Perceptual and Motor Skills, 1997, 84, 527-536.

DIFFERENTIAL ENTRAINMENT OF ELECTROENCEPHALOGRAPHIC ACTIVITY BY WEAK COMPLEX ELECTROMAGNETIC FIELDS[1]

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Summary.—The hypothesis was tested that compensatory susceptibility to electroencephalographic driving and entrainment by weak (1 microT) time-varying, externally applied complex magnetic fields would occur in normal subjects following successive stimulation by different patterns. 43% of the volunteers showed evidence of driving during the application of the complex magnetic fields and indications of resonance (entrainment) during the first 10 sec. following the cessation of the fields. The volunteers who exhibited driving and entrainment could be discriminated from those who did not by their more frequent reported experiences of fear and odd tastes during the stimulation. They were also more likely to have a preexposure history of a sense of presence and to experience intense meaningfulness when reading or writing prose or poetry.

The phenomenon of resonance interaction between applied patterns of stimuli (energies) and the locus within which the information contained within these stimuli is induced has been shown for both living and nonliving mechanical and electrical systems. We have defined two logical forms as contiguous (driving) and postcontiguous (entrainment). Driving is defined as the temporally coupled occurrence of a reliable representation of the pattern (or its systematic transformation) within a system. For example, driving of a photic stimulus by cerebral cortical neurons has been shown to occur during electroencephalographic recordings for both normal and epileptic individuals. Entrainment or "ringing" is defined as the continued representation or residual of the applied stimulus within the system even after the exogenous stimulus has been terminated.

The possibility that stimuli induced directly within volumes of neurons rather than transduced through normal afferent neuropathways could encourage neuronal resonance has significant theoretical and practical relevance. If, as we have reasoned, the spatial resolution at which resonance occurs is the level at which the processes leading to cognition and experience also emerge, then people who are more prone to exhibit specific subjective expe-

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riences spontaneously may be more prone to show driving and entrainment of the neuroelectrical arrays which generate these experiences.

The capacity of the human brain to respond to brief singular applications of electromagnetic fields at biofrequencies has been shown within several experimental contexts (Bell, Marino, & Chesson, 1992; von Klitzing, 1991). Response latencies range between 2 sec. and 10 sec. for sine-wave patterns whose amplitudes are within the mT (milliTesla) range. Similar response latencies have been observed for epileptic patients who had not responded to antiepileptic medication when 1 to 2 mT dc (steady-state) magnetic fields were applied through the brain volume by a pair of coaxial coils (Fuller, Dobson, Wieser, & Moser, 1995). The fields consistently triggered *subclinical* epileptiform discharges within the primary epileptogenic zone of the patients such as the right hippocampal formation.

We hypothesized that driving or entrainment, which would be sufficiently conspicuous to be measured by the gross field potentials recorded by electroencephalography, could be induced with complex waves whose magnitudes were within the microT and ultimately within the nanoT range (Subrahmanyam, Sanker Narayan, & Srinivasan, 1985). Three conditions, however, are required. (1) The wave shape or envelope must contain neuronally relevant information. (2) The interwave presentation or interstimulus interval must be optimal for entrainment. And (3), a different wave pattern must be initiated frequently to attenuate reactive inhibition (habituation) within the protective hierarchy of neurons which attenuates exogenous interference.

Method

A total of 9 men and 12 women, 20 to 25 years of age, volunteered as subjects. Participation was reinforced by a 2% bonus mark for a first-year university course in which the students were enrolled. They had completed the Personal Philosophy Inventory (Persinger & Makarec, 1993) during a class period about four to six weeks before testing. On the day of the experiment, each subject (tested singly) sat in a comfortable arm chair housed within a commercial acoustic chamber. Goggles were placed over the eyes and a pair of electromagnetic stimulation units (containers) were fastened on each side of the head by a Velcro strap. Each container housed four solenoids, each of which was connected to the homologous solenoid within the container placed against the scalp over the opposite hemisphere. The pairs of containers were placed either over the frontal, temporal, or occipital regions (7 subjects per placement; 4 women and 3 men). The chamber doors were closed and the lights were extinguished.

Each subject received the same sequence of magnetic field patterns generated by a Zenith 1211-DE (159 series) computer. The patterns were produced by converting a sequence of between 200 and 1000 8-bit values ranging between 0 and 255 (128 = zero polarity) to a corresponding voltage at a rate measured in millisecond per point. The time between generation of each pattern was also measured. The output signal was applied across each pair of solenoids in a sequence determined by a commutator circuit set at 0.5 Hz (the component of spatial rotation). This apparatus was previously described by Richards, Persinger, and Koren (1993). The intrinsic delay per pixel (point) was 190 microsec.

The wave patterns, defined as the characteristics of the variations within one cycle, were blank (zero polarity), 5-Hz sinusoid (generated by a mathematical equation), 10-Hz sinusoid (generated by a mathematical equation), low-intensity random variation (created by a sequence of random numbers between 120 and 136), high-intensity random variation (created by a sequence of random numbers between 0 and 255), negative polarity (a continuous series of numbers from 128 to 0 and then to 128), positive polarity (a continuous train of numbers from 128 to 255 and then to 128), sinusoidal complex [successive equal (in time) shifts from 5 Hz to 10 Hz to 40 Hz to 60 Hz within the same envelope], burst-firing (figural pattern published by Richards, *et al.*, 1993), and a pattern that amplified long-term potentiation in hippocampal tissue (Richards, Persinger, & Koren, 1996; Rose, Diamond, Pang, & Dunwiddie, 1988). The parameters for each pattern are shown in Table 1.

The order was selected on the basis of our theoretical model (Persinger, 1995) and was designed to flood the initial neuroprocess which inhibits responses to externally applied weak magnetic fields such that subsequent patterns would evoke a compensatory enhancement of resonance interaction. The concept could be considered analogous to the classical muscarinic-nicotinic response of the cholinergic system whereby a mild vasodilator response becomes a marked vasoconstrictive response to similar stimuli once the muscarinic receptors have been rendered functionally inoperative by a competitive antagonist (atropine).

During the series of exposures, bipolar electroencephalographic measurements over the occipital (O1, O2) and temporal (T3, T4) lobes were recorded continuously. A third channel which was connected to a sensor placed adjacent to the left cluster of solenoids was employed to record (and to verify) the occurrence of the fields and their patterns. A field meter indicated that field strengths within the spatial extension of the pairs of containers ranged between 1 microT and 5 microT.

At the end of the experiment (45 min.), each person completed an Exit Questionnaire designed to monitor the primary domains of subjective experiences that occur within these settings. These 20 items have been published elsewhere (Persinger, 1994; Ruttan, Persinger, & Koren, 1990) and employ a rating of 0 (no experience), 1 (experience occurred at least once) or 2 (expe-

TABLE 1

NUMBERS OF PRESENTATIONS, DURATION (IN MSEC.) OF EACH PIXEL, AND TIME (IN MSEC.) BETWEEN PRESENTATIONS OF WAVE PATTERNS

Pattern Name	Number of Cycles	Pixel Duration	Time Between Cycles
Blank Field	240	1	0
Complex Sine Wave	60	1	0
Blank Field	120	1	0
5 Hz Sine	150	1	0
10 Hz Sine	150	1	0
Blank Field	120	1	0
Long-term Potentiation	60	1	275
Blank Field	30	1	0
Long-term Potentiation	60	1	275
Burst Firing Pattern	49	1	3000
Blank Field	90	1	0
Negative Polarity	150	1	0
Positive Polarity	150	1	0
Negative Polarity	150	1	0
Positive Polarity	250	1	0
Complex Sine Wave	180	1	0
Complex Sine Wave	90	2	0
Blank Field	60	1	0
Low Amplitude Random	150	1	0
High Amplitude Random	150	1	0
Blank Field	60	1	0
Complex Sine Wave	45	3	0
Long-term Potentiation	264	1	0

Note.—The order of the pattern in this table reflects the temporal order of their occurrence during the experiment.

rience occurred frequently). The subject was instructed to contact the experimenters if any untoward experiences occurred within the subsequent few days.

Each subject's electroencephalographic record was evaluated by two separate examiners. Driving was defined as the emergence of visually discriminable, nonartifactual, i.e., not a conspicuous replication of the applied field pattern, signature. An example of driving is shown in Fig. 1 in which a burst of slower wave activity emerged primarily during the burst periods of the applied field. In this instance, the solenoids had been positioned over the prefrontal lobes and the driving was noted from the occipital but not the temporal region. The continuation of the 1-sec. bursts of slow-wave activity at the same interval as the stimulus presentations, but after the stimulus had been terminated (indicated by horizontal bars; amplification in Fig. 2) was considered entrainment (or "ringing"). This poststimulation emergence occurred, after a brief period (10 sec.) of no emergence within the temporal regions in particular and within the occipital regions intermittently.

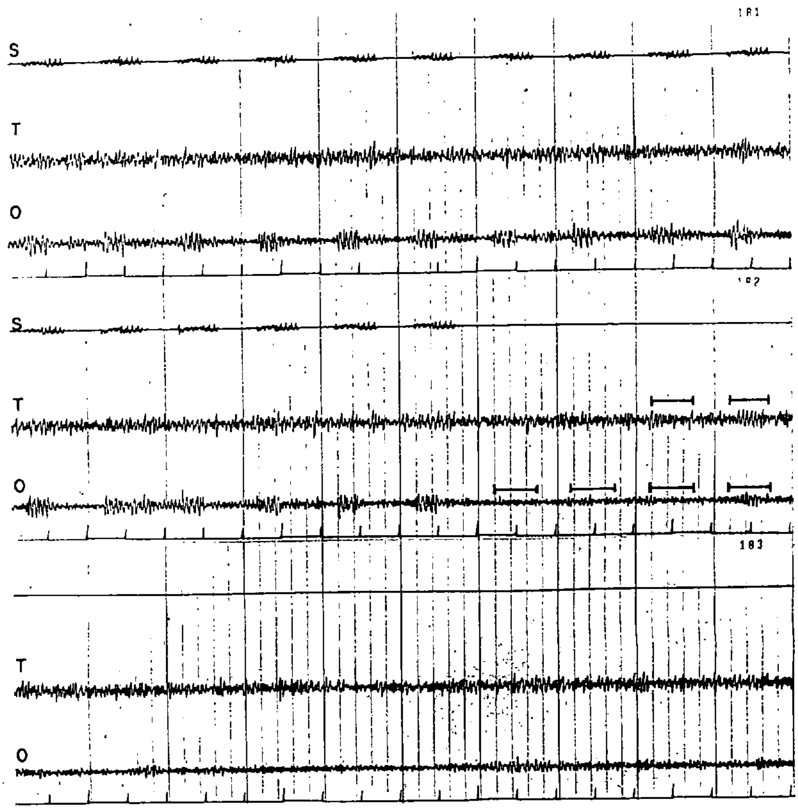

FIG. 1. An example of entrainment within the occipital (01/02) bipolar comparisons during presentation of the long-term potentiation pattern. Note the potential continuation (horizontal solid lines in panel 2) of the induction sequences for several seconds after the termination of the signal within both the temporal and occipital measurements.

Discriminant analyses were completed between the subjects who exhibited the driving and the entrainment relative to those who did not. The 15 primary phenomenological clusters including histories of a sense of presence, depersonalization, odd smells and auditory-vestibular experiences (Persinger & Makarec, 1993) were extracted from the subject's Personal Philosophy Inventory. The ratings for each of the 20 items from the Exit Questionnaire were also included. All analyses involved SPSS software on a VAX 4000 computer.

RESULTS

A total of 9 subjects (6 women, 3 men) displayed evidence of driving; these same subjects also showed evidence of entrainment. For all cases, the driving occurred after at least the first six different patterns had been applied. Discriminant analysis was completed for ratings on the 20 items from the Exit Questionnaire between the 9 subjects who displayed driving-entrainment and the 12 who did not. Because the sample was small, no more than four steps were allowed before the function was constructed.

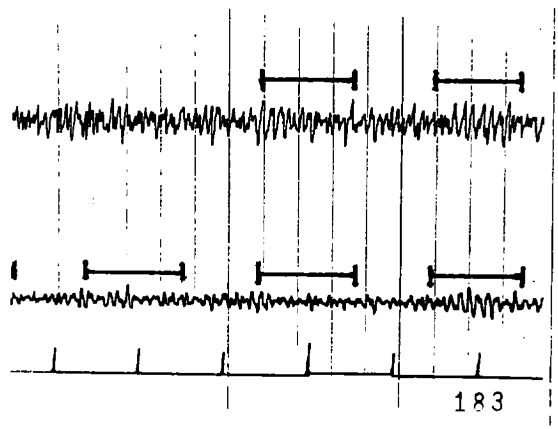

FIG. 2. Magnification of the "ringing" or periodic bursting of slow wave activity [horizontal solid lines] within the temporal and occipital regions of an illustrative subject shortly after the termination of the complex, pulsed magnetic field

The discriminant function was statistically significant ($\chi_4^2 = 16.24$, $p < .01$; canonical correlation = .78) and accurately classified all of the subjects who did not display entrainment and 7/9 subjects who did (91% total accuracy). Compared with subjects who did not exhibit entrainment, those who showed entrainment exhibited higher subjective scores (standardized discriminant coefficients in parentheses) for sensations of fear (1.22), odd tastes (1.02), and alterations in the brightness of the background (red) light (0.76) in the context of less frequent feelings of being somewhere else (−0.54). It may be relevant that 6 of the 9 who exhibited entrainment had been exposed to the sequential stimulation over the occipital regions.

Discriminant analysis (number of steps set equal to 4) of the subjects' scores for clusters of phenomenological experiences from the Personal Philosophy Inventory (collected several weeks before the experiment) generated a function (canonical correlation = .80, $\chi^2 = 17.47$, $p < .01$) contingent upon a single cluster (the sense of a presence) entering the function first. The subjects who exhibited entrainment were more likely to have experienced a sense of presence (32%) before the exposure than those who did not display entrainment (11%). Subjects who displayed entrainment were more likely to endorse (standardized coefficients in parentheses) experiencing of widened affect such as personal meaning for mundane events (0.91), sense of presence (1.13), and a preference to read poetry, and to keep written records of their emotional experiences (0.67).

Discussion

The possibility of artifactual induction of the applied wave pattern into the electroencephalographic records cannot be excluded. Even though, for example, the application of the field was over the prefrontal region for Fig. 1 and the "driving" occurred within the occipital region and not within the intervening temporal region, the time-dependent symmetry is conspicuous. It is possible that the nine subjects who met the criterion of entrainment contained electrode montages within which minute variations in planar orientation with respect to the applied field were more optimal for the induction of artifacts.

However, this would not explain the continued but less synchronous "ringing" or repetition of a brief signature within the record after the signal had ceased. Such paroxysmal patterns whose temporal parameters match the interstimulus presentations of the envelopes of magnetic field stimulation meet the criterion of our definition of entrainment. This continuation of the slow-wave bursts for a similar duration (as the magnetic field burst) at the precise times when the magnetic stimulus would have occurred had the presentation been maintained is strongly suggestive of a brief resonance of the stimulus.

Intuitively and realistically, considering the limits of electroencephalographic detection and the nature of the large field potentials that are measured by the sensory array, both the weakness and brevity of the signatures are expected. The possibility that the offset or termination of a stimulus train of complex magnetic fields might produce compensatory or "negative afterimages" of the characteristics of the stimulus train must also be considered. Fuller, *et al.* (1995) also found that subclinical epileptiform discharges occurred in epileptic patients when a dc magnetic field of about 1 mT (1000 times the intensity of our field strengths) was terminated. A very recent study by Charles Cook (1996, unpublished data) showed that the numbers of button presses by subjects who received the stimulus envelope containing the pulse which has enhanced long-term potentiation in hippocampal slices (Rose, *et al.*, 1988) occurred during the decasecond period *after* the termination of this field. Although potentially spurious, this pattern of long-term potentiation was first presented in the present study after five previous sequences. This was the approximate latency for the emergence of poststimulation entrainment.

Our working hypothesis is that a direct effect upon the cortical manifold is unlikely and that the bursts of slow-wave activity as reflected by surface electroencephalography are more likely to represent a direct effect of the applied magnetic field upon the clusters of intrinsic "burst-firing" cells within the thalamocortical system (Steriade, McCormick, & Sejnowski, 1993) or the entorhinal-amygdalohippocampal-thalamic system (Pare, Dong, & Gaudreau, 1995) which then modulate the fields of cortical neurons. This model is consistent with the observations of Fuller, *et al.* (1995) who found that the hippocampal formation displayed epileptiform activity in response to the applied dc magnetic fields. It may be of interest to note that the apparent suppression of the resonance within the 2 sec. after the cessation of the applied fields in our study and the transient emergence of the oscillations for the equivalent of two to five stimulus presentations, i.e., 4 to 10 sec., was noted in seven of the subjects whom we considered entrained. This transient effect is similar in duration to that reported by Bell, *et al.* (1992).

If our theoretical approach is valid, we would not expect every person who is exposed to this particular paradigm to exhibit discriminable electrocortical entrainment. We assumed that, given a limited number of fundamental strange attractors, at least a subset of our population would respond. The report of more intense sensations of fear, odd tastes, and alterations in brightness by those who exhibited driving would be consistent with the involvement of the insular cortex and its subcortical claustrum. Persinger and Richards (1995) suggested an area within the region of the transverse gyri and insula which may be vulnerable to these particular magnetic field patterns.

The occurrence of electroencephalographic patterns that we interpreted as due to transient entrainment did not emerge immediately but occurred only after several different signals had been presented. That the artifact of duration was not totally explanatory is indicated by the absence of this phenomenon in our many other studies in which a single stimulus pattern was presented for 20 min. We suspect that the more sensitive neuronal ensembles initially respond to electromagnetic patterns by generating counterfields which inhibit (and hence cancel) induction and thereby decrease the probability of the type of recruitment that would promote paroxysmal propagation. However, after repeated presentation by discrepant signals whose inter-event intervals interfere with this normal capacity to maintain neurons within these opposing "paroxysmal" patterns, these inhibitory responses collapse and the induction, driven by thalamic input, becomes visibly discernable by electroencephalography.

Our group has been particularly interested in the neurocognitive substrate for the sense of presence. We have hypothesized that this normal experience is the likely basis for the "Muses" (Persinger & Makarec, 1992) in Greek mythology as well as the epidemics of reports of visitations and "abductions" by succubi (incubi), angels, demons, and more recently, extraterrestrials. In this study, the subjects who were most prone to electroencephalographic entrainment also reported histories of a sense of presence and the type of widened affect that would be consistent with Bear's (1979) hypothesis of sensory-limbic hyperconnectionism. His argument was that enhanced input from the amygdaloid-hippocampal complex, most likely through the entorhinal cortices (Heinemann, Zang, & Eder, 1993), infuses experiences and verbally evoked images with marked personal and affective meaning. The possibility that nonepileptic individuals with this proclivity [as defined by elevated scores on psychometric inventories that might detect enhanced limbic lability or complex partial epileptic-like symptoms (Persinger & Makarec, 1992)] may be prone to a variant of entrainment by electromagnetic patterns derived from natural extracerebral sources (Budden, 1994) must still be considered.

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Accepted December 20, 1996.