from endogenous rhythms, which are described by Sterman (1996) and Lubar (1997). Whereas the former are mediated by sensory and perceptual mechanisms and are synchronized to the incoming stimulation, endogenous rhythms are self-paced and involve a complex interaction between the cortex and the thalamus. As a result, short-term variations in amplitude and frequency of endogenous rhythms are mediated by different mechanisms than sensory evoked potentials. One potential commonality that exists between the two is the involvement of the cortical response, which partially determines the amplitude and shape of the rhythmic EEG activity, whether it is responding to repetitive sensory stimulation, or to intrinsically controlled pacemaker activity.

Figure 2 shows the signal relationships between the transient EP, the repetitive stimulation, the steady-state response, and the frequency spectra of each. The top traces represent a single EP, and its corresponding frequency spectrum. This is portrayed in the form shown by Childers and Perry (1971) and McGillem and Aunon (1977). The middle traces portray the repetitive stimulus as a train of impulse functions and their frequency spectrum. This spectrum is a train of impulses in the frequency domain (Brigham, 1974). The bottom traces show the repetitive evoked potential, and its frequency spectrum. The evoked response is given by the convolution of the single EP and the input train, and the spectrum of the evoked response is given by the product of the corresponding spectra of the single response, and the stimulus train, as a result of the convolution theorem of the Fourier Transform (Oppenheim & Schafer, 1975). Because of this frequency-domain multiplication, the spectrum of the SSVEP is essentially a sampled version of the spectrum of the individual EP's, thus providing an estimate of the size of the

FIGURE 2. Signal and frequency spectral properties of a visual evoked potential (VEP), a repetitive stimulus train, and the resulting steady-state visual evoked potential (SSVEP). Left traces: time-domain signals. Right traces: corresponding frequency spectra (magnitude of the Fourier Transform). Top traces: single VEP and its spectrum. Middle traces: stimulus train and its spectrum. Bottom traces: SSVEP and its spectrum. All right-hand traces are Fourier Transforms of the corresponding left-hand traces. The bottom left signal is the convolution of the two signal above it, while the bottom right spectrum is the product of the two spectra above it, due to the convolution theorem of the Fourier Transform. This analysis explains the observed EEG spectral peaks at the fundamental and harmonic frequencies, when a repetitive visual stimulus is presented.



peaks of the top spectrum, at frequencies defined by the rate of stimulation, and its integral harmonics. This analysis demonstrates that while the rate of stimulation determines the frequencies at which SSVEP energy will exist, the morphology of the individual EP responses determines the amplitude of those peaks, and also introduces the short-term variations in response amplitude.

METHOD

The SSVEP can be recorded by filtering the EEG using narrow-band filters. The filters are designed with center frequencies that match the stimulus frequency, and its integral harmonics. This provides the ability

to measure the signal components in real-time. By reconstructing the periodic waveform from its harmonic components, the entire SSVEP can be estimated. The underlying signal model and method of measurement has been described by Collura and Loring (1977) and Collura (1978a,b; 1990; 1996). This method focuses on analyzing the EEG components that are locked to the stimulus, and is designed to reject other activity. Thus, this method does not attempt to determine any effects that the stimulation has on intrinsic rhythms or background activity. Instead, it focuses on measuring the response to the stimulation only, thus reflecting sensory and perceptual activity, both from primary sensory areas, and also any broader cortical late activity that may also be stimulus-locked.

In summary, in order to record evoked potentials in this manner, we stimulate at the rate F flashes per second, and then filter the EEG at 1F, 2F, 3F, and so on. All of the recordings shown here were measured using specially constructed analog filters using standard design methods (Millman & Halkias, 1972). The SSVEP can be measured in real time, and it could be fed back, permitting the trainee to hear the visual cortex as it responds to the lights that are being seen. In the studies shown here, there was no feedback to the trainee.

Subjects in this study were four normal males of college age. They were screened to ensure that none had a psychological or neurological disorder, including epilepsy or ADD. Example data were recorded during a single session for the 4 Hz studies, and another session for the 7.5 and 8.5 Hz studies. Data shown are typical, and are illustrative, being from single trials of the methods described below.

Visual stimuli were presented using yellow LEDs mounted in welder's goggles positioned over the subject's open eyes. LEDs were positioned to achieve visual overlap ("fusion") of the two spots. LEDs were driven by 10-millisecond current pulses, providing an averaged light output of 0.0023 milliwatts per eye. A Grass silver chloride electrode was placed at Oz, referenced to the right ear, with a left ear ground. EEG was measured using a Grass Model 12 EEG amplifier (type 7P511) with bandwidth set at 0.1 to 30 Hz. This signal was fed into channel 1 of a Hewlett-Packard Signal Averager, which was set to average 64 successive responses. The signal was also sent to a custom-built comb filter that filtered the EEG at 4, 8, 12, and 16 Hz, using third-order analog filters (Butterworth type). The time-constant of the filters was set at 2.5 seconds. This provided an effective bandwidth of 0.13 Hz, which is sufficient to reject unrelated EEG activity, while responding quickly to changes in the evoked responses. The output of this filter was fed into

channel 2 of the Signal Averager for display, where it could be superimposed on the averaged signal computed within the instrument. Channel 2 was not averaged, however. As channel 1 was collected and averaged, channel 2 was set to free-run, providing a single sweep display that synchronized the two signals for visual comparison. Screen images were captured using a Polaroid camera attached to the bezel of the Averager.

As an alternative presentation, time-series were recorded on a Gould Model 2400 4-channel strip chart recorder. All four banks of the comb filter were summed into one channel of the strip chart, to reveal the composite SSVEP as an ongoing waveform. This was plotted simultaneously with the raw EEG signal, for visual comparison.

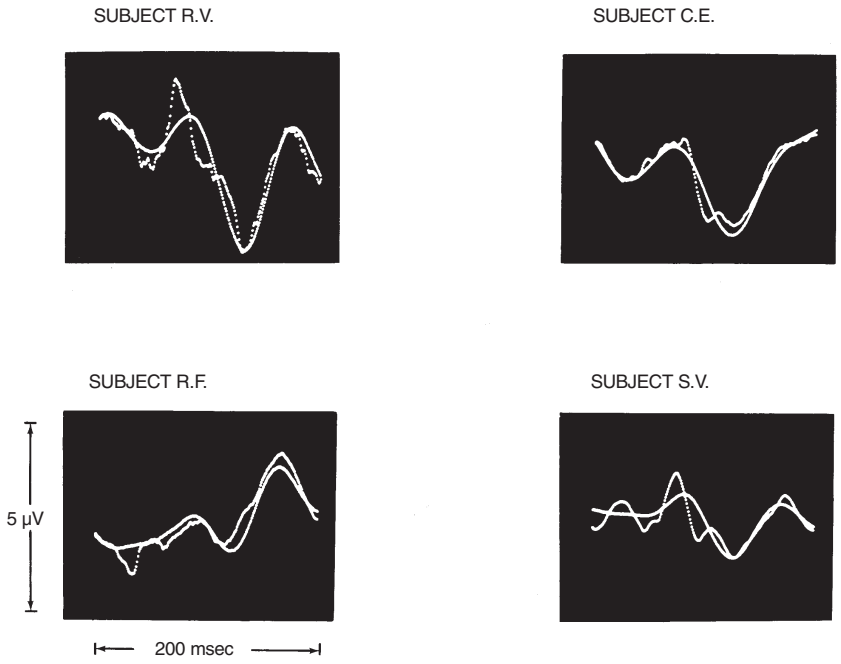
When monitoring short-term state changes, visual stimulation of 8.5 flashes per second was used. Auditory stimulation (clicks) at 7.5 per second was also presented, as an alternative target for the subject's attentive focus. EEG was fed into the comb filters described above, with center frequencies set at 7.5, 15, 8.5, and 17 Hz. The output of the comb filters was fed into a Gould Model 2400 4-channel strip chart recorder that used pen and ink to record the traces on moving paper. These traces provide a continuous readout of the filter signals. The chart speed was slowed so that one page of data covered two minutes. Because the traces run slowly, the sinusoidal filter outputs draw a solid area that describes the amplitude (envelope) of the signal. For the 7.5 and 8.5 Hz recordings, individual filter channels were fed to separate traces, so that they could be seen independently.

RESULTS

A typical result of the 4 Hz study, including a comparison with the averaged VEP, is shown in Figure 3. What is seen is the response of the brain to a light flashing four times per second. There are two traces superimposed on each of the four graphs. One trace, the smoother of the two, is the "free running" output of the bank of filters set at 4, 8, 12, and 16 cycles per second. Superimposed on each of these filter responses is the average evoked potential computed by the signal averager.

The responses in Figure 3 exhibit the familiar ERP components, including the usual positive and negative transitions. The filter outputs are seen to superimpose on the average evoked potential demonstrating that even as we begin to flash repetitively, the resulting wave is a composite evoked potential. During the time that the average is being computed, the filter output was seen to change in shape, as is also evident in Figure

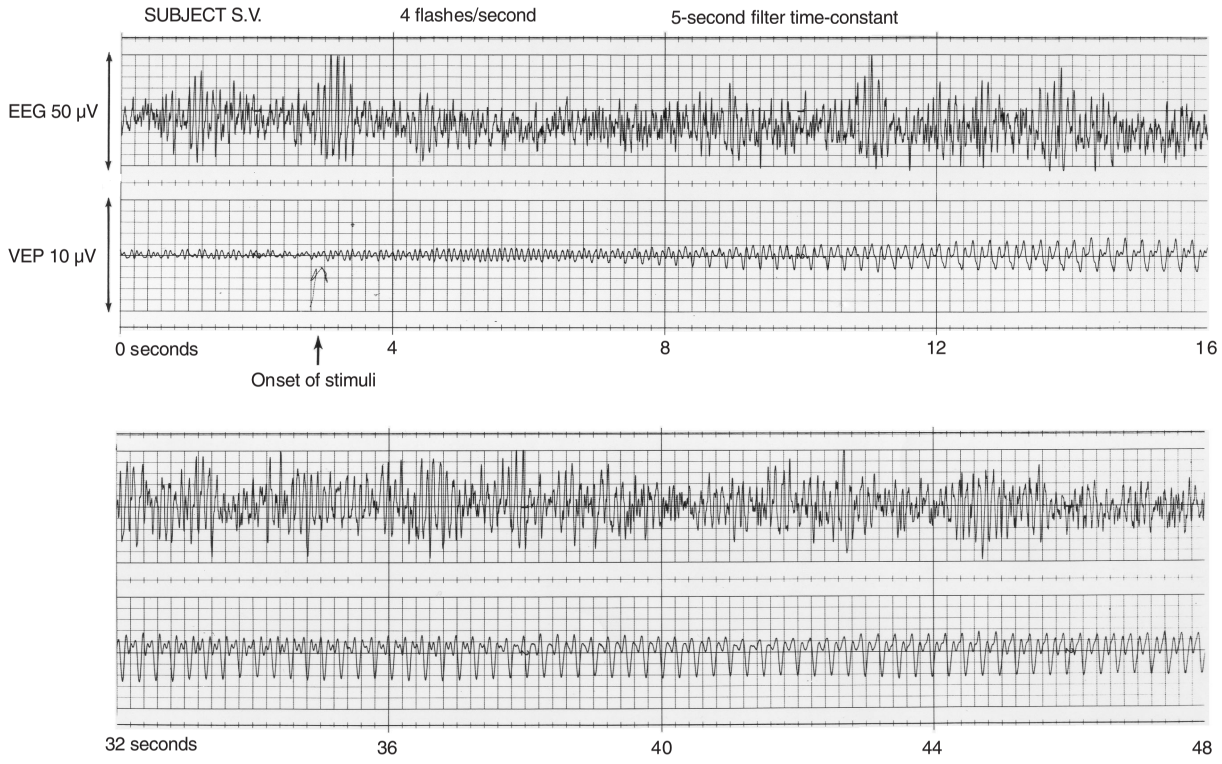
FIGURE 3. Superimposed traces for 4 trials. Each trace contains both the SSVEP (real-time) waveform, and the averaged VEP as computed on a computer.



4. For example, the bottom right trace of Figure 3 (Subject S.V.) shows two leading peaks at approximately 40 and 80 milliseconds in the average, but only one (at approximately 90 milliseconds) in the SSVEP. However, during this acquisition, both peaks were observed in the SSVEP to wax and wane, and also to change in latency; in the final SSVEP sweep which is the one shown on the display, only the 80 millisecond peak happened to be evident. This illustrates that the SSVEP is capable of dynamically tracking latency (and amplitude) changes that are obscured in the averaged EP, because the averaged EP combines changing features into a single waveform that represents the entire acquisition period. When the average is complete, the screen depicts the final sweep of the filter output, which is an estimate of the most recent SSVEP wave. These time variations are seen more clearly in a continual waveform display, as follows.

Figure 4 depicts a subject with an EEG trace running across the top of each pair and the combined output of the filters beneath it. It has been

FIGURE 4. A pair of 16-second traces. Top trace in each pair: Raw EEG waveform. Bottom trace in each pair: Synchronously filtered EEG revealing the time-locked steady-state evoked potential wave. Note time variations in the evoked wave, over periods as small as several seconds.

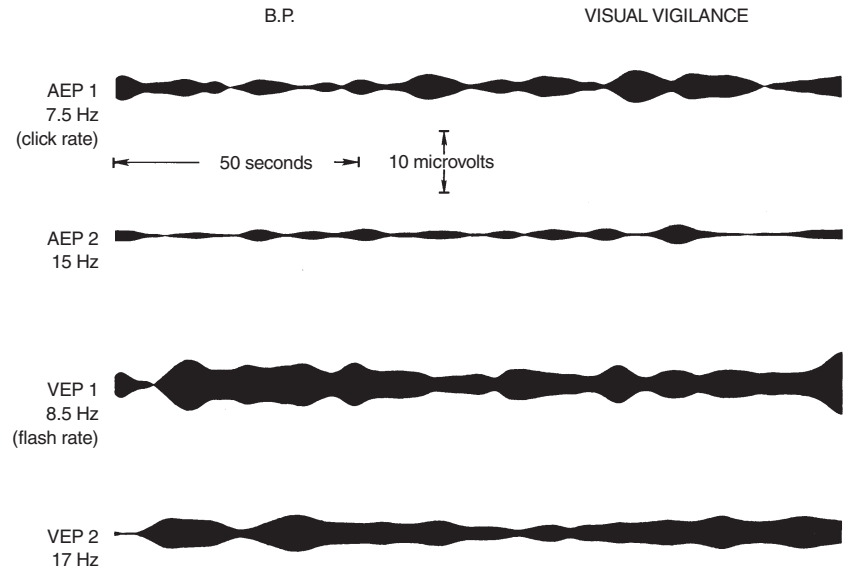


seen that the output of the filters is in fact a good estimate of the evoked potential that would be measured with an averager. The benefit of this technique is that the SSVEP is measured in real time, based upon the properties of the filters. Along the top we have the first 16 seconds of the recording. Before the stimulus is presented, the filters have a small output, as seen on the beginning trace. The stimulation is turned on 3 seconds into this trace. By the time 16 seconds have passed, the filters are already producing a very good estimate of the evoked potential. This SSVEP signal consists of a continual series of SSVEP waves that are the same as one trace of Figure 3, only shown concatenated in time. The start of each SSVEP wavelet is synchronized with the light flash that is occurring four times per second. If this trace is magnified, it produces an estimate of the waveform that would be obtained from signal averaging. However, instead of waiting a minute or more to see an estimated averaged VEP, it is possible to see the SSVEP result in real time. This output reveals the connection between the transient evoked potential wave morphology, and the complex SSVEP wave that consists of the fundamental plus harmonics of the stimulus rate.

On the bottom trace that extends from 32 seconds to 48 seconds after stimulus onset, even though the stimulation period has not approached one minute, visible changes are evident. Careful inspection reveals a fine detail in the evoked potentials, and one can identify particular peaks and valleys with particular latencies and amplitudes. These features can be seen changing about every 4 or 5 seconds. This method thus allows us to probe the brain functionally, allowing us to see what is occurring live, and in real time. This is much different from signal averaging, which provides a single, static wave estimate, after a minute or two. The real-time ability of this technique opens the door to doing biofeedback on this type of a response. This is, therefore, EEG evoked potential neurofeedback, and can be performed in real time.

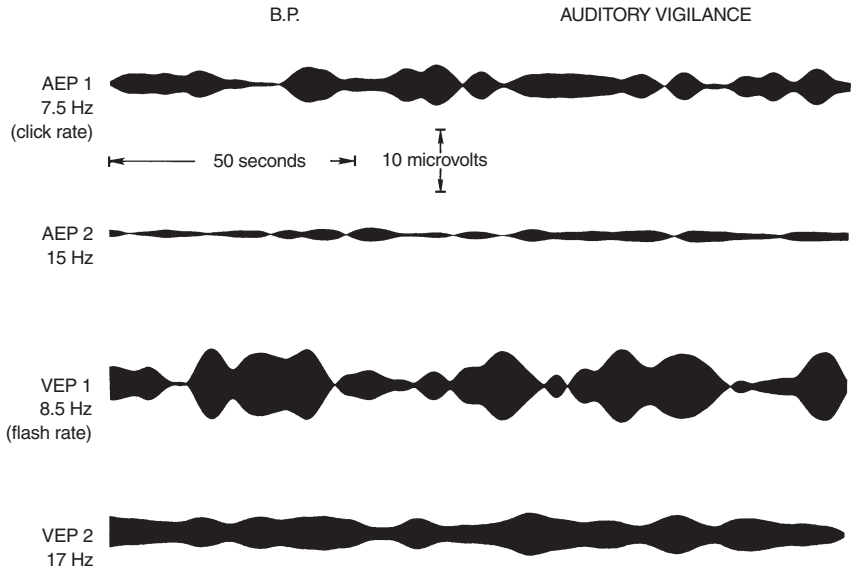
The next two figures illustrate short-term variations in signal amplitude under two different task conditions. As an example of short-term variations in SSVEP component amplitudes, Figure 5 shows filter outputs during the case of visual vigilance. In this example, the trainee is performing a visual vigilance task, and is pressing a button whenever a small (less than 3 dB) change is seen in the visual stimulus. The two upper traces show the filtered activity associated with auditory stimulus (clicks), used as an alternative attentive target for the vigilance task. Observing the lower two traces, we see the visual evoked potential at the primary frequency, which happens to be 8.5 Hz. Beneath this is the secondary component at 17 Hz. Visually, a candlestick type of appear-

FIGURE 5. SSVEP evoked-potential envelopes recorded during a visual vigilance task. Top 2 traces are auditory responses, and bottom 2 traces are visual responses. Waxing and waning of the VEP1 component should be noted.



ance is evident, reflecting the characteristic waxing and waning. A moment later, the subject performs the corresponding auditory vigilance task (Figure 6). There is a visible difference in the time-course of the evoked potentials. The entire time here is about two minutes. One can actually see the changes in how the brain responds moment to moment. In the case of auditory vigilance the visual cortex appears to be much more labile, with much more waxing and waning. The experimental design and statistical results are described in more detail by Collura (1996). These observations are consistent with a sensory gating model, such as that described by Hillyard and Mangun (1987). Based upon our earlier considerations, these results suggest that the observed variations occur in the attentional pathways that produce the later (lower frequency) components, rather than in the sensory/perceptual pathways that produce the earlier (higher frequency) components. This thus provides a very selective mechanism, by which we can selectively feed back (and train) the neural pathways of interest, exploiting the signal characteristics as a way to pinpoint the neuroanatomical mechanisms we wish to affect.

FIGURE 6. SSVEP evoked-potential envelopes recorded during an auditory vigilance task. Top 2 traces are auditory responses, and bottom 2 traces are visual responses. Waxing and waning of the VEP2 component is noticeably different from Figure 5. This illustrates a difference in how the visual attentive mechanisms are responding to the stimulation.



DISCUSSION

We have seen that the response to flashing stimuli produces energy at the fundamental and harmonics of the stimulus rate, and that this is a simple outcome of the generation of a complex periodic wave, which is the SSVEP. It is thus possible to interpret real-time filtered SSVEP data in light of the corresponding EP model. Consider the case with 8.5 Hz stimulation. The response to 8.5 Hz flash represents the energy in the low-frequency band of McGillem and Aunon (1977), and the 17 Hz response represents the energy in the high-frequency band. We are, in effect, sampling the amplitude of the EP frequency spectrum, by performing repetitive stimulation and filtering the corresponding components from the raw EEG. We observe these responses to wax and wane independently, suggesting independent generators in the brain. Our interpretation is that the high-frequency response reflects primary sensory mechanisms that produce short-latency EP components (less than 120 msec),

while the low-frequency response reflects secondary mechanisms that produce longer latency (between 150 and 250 millisecond) components. We are thus able to separate, in frequency, the brain processes that conventional EP averaging endeavors to perform in the time domain. Despite the ease with which visually evoked potentials are measured, we saw no such correlate in the auditory realm. Figures 5 and 6 do not show visually, nor did statistical studies show, that the auditory steady-state evoked potential is sensitive to attention in this type of study.

It should be emphasized that the appearance of harmonics in this case is not due to any non-linearity in the brain. They appear due to the simple signal properties of creating a repetitive signal, which is not just a simple sine wave. The measured EEG response of the brain is what would be predicted if we took the responses to a slower flash and sped them up. It is important to realize this, because there is a tendency to talk about entrainment and driving of brain rhythms, and what we see here is that, electrophysiologically, there is no evidence for any entrainment or EEG driving in this case. Entrainment is a nonlinear, plastic process that would produce: (a) larger than expected evoked responses, and (b) lasting EEG changes after the withdrawal of the stimulus, hopefully for a long period of time. For example, Childers and Perry (1971) argue that their data provide evidence for an alpha "driving" phenomenon, attributed to cortical resonance. However, upon careful inspection, the waveforms presented are as indicative of linear superposition as they are of a resonance phenomenon. Lubar (1998a, b) was motivated to look for both the alpha "resonance" phenomenon, and for lasting changes in EEG power spectra at the frequencies of stimulation. In these studies, neither effect was observed.

The entrainment perspective is well articulated by Siever (1997), which presents (page 2.3) EEG traces as evidence for squarewave photic stimuli producing a "frequency following response" that is "most effective" at a rate that matches the natural alpha frequency. The cited traces are, however, entirely consistent with Van Hof (1960), which demonstrated that such traces are in fact produced by linear superposition of evoked potential wavelets. Our studies are consistent with Van Hof's and did not demonstrate any unexpectedly large responses, or lasting EEG changes in response to flickering light stimuli. The observed "resonance" at "alpha" is in fact an EP response maximum that happens to occupy the same frequencies as low alpha (7 to 9 Hz). This SSVEP response peak is predictable based upon the morphology of single EPs, and the presence of a spectral energy maximum at

this range, because the EP itself contains appreciable signal components in the 120 to 140 millisecond range.

There appears to be no direct evidence that repetitive flash stimuli can produce an EEG response that goes beyond the production of a series of transient visually evoked EEG responses. There are various reports and methods that make use of the concept of entrainment in a therapeutic role (Patrick, 1996; Carter, Russell, Vaughn, & Austin, 2000). These require model-specific design of equipment and procedures, and appeal to the notion that the frequency of stimulation is tightly coupled of the trainee's endogenous EEG signals and changes therein. Our approach is entirely different. We do not appeal to any notion of entrainment and our current interests are specifically twofold: to record, measure, and train the sensory pathways that are associated with the evoked activity itself, and to produce EEG systems that are able to control visual stimulation as an assist to neurofeedback, without being restricted to specific frequency or entrainment-based approaches. The evoked-potential-based approach appeals to a different set of physiologic considerations, involving the learning processes in sensory-related pathways, and interactions between them. These interactions define the nature of the induced SSVEP activity, as well short-term variations in the evoked responses.

How might this be relevant to attention, learning, or task-related performance? One might expect that there would be important differences in the time-behavior of these real-time measurements. Previous studies of visual evoked potentials have revealed a systematic dependence on attention and other brain state variables (Naatanen 1975; Regan 1989). However, the time-course of the relevant mental processes is not revealed by conventional averaged evoked potential techniques.

At the simplest level, photic stimulation can be used with EEG neurofeedback, as a simple adjunct. This might precondition an individual before training, or postcondition them afterwards. This is not integrated with the neurofeedback. This could be used before, during, or after neurofeedback, but it is not controlled by the EEG in any way. However, using the EEG to control the stimulus parameters offers additional possibilities. We are exploring methods that use such control in simple ways. One method is called non-volitional EEG neurofeedback in which the EEG is used to control a stimulator, generally to train an increase in the evoked response. This approach could also be used to decrease a rhythm. Simple nonvolitional neurofeedback was introduced by Srinivarsan (1988). Figure 7 shows the basic design of this type of system.

FIGURE 7. Basic system for nonvolitional EEG biofeedback (Adapted from Srinivarsan, 1988). The EEG signal is filtered and used to control a photic stimulator.

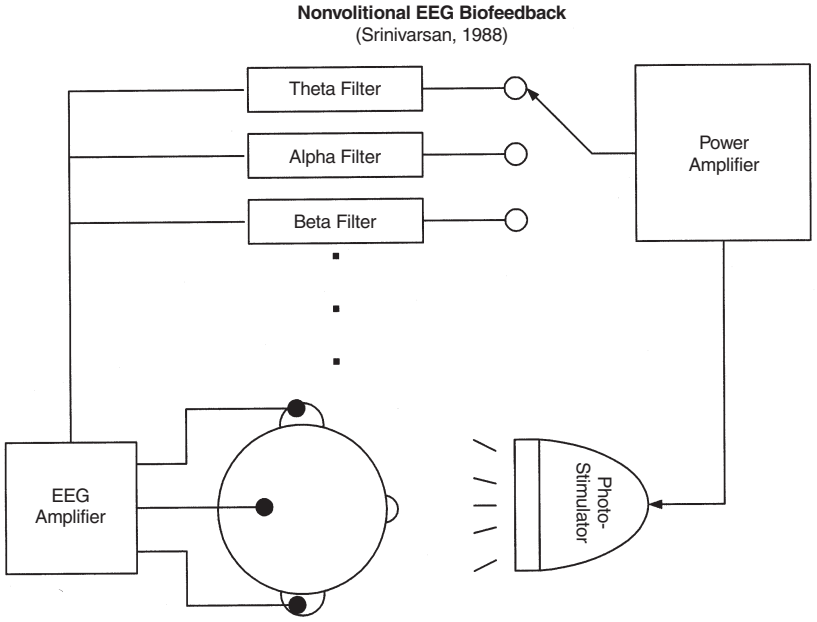
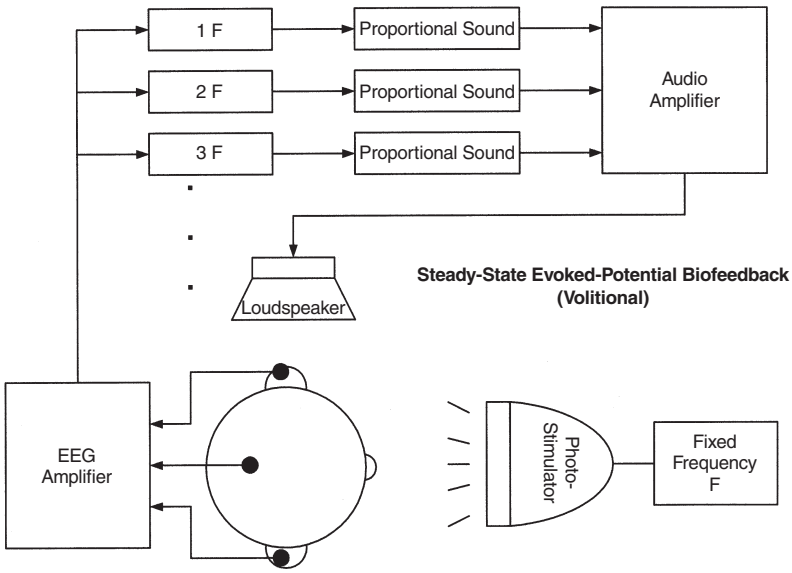


Figure 8 shows the basic approach to using the SSVEP signal itself for feedback. In a system of this type, the trainee hears the brain's sensory and perceptual response mechanisms in real time, and can use these for training purposes. The audio feedback reflects the brain's response to the repetitive stimulation, and allows the trainee to receive feedback regarding their current state of attention. This trains different pathways and mechanisms than conventional neurofeedback. It actually trains the sensory/perceptual pathways based upon evoked activity, using a volitional technique.

It is also possible to perform simple EEG controlled photo stimulation, based upon simple control of the light and sound system based on EEG (Figure 9). In order to perform EEG-controlled photo stimulation, one measures the EEG and filters it, then adds control logic to turn the lights on and off under control of the EEG. This can be used to stimulate at a fixed frequency that has no particular relationship to the endogenous EEG. Initial trials using this method have shown that it may provide a useful assist. The system can turn the stimulators on or off, and

FIGURE 8. Basic system for SSVEP biofeedback. The trainee is photically stimulated at a fixed frequency, and the resulting EEG response is measured using comb filters. This information is fed back to the trainee in the form of variable tones.

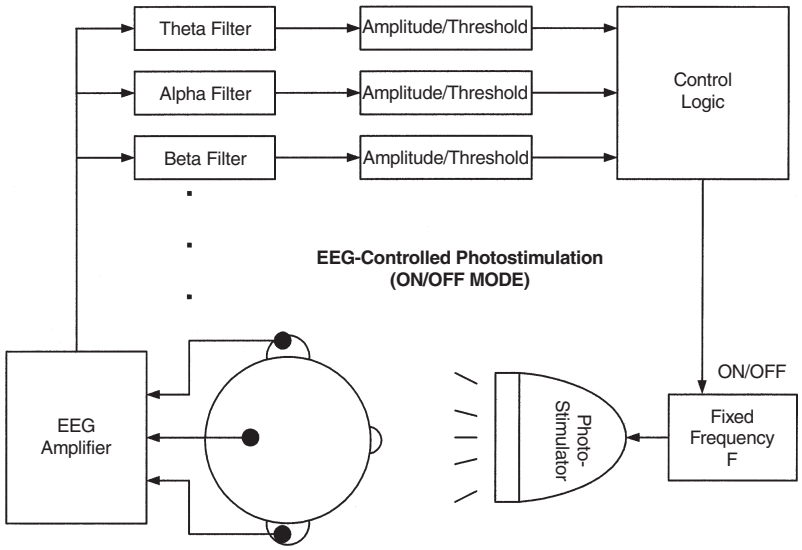


can add a non-volitional aspect to enhance the neurofeedback experience. For example, if 12 flash per second stimulation is delivered whenever the subject's theta (4 to 7 Hz) wave exceeds a threshold value, the system has an effect of extinguishing excessive EEG theta by the simple mechanism of distracting and engaging the cortex, so that theta cannot be produced at such a high level.

One can make a distinction between volitional and non-volitional methods using this approach. A volitional method requires instructions to the trainee, and presupposes expectation of a reward or a goal. The feedback provides information that must be rapid, accurate, and aesthetic. The trainee must find and recognize states reflected in the feedback information, consciously or unconsciously. Learning occurs with practice under an operant conditioning model, and generally produces lasting effects.

In non-volitional methods, on the other hand, there are no instructions to the trainee and the stimulus itself introduces a state or a change in a state. It may introduce the brain to a state, or it may remove the

FIGURE 9. Basic system for EEG-controlled photostimulation. Photic stimulation occurs at a set frequency. Based upon a control protocol, the EEG system activates and de-activates the photic stimulation, for a variety of uses.



brain from a state. One example of this is theta blocking described previously. In this case, the effect of the stimulation does not depend on instructions to, or the intent of, the trainee. In time, the trainee may become more accustomed to being in a different brain state. This type of learning is closer to classical conditioning than operant conditioning.

In all of these examples, regardless of volitional or nonvolitional aspects of the neurofeedback design, the direct effect of the stimulus on the EEG is transient and disappears once the stimulation is withdrawn. It is thus possible to introduce the brain to a frequency experience, and after a brief period of this experience, discontinue the stimulation. Such methods may reduce neurofeedback training times, but do not depend on any determination of the dominant EEG frequencies, or appeal to any nonlinear entrainment phenomena. When we combine volitional and non-volitional neurofeedback, we may be able to produce a more rapid initial ramp-up to the learning process. We can provide an ongoing assist ("training wheels") or we can assist with difficult aspects; for example, a trainee having difficulty with theta reduction. This can provide more aggressive reduction of undesirable rhythms, can introduce

the brain to particular states, and may combine such effects, in a single neurofeedback protocol.

CONCLUSIONS

This report has outlined some specific issues and technical aspects of using repetitive stimulation in conjunction with EEG neurofeedback methods. Repetitive stimulation introduces a periodic evoked response in the EEG that can be measured and fed back in real time. It is shown that these methods provide an extension of classical EP methods, introducing a real-time aspect. As a result, when we use repetitive stimulation with neurofeedback, there are a range of possible methods and configurations, many of which remain to be explored. We can add non-volitional aspects to the volitional neurofeedback, which may have significant effects. We can also probe specific brain pathways and mechanisms. It is clear that we have just begun to scratch the surface, and considerable research and development should be anticipated before we have explored all of the possibilities that are apparent.

CAUTIONARY STATEMENT

Repetitive photic stimulation may produce adverse reactions including anxiety or nausea, and may cause seizure activity in subjects with photosensitive epilepsy. Care should be exercised when using any of these methods. When there is a possible concern, a neurologist should be consulted, and a clinical workup and EEG may be desirable, to determine any risks that may exist.

STATEMENT OF INTELLECTUAL PROPERTY

Some of the methods described herein are contained within a pending patent application by the author.

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