Hypothesized neural dynamics of working memory: Several chunks might be marked simultaneously by harmonic frequencies within an octave band of brain waves

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ABSTRACT: The capacity of working memory (WM) for up to about seven simple items holds true both for humans and other species, and may depend upon a common characteristic of mammalian brains. This paper develops the conjecture that each WM item is represented by a different brain wave frequency. The binding-by-synchrony hypothesis, now being widely investigated, holds that the attributes of a single cognitive element cohere because electroencephalogram (EEG) synchrony temporarily unifies their substrates, which are distributed among different brain regions. However, thought requires keeping active more than one cognitive element, or WM “chunk,” at a time. If there is indeed a brain wave frequency code for cognitive item-representations that are copresent within the same volume of neural tissue, the simple mathematical relationships of harmonies could provide a basis for maintaining distinctness and for orderly changes. Thus, a basic aspect of music may provide a model for an essential characteristic of WM. Music is a communicative phenomenon of “intermediate complexity,” more highly organized than the firing patterns of individual neurons but simpler than language. If there is a distinct level of neural processing within which the microscopic physiological activity of neurons self-organizes into the macroscopic psychology of the organism, it might require such moderate complexity. Some of the obvious properties of music—orderly mixing and transitions among limited numbers of signal lines—are suggestive of properties that a dynamic neural process might need in order to organize and reorganize WM markers, but there are a number of additional, nonobvious advantageous properties of summating sinusoids in music-like relationships. In particular, harmonies register a stable periodic signal in the briefest possible time. Thus, the regularity of summating sinusoids whose frequencies bear harmony ratios suggests a particular kind of tradeoff between parallel and serial processing. When there are few copresent waves, at EEG frequencies, this sort of parallel coding retains behaviorally meaningful brief periods. A necessary companion hypothesis is that the brain wave frequencies underlying WM are confined to a single octave; that is, the upper and lower bounds of the band are in the ratio of 2:1. This hypothesized restriction, suggested by an empirical property of EEG bands that has been widely reported but rarely commented upon, has the important property of precluding spurious difference rhythms. A restriction to an octave, of “harmonious” frequency-markers for WM items, also seems consistent with a great deal of behavioral data suggesting that WM comprises a rapidly fading trace process in which only up to three or four item-representations are strongly activated simultaneously. There is also an additional, sequential renewal-or-revision process, within which up to another three or four items are being actively refreshed by rehearsal or replaced. Such serial processing may involve a less stringent octave band crowding problem.

KEY WORDS: Binding, Brain waves, Consciousness, EEG, Harmonic, Harmony, Short-term memory, Synchrony, Working memory capacity.

MIND/BRAIN RELATEDNESS WITHIN WORKING MEMORY CAPACITY

The Enigma of Modest Working Memory Capacity

A basic characteristic of cognition is that we can consciously commit to little more than one organized behavior or line of thought at a time [19,94]. Taking elementary items—digits, letters, or short words—as expedient objects for quantitative measurement of capacity, George Miller’s 1956 classic review characterized what is now usually called working memory (WM), as having a limited span for ordered recall of about seven independent, simple items—“the magical number”([83]; see [8,110] for systematic historical reviews of the terms “working memory” and “short-term memory”). This finding is easily replicated, and versions of this
experiment are regularly found in software packages for teaching undergraduate psychology laboratories (e.g. Mind Scope, Version β.2c; West Publishing Company, 1991). Miller [83] also reviewed many findings indicating that when people make quantitative judgments using a linear rating scale (“absolute judgment”), such estimations are reliable only so long as we are required to use up to 7 ± 2 scale divisions. Remarkably, this constraint on numerosity of rating scale divisions for reliable quantitative categorization holds almost independently of the particular dimension of experience or size of the interval of the dimension along which magnitudes are being estimated (e.g., length of line, pitch of tones). Although Miller was circumspect in joining his considerations of immediate memory capacity and rating scale capacity, the latter set of findings concerns our ability to maintain a number of ordered items in mind at once, and thus suggests an underlying property of WM [45].

Other methods of measuring recent memory routinely yield quantitative results not very different from those with ordered recall tasks. When participants are asked to reproduce in any order (method of “free recall”) an arbitrary list of 20, 30, or 40 unrelated words after a single hearing, many individuals recall a total of more than nine words. Yet across a group of participants only about nine of the words, most of them from the end of the list (“recency portion of the serial position curve”), stand out from the rest in probability of recall, and only about four or five of these words are recalled at better than 50% probability [89]. This is now also a “textbook finding” about memory (e.g., [6], pp. 156–158, esp. Fig. 4–4).

Today, a prevailing judgment of cognitive psychologists is that WM capacity is somewhat less than seven items. For simple verbal items recalled with high reliability, WM capacity seems to be closer to 6 [8,120]. “Complex span” procedures, in which simple verbal or mathematical tasks are interspersed with the items to be remembered yield WM capacity of two to five items [57]. For any given moment in a typical laboratory procedure, WM seems to briefly capture about three or four items at once in a trace, as suggested by the recency portion of the serial position curve [89]. The remainder of the six, or 7 ± 2, items are meanwhile undergoing refreshment as the participant sequentially rehearses as many items as can be mentally articulated within the approximately 2-s span of the “phonological loop” ([8]; also see [24,119,139]). When rehearsal was precluded by the requirement to constantly update a WM trace, capacity was about four items [138].

Interestingly, the recency portion of the serial position curve comprises approximately the same numerosness as is evident in simple perceptual experiments requiring a participant to report the number of a briefly seen small set of dots, with no time to sequentially count (about four or five dots; [83,123]; pp. 422–424 of ref. [141]). Recent research on briefly flashed arrays of color patches of lines at different orientations has revealed visual WM capacity for up to four items, whether or not they comprise single features or conjunctions of features [78]. Although much contemporary neurocognitive theory defines multiple subsystems of short- and long-term memory [72,110,129], the foregoing coincidences of modest numerosness remain suggestive of a common neurocognitive source, or reason, for limitation of simultaneously graspable, separate elementary items.

Comparing Species in a Spatial WM Task: Persistence of 7 ± 2

In our laboratory, to better link knowledge of human WM to that of other species, we have tested human participants in versions of the radial-arm maze, a device that has been widely used for testing laboratory rats. Our procedure discourages strategic use of response patterns, and thus presses the human participants to contend with the same memory load as do rats in radial mazes. Our findings, with probabilistic correction for guessing, indicate that capacity for remembering locations that have just been visited falls into the range 7 ± 2; the quantitative results for humans and lab rats are about the same with mazes having 8, 13, or 17 arms (i.e., numbers of sites to remember; [47,48]).

It is not known whether the modest capacity of WM for simple items involves a constraint necessary for the inner logic of memory, for example whether it concerns manageable combinatorial effects in organizing coherent knowledge (e.g., see [79,137]; briefly reviewed in [45]), or whether it is merely the best that evolutionary natural selection has done so far. In either case we may ask what attributes of the brain are most relevant.

Attributes needed for WM at the neural level. Which attributes of the brain seem to have appropriate potential for quickly referencing stored information, maintaining and creating distinctions among a small number of simultaneously active signals, and for unifying some of those signals at a pace that might be relevant to WM?

 Associated Levels, or Scales, of Mind/Brain Dynamics

Organisms’ behaviors are organized in three dimensions of space and one dimension of time. This obvious consideration might be placed tendentiously alongside the most general facts about the brain: It is an exquisite three-dimensional organization of elements that are largely linelike, or one-dimensional, in their microscopic structure. In some way, the linear temporal sequences of electrical and chemical events that are embedded along those physical lines must be causally related, comprehensively, to all aspects of organisms’ behaviors.

To avoid a gappy, mystical dualism we must assume certain kinds of connections between mind and brain, before we have empirical knowledge of their character. Thus, we assume that there are comprehensive causal links between the microscopic, relatively high-frequency scales of neuronal and subneuronal activity and the more middle-sized, mid-frequency scales of thought, emotion, and behavior. Each of these levels has been the subject of a great deal of research, yet they remain largely separated in our understanding. Myriad neuroscientific findings remain only patchily connected to myriad data about the experimental psychology of mind. The “engram” [15] remains sufficiently puzzling that some particle physicists have been taken seriously in a speculative excursion that neglects the middle levels and, with that, the explanatory connectedness across scales that science requires. By placing neurobehavioral integration out of reach of neuroscience and experimental psychology, and attributing it to subatomic quantum phenomena, they introduce an element of mysticism (see e.g., [67] for a critical review).

If the mind/brain problem is inherently unlucky for the scientific enterprise, it may be beyond heuristics. Then, achieving an adequate description of a memory event will require piecing together knowledge of thousands of neural elements behaving in diverse ways, not describable in any general terms. Such a description will be too complex to be intuitively satisfying or to deserve to be called "understanding." Hence, nature may be complexly mazelike, or like an extremely obscure cryptogram, refractory to analogical leaps. Does scientific intuition end at the mind/brain junction?

A Possible Intermediate Scale: Brain Waves

Alternatively, there may be physiologically identifiable, robust transitional phenomena at an intermediate scale. During the past several years some neuroscientific ferment has centered on possi-
ble significances of oscillatory activity at different spatiotemporal scales (e.g., [36]). For example, electroencephalogram (EEG) activity may play causal roles, in some of its manifestations, even if it is epiphenomenal in others. Graded potentials and currents are more ubiquitous aspects of neural physiology than are the action potentials that they sometimes generate. So, also, are oscillatory graded electrical phenomena necessarily more ubiquitous than the trains of action potentials that they may generate.

The possible functionality of graded activity synchronized across neural aggregates is controversial. Oscillations of neural masses are well-known to be reliable correlates of such global behavioral phenomena as sleep and attention, and the behavioral effectiveness of electrical brain stimulation at natural oscillatory frequencies suggests that such mass-oscillations are part of a causal sequence ([64]; also reviewed in [50]). However, we do not yet know a great deal about whether neural oscillations play a role in more finely differentiated functions of cognition [32]. One theory proposes that neuroelectric oscillations in resting wakefulness and in deep sleep serve the primary function of refreshing synaptic memories across the brain ([71]; also [50]).

Binding-by-synchrony: A possible neural dynamic basis of a single WM chunk. Synchrony of neuroelectric oscillations may bind together neural activity that is broadly distributed among brain systems, evoked by the various attributes of a stimulus object or other cognitive item ([73,84,85,117,126,134]; and see, e.g., [35], for evidence conflicting with the binding-by-synchrony hypothesis). The gamma band of EEG has been proposed as the vehicle for such binding [26]; however, recent evidence suggests a role of low beta frequencies (13–21 Hz) in coherence of visual and motor cortex during a tracking task, in humans [22]. The binding hypothesis is now being widely considered, at a time when neuroscientific empirical techniques from macroscopic to microscopic levels of analysis are well-prepared for it. Relevant examples are in coherence analyses of EEG activity [23,97,103] and in studies of active and passive properties of dendrites, which suggest that they might exploit subtle differentiations in timing and synchrony of incoming signals, to yield local dynamic patterns for memory retrieval or storage (e.g., [20,86,121,122]). A series of satellite symposia at the Annual Society for Neuroscience meetings has been devoted largely to these issues [36].

A possible mechanism of causal linkage, between widespread EEG synchronies and more microscopic activation patterns at the neuronal level, involves the concept of the “Hebbian neuron.” That is, EEG synchrony implies spatial and temporal convergence of excitation (or of inhibition) upon neurons in the areas of the brain that are within its field. This suggests a means for neural structural revisions, which might underlie the creation of new long-term memories: “Neurons that fire together wire together” [14]. Binding-by-synchrony, with action potentials resulting as target neurons are pushed past their thresholds, is readily envisioned on a foundation of classical integrate-and-fire neurons, which respond to synaptic transmission with intradendritic passive summations of graded potentials. Active dendritic potentials [86,121] may also be involved.

Conceivably, volume conduction [1] provides still another possible route for information processing across larger masses of brain tissue. Volume conduction is like an electrical short-circuit, not dependent upon the microanatomical routes of connecting fibers and their synaptic contacts. However, ordinary synaptic transmission and dendritic electrodynamics may be so much stronger than volume conduction that the latter is no more than an epiphenomenal signature, visible to a researcher reading an amplified EEG recording from a point in the brain, but “invisible” to the tissue itself at that point in the brain. Indeed, if short-circuiting by volume conduction were too powerful, that would negate the very reason for being of the brain’s exquisite microscopic spatial organization and neurochemical specificities. Nevertheless, it seems possible that a gentler influence of volume conduction might sometimes act as an additive factor that achieves effectiveness by working “at the margin,” or near threshold.

Informational combinatorics? Subtle volume conductive influences might act in summative or synergistic interactions with other neural information coding processes, perhaps at temporarily sensitized particular locations, which thereby act as receivers of an electrical rhythm “broadcast” across a volume of tissue. Such an effect might be analogous to the various degrees of diffuse influence effected by neurochemical modulators and by tiny concentrations of hormones in the body [1]. A combinatorial effect of diffuse activity that is no more than weakly informational might have a disproportionately large, even exponential, effect on the information capacity of the system of which it is a part [41]. For example, if only two different state-markers were provided by diffuse EEG activity (e.g., via two different typical frequencies, amplitudes, or phases), that could double the number of possible informational states of the system as a whole [41].

HARMONIC PRINCIPLES AND HOW THEY MIGHT APPLY TO BRAIN WAVES

Octave EEG Bands: Informational Safe Zones

General knowledge about brain waves is consistent with the inference that each band of EEG falls within approximately an octave; that is, the high-end frequency is about twice the low-end frequency. This seems particularly clear for theta (ca. 4–7 Hz), alpha (ca. 8–14 Hz), and gamma (ca. 40–80 or 60–90 Hz). (See, e.g., [93] pp. 5–9; [37], for general description of traditional EEG categories, and [134] or [26] for a description of the gamma band.) Might such a band limitation have adaptive significance?

A possible reason for the apparent octave restriction is that any set of two or more frequencies occurring at the same time within an octave cannot create beats ([98,114]) nor any difference rhythms of quadratic or higher order [101] which are also within that same octave. A basic arithmetic principle is that for any two numbers in the interval between x and 2x, the difference of the two numbers cannot fall within the interval x to 2x, even when either of them is raised to any exponent. Thus, if brain information processing uses regular rhythms in time series as signals, the octave comprises a safe zone, protected from confusions that could be caused by emergent beats or other difference rhythms [43].

A brain wave octave of harmonics: Possible neural dynamic basis of multiple WM chunks. Consideration of basic properties of musical scales (e.g., [56,98,114]) suggests that the octave ratio might naturally encompass a biological informational band that is restricted to a small number of simple signals. While some present theory and empirical testing concern the possibility of quasiperiodic, “chaotic” generators of separable components of EEG signals [11,33,114] the simple mathematical relationships of harmonics [98,114] remain unexplored as a possible foundation of signal composition. Indeed, hypothesizing relevance to EEG of harmony ratios seems a natural extension of the hypothesis of binding-by-synchrony for single percepts or concepts.

Brief Historical Note

Johannes Kepler’s fascination with harmonies and British chemist John Newlands’ conjecture about octaves were followed, respectively, by the discoveries of “Kepler’s Laws” describing the periods and spacing of the planets ([76], p. 112; [96], pp. 70–71), and the periodic table, with its prominent groupings of eight elements ([100], pp. 194–195; [143], pp. 261–263). Historians of
science are uncertain, however, about the issue of logical entailment, with these two cases. Speculation about “vibrations” as the foundation of neural codes appears in Isaac Newton’s 1723 edition of Principia (91); this was extended by David Hartley in a 1749 book [54]. Such speculation was rejected as untestable by Priestley [112], but the essayist Coleridge [127,128] objected. Speculations about neural vibrations recur historically in an 1884 book by Henry Maudsley [80] and one by T. H. Huxley in 1880 [63]. Recently, Nunez [93] also has suggested exploiting knowledge of the physics of music for understanding EEG wave phenomena (pp. 139–144).

**Higher-Level Binding of Memory Item-Markers: Simultaneous Synchronies**

The present hypothesis is as follows:

Specific EEG frequencies comprise the distinguishing marks for simple items in WM, i.e., WM “chunks.” The capacity to hold several chunks in mind at one time is limited by basic properties of oscillations when they are simultaneously present in a medium. The simple ratio relationships of harmonics, including octaves, are relevant to this limit.

**Fundamental Problems of WM Design: Elemental Distinctness and Miscibility**

The natural functions of working memory are to serve the ongoing organization and updating of cognition, and ongoing sensory-motor interaction with the world. Whatever codes WM uses must have powerful implications for the efficacy of such commerce, and for survival. The brain, remarkably, conserves the restriction of modest numerosness of elements in WM capacity, across wide variations in size, duration, and dimensional ranges of the referents of WM items, and surprisingly wide variations in the pace of some of the tasks in which WM items are embedded (reviewed in [45]).

If the brain follows the evolutionary principle of hierarchical decomposability—an also aspect of engineering and of structured computer programming [51], then the general problem of unifying individual WM chunks must be solved at one sublevel, relieving higher sublevels of the burden of micromanaging the composition of the elements which interact as wholes at those higher levels. The most general problem of interaction of elements in a system of working memory must concern clarity of distinctness among elements. Because WM is the crucible for dynamic revision of cognition, its most general issues must also include the means of interaction among elements: When do interactions suggest revising of chunks and how or when is that task shifted elsewhere (“down to a lower level”? ) to enable WM to get on with the next moment’s business?

More specifically, the nature of WM seems to require the following four subtasks: (1) entrances of elements driven by perception or by elicited associations; (2) exits of elements as a result of one of the following—passive loss following attentional neglect, exceeding the modest capacity, active rejection, or storage in long-term memory; (3) new differentiations of “smaller” elements; and (4) new combinations of “larger” elements into single chunks. As already noted, these fundamental issues of WM design may imply a mind/brain research issue of immense complexity, with diverse mechanisms. However, as suggested above, the temporal structure of music, as well as a listener’s experience of interacting musical lines, suggest the present harmonics model might be fertile enough for possible future expansion beyond the present main concern with the state of WM as it briefly holds a single complement of several chunks.

If each of the hypothesized chunk-signals in WM must be optimally discriminable, then their frequencies might well have evolved even spacing within the octave. For a fixed number of divisions of a linear interval, any one subdivision can become longer only at the expense of making another of the subdivisions shorter by the same amount (Fig. 1). The maximal differences among dividing points can be achieved via equal differences among neighboring pairs. However, when the interval in question is a range of frequencies of an oscillatory signal, the importance of harmony ratios may supervene and force a compromise. A self-consistent set of harmonic ratios would allow the differences between neighboring pairs of signals to be approximately, but not exactly, equal.

**Properties of Sinusoidal Waveforms and Harmonic Relationships**

There follows a basic review of properties of sinusoids and of harmonic and harmony ratios, with indications of how these properties might be useful in tagging information. Among these, the hypothesis that brain waves in harmony ratios serve as WM chunk-markers entails an implication regarding the pace of cognition and a tradeoff between advantages of serial and parallel processing.

The simplest waveform. Rhythms are a rudimentary form of activity, organized linearly in time. Although a sinusoidal curve has a beguiling shape, elementary trigonometry tells us that it is generated simply as the projection on a line of a radius revolving in a circle ([114], pp. 143–146). Sinusoids represent an interesting abstract similarity among a large class of disparate physical phenomena in various media, including pendulums, sounds and other mechanical vibrations, waves in water, aspects of some biological rhythms, and the natural oscillation of a simple electrical circuit in which a capacitor discharges through an inductor [62,118,140].

Brief overview of harmonic and harmony mathematical relations. It surprises the intuition that the simple sinusoid shape, in various frequency, amplitude, and phase summations, can be used to build any single-valued waveform. About 70 years ago, Dayton Clarence Miller delightfully illustrated Fourier synthesis of a repeating profile of a woman’s face, using only the delicate mechanical generators of sinusoids then available (Fig. 2; from [82], pp. 119–120). Synthesis of any waveform, in like manner, involves harmonic exact multiples of the lowest (fundamental) frequency.

Harmonics and harmonies are the two related ways in which rhythmic signals can have integer-ratio relations. Harmonics occur when one signal frequency is a whole-number multiple of the other and is therefore in a different octave; harmonies occur, when the signals are related to each other by fractional multiples that are low-number ratios. Prototypically, harmonics occur within the same octave, although a doubling, halving, or any 2ˢ multiple of any of the notes in a musical harmony, which places that note in a different octave from the rest, will remain harmonious with the other notes. Harmonics of a given fundamental frequency are often in the same octave with each other, with this octave above the octave of the fundamental. This implies that all the harmonics of a fundamental are also in harmony ratio relationships with each other [98,113,114].
Harmonics: Further Explanation

A harmonic is an exact integer multiple of another frequency, called the “fundamental.” For example, middle C (C₄) has been standardized at a frequency just under 262 Hz. The “first overtone,” or “second harmonic” of this frequency comprises twice as many oscillations per second: \(2 \times 262 = 524\) Hz (C₅). The second overtone, or third harmonic, comprises three times the frequency: \(3 \times 262 = 786\) Hz (G₅), etc. For all notes of a given musical instrument the distribution of relative amplitudes of the set of harmonics is fairly constant, and that amplitude distribution of harmonics comprises the distinctive timbre, which clearly differentiates a piano from a clarinet or a viola, etc.

Harmonics must involve integer multiples because only integer multiples can possibly stay synchronized with the fundamental frequency. Thus, harmonics are required for a structured, regular waveform. Figure 3 illustrates this point with a sinusoidal fundamental (\(y = \sin x\)) and an equal-amplitude harmonic three times the frequency of the fundamental (\(y = \sin 3x\)). When the two signal sources are summed, the harmonic always rides at the same phase positions on the fundamental. Even if these two waves had different relative phases, the exact harmonic relationship of 3:1 would ensure that the resulting wave shape would repeat itself over and over indefinitely, at the same frequency as the one in this illustration. Helmholtz’s 1885 classic exposition, based theoretically on his use of Fourier mathematics and empirically on mechanical resonators that did not permit direct writeout of waveforms, remains among the most extensive and lucid [56].

Tones an octave apart (frequency ratio of 2/1) sound highly consonant, so much so that they are sometimes mistaken for each other. What happens when tones are closer in pitch? The maximum possible consonant spacing that is bounded by both ends of the octave involves the highest possible whole-number ratio of frequencies that is lower than the octave ratio of 2/1. Thus, the “perfect fifth” (for example C to G), comprises a ratio between frequencies of 3/2 (e.g., G₄/C₄ ÷ \(392\) Hz/261 Hz = \(3/2\)). The next lower ratio between small integers is 4/3, or the “perfect fourth” (e.g., C to F); this pairing also sounds highly consonant so long as the frequencies are above about 150 Hz [114]. The smallest ratio that is ordinarily considered to sound consonant when both notes are sounded simultaneously is the minor third, or 6/5 (e.g., C to Eb). At closer ratios than this there is generally an unharmonious fusion and roughness, or dissonance.

Cross-cultural consistencies and cultural variations. Significantly, these perceptions of harmony appear to be basic, rather than accidents of cultural history. Cross-cultural consistencies such as octave equivalence [25] may reflect an innate characteristic of the brain ([16]; also see [68] on “Pythagoreanism,” and [55]. Although the music of India is quite different from Western music, in its uses of small intervals and glides, the octave interval (2/1 ratio) and fifth (3/2) play primary roles. Moreover, the scales in Indian music, which comprise the foundations of improvisational “ragas,” each have six defined notes between the anchoring tones at either end of the octave [107]—as does the Western diatonic scale.

Further evidence that the musical octave is of basic perceptual significance arises from experiments, carried out with Western listeners, in which attempts were made to “stretch the octave.” This manipulation left the ordering among notes about as in the standard octave but systematically corrupted their low-integer ratio relationships. The resulting sounds turned out to be intractably weird, and they could not be relearned as possessing consonance ([98], pp. 89–92). Even such an experimentalist in 20-century genres as the composer/conductor Leonard Bernstein believed that musical perceptions reflect innate brain characteristics (as cited in [2], p. 43).
In his classic *The Sense of Music*, Victor Zuckerkandl ([142], p. 69) follows his explanation of the ancient Greeks’ discovery of the effects of small-integer ratios of the lengths of musical strings, with this comment:

> As no ancient Mathematician-King is known to have constructed the diatonic scale according to a mathematical order and to have imposed it by decree on the peoples of the Western world, we must conclude that these people, when choosing to adhere in their melodies to the intervals of the diatonic order, unconsciously followed the Law of Number. Their singing, certainly one of their most spontaneous activities, appears secretly governed by mathematical necessity.

The present paper does not take up the interesting additional matter of how musical sophistication can lead to tolerance and enjoyment of deviations from the basic harmony ratios, and whether this fact suggests further relevance to neural modeling.

**Harmonics Entailed by Harmonies**

A property of consonant pairs of tones is that their low-integer ratios entail more possibilities of harmonics of the two tones that are in synchrony with each other, and more possibilities of relatively wide intervals among the remaining harmonics of the two tones ([98], p. 83, esp. his Fig. 5-6). One possible relevance to brain waves is that a brain wave frequency in the gamma band might be a harmonic of a lower-frequency generator brain wave. Possibly consistent with this idea are findings, currently being interpreted in other ways than proposed here, that gamma waves bearing WM item information are synchronized with, and embedded in, cycles of theta waves ([66,77]). Other evidence suggests gamma waves are harmonics of alpha [69]. Although harmonics might also be a mere epiphenomenon, having no informational significance, the following point explains why such a state of affairs would represent a missed opportunity in the evolution of cognitive brain functions.

**Harmonics clarify a fundamental frequency.** It seems unlikely that natural selection would allow a phenomenon as robust as the tendency of a wave to carry harmonics to remain epiphenomenal, in a system in which waves bear information, because the presence of harmonics clarifies the distinction between fundamental frequencies. In simple listening tasks, with musical tones having timbre, the low-integer ratios among the fundamental frequencies must be more precise for there to be an experience of harmony, than if the fundamentals exist alone as pure tones ([98]). This must be because additional convergent, disequivocating information is provided by the harmonics. Our ears can hear the sharper, clarifying “edges” or “contours” that they add to the shape of the otherwise smooth sinusoid. These edges and contours are evident in a literal sense when looking at a graphic representation of the oscillation in which harmonics are present.

**Do brain waves have timbre?** The fact that the brain exploits an advantage of timbre in the auditory system implies that there is a biological evolutionary route to this feat of “engineering.” This suggests that an analogous evolutionary route is available in any living system where waves carrying information linearly summate in a volume, for example in brain tissue at the scales of dendritic potentials or of volume conduction. Thus a possible reason why brain waves often depart from a purely sinusoidal shape is that they have “timbre.” This might help them to establish a small set of frequencies more quickly or reliably, or it might comprise a code-component which enables additional information to be borne in the “tonal color” of brainwaves, i.e., in waveshape recognition.

A possible basis for new chunking. Turning this consideration around for a moment, it is conceivable that instances of coherent activity at lower EEG frequencies may be signatures of integrative merging of harmonics at higher frequencies. That is, as two or more WM chunks enter into a newly forming concept, there may emerge a common fundamental. This could happen if two or more EEG signals glide together into a low-integer ratio relationship from frequencies that previously bore “poorer harmonies” with each other (i.e., either a nonrational relationship between any two of the frequencies, or a ratio expressible only with large integers). Following such harmonic merging, a subsequent doubling or other multiplication of the emergent chunk-frequency could bring it up into the octave where the WM chunk-markers are mixing. It would be premature to pursue this more elaborate possibility of modeling music-like transitions of brain waves in this paper. The important point here is that the present hypothesis is fertile with testable implications and additional theoretical possibilities. It is also worth noting that frequency multiplication easily occurs in many, simple natural and artificial physical systems.

**The Virtual Pitch Illusion as a Model of an EEG Mechanism**

A more concrete way to consider the informationally convergent aspect of harmonics is by analogy with the auditory illusion of virtual pitch. The illusion arises from the fact, noted above, that any set of harmonies must also comprise a set of harmonics of an implied fundamental frequency one or more octaves below the set of harmonious frequencies. This implied fundamental can often be heard whether or not it is actually present. An analysis of the “fundamental bass,” perhaps first offered by Rameau in 1722 ([98], pp. 96–101), accounts for this virtual pitch illusion. The simultaneous presence of adjacent harmonics (e.g. fourth, fifth, and sixth) is most effective in eliciting the effect ([113], p. 44), perhaps because neighboring harmonics imply a particular fundamental unequivocally.

Our ear-brain system thus does something very much like a Fourier analysis. In common experience, the virtual pitch illusion enables us to follow a piece of music emerging from the speaker of a small, inexpensive radio whose cutoff of lower frequencies eliminates the fundamental frequencies in which the melody was originally recorded. Thus, as with certain visual phenomena such as subreceptor vernier acuity, the perceptual performance of neural aggregates operating over a time interval normally allows the organism as a whole to “see through” a degraded signal to the underlying reality. As with other contrived illusions, the illusion of virtual pitch is representative of an underlying system propensity that is an adaptive aspect of ordinary functioning.

In a human electrophysiological study, the harmonics of a fundamental, indeed even with the fundamental missing, yielded a more discriminating mapping to the auditory event-related potential N1 latency than did the respective fundamentals themselves [104]. Thus, the auditory phenomenon of illusionary, virtual pitch serves as a model of a possible more general competency of the brain to cope with simultaneously present rhythms. The phenomenon depends on simple quantitative relationships among the different frequencies, which seem as if they might readily be analyzed at low levels of neural processing.

**EVOLUTIONARY PLAUSIBILITY OF BRAIN WAVE INFORMATION PROCESSING**

Evolutionary, psychological, and neurological plausibility have been prime considerations with models of cognitive binding (e.g., [61,124]). Because music is a form of sound-communication more primitive than the symbol and grammar systems of natural languages it suggests a plausible inner “language of the brain.” Similarly, the basic generative processes described by applying chaos theory to dynamical systems have been considered by theorists to be sufficiently simple to be evolutionarily plausible as possible sources of biological rhythms (e.g., [11]). However, one
investigation of this possibility showed an inverse relationship between dimensional complexity, or degrees of freedom, of the EEG and WM load [115].

There are a variety of other, complex mathematical wave functions which it might be possible for us to set aside from consideration, as far as brain rhythms are concerned. For example, waves are modulated in a variety of ways to code information in radio signals; but like the wheel and many other inventions of the human brain as a whole, most of these outcomes of engineering genius probably do not have access routes via the raw biological natural selection that preceded the emergence of human brains. Evolutionary natural selection seems unlikely to desultorily find its way to exploitation of such ingeniously engineered, naturally improbable phenomena as FM sidebands [118,130,135].

Naturalness of Sinusoids for Biological Information Processing

What are some possible ways in which sinusoids ([60,88], and [108], p. 70) might provide a basis for a naturally selected flexible information processing system?

Any single-valued repeating wave is mathematically decomposable, by Fourier analysis, into a sum of sinusoids; likewise, any such wave can be synthesized by addition of some set of sinusoids. However, it is uncertain whether the physiological generation of EEG waves involves a basically sinusoidal process. Barlow [9] argues for viewing the triangle wave as basic. That view might be considered consistent with "flush and fill" models of membrane potential generation ([58], p. 28) and perhaps with widespread empirical evidence of rather sharp peaks of sleep spindles (see, e.g., [132,133]; also [46]). On the other hand, if phenomenological waveform is a valid clue, EEG waves do often have a rounded, somewhat sinusoidal appearance (e.g., [93], p. 6).

Continuous electrical waveforms with rounded peaks and/or troughs occur in the brain both at more global and more microscopic scales. Even at phylogenetic levels below mammals and birds, in whom spontaneous EEG reliably appears, there is a tendency for inputs to induce a rhythmic brain response [12] sometimes having an approximately sinusoidal appearance.

In many simple physical systems there is a natural tendency for abrupt perturbations to drive a sinusoidal dynamic, when there is rhythm repetitiveness associated with range-limited energy kinetics. Familiar examples are in pushing a swing, or in the mechanical pendulum of a clock. Close analogs in electrical circuits are easily constructed from passive elements, i.e., capacitors, inductors, and resistors [62]. Thus, the rounded shape of the space and/or time distribution of many biological potentials is not an improbable evolutionary contrivance but a natural outcome, likely based largely on passive properties of membranes (see [125], p. 31; [43,121]).

Simple Combinatorial Systems?

Although neurons do not act in the same way as elements of digital computers, some of the same information-theoretical concepts can be relevant. For example, the possibility that simple signals such as sinusoids might be neural markers for WM items raises the matter of range and resolution. Does a given sinusoidal frequency in a particular communication line act in a simple binary way, as an on-off event? Or can the amplitude of this signal frequency, and some number of copresent others, vary meaningfully along a broader range of activation levels? One metaphor that is familiarly applied to a biological information system is the so-called “four-word language” of the genetic code. As in natural language, the presence or absence of each “word” is essentially a binary phenomenon, because each of the four chemical bases is either present or absent at a given position on a chromosome.

Pinker [99] observes that this quality of speech and natural language gives it the character of a “discrete combinatorial system”; that is, one that has the advantage of preserving the integrity of the basic informational building blocks in the face of constant copyings and mixings. In contrast, an analog communicative system runs greater risks of degradation of the information bearing units, via gradual drifts or erosions. Perhaps, in like way, there is some limited set of quantities in the brain that can reasonably be characterized as a gene-like small “language of the brain.” One such possibility is in the present hypothesis that an octave band of brain waves contains WM item-markers. A small set of discrete brain wave frequencies may wax and wane in amplitude, combinatorially. The character of a discrete combinatorial system might be enhanced if the brain wave frequencies were standardized. On the most general level, this might be the significance of the beta or the gamma octave in mammals. More specific frequency settings, within the hypothesized octave WM buffer, might occur as individual personality characteristics, or perhaps as opportunistic settings over brief task-related time intervals. The orderliness of a piece of music is a model of this latter possibility. Within any brief time interval there is a more highly restricted set of possible frequencies contributing to a harmony than over the longer run, which can include transitions between keys.

Sinusoids as Markers That Might Evoke Distributed Representations

A simple sinusoid, in the neural oscillatory range of up to about 100 Hz [95] by itself cannot carry a great deal of information. By comparison, radio carrier waves are available for amplitude, frequency, or phase modulation, because their high, radio frequency entails a fine grain of wavelengths many times smaller than the detailed informational patterns that are sculpted across them. For example, the longest wavelength (coarsest grain) AM radio broadcast frequency in the United States is 550 KHz. Speech and conscious thought take place at far fewer events per second. Our spoken words can easily make a fully detailed impression across the fine grain of 550,000 waves per second; thus, amplitude modulation of radio carrier frequencies can easily support variations at the speed of thought.

An EEG gamma wave cannot possibly do anything comparable to a radio carrier frequency. Thus, it seems that EEG activity might carry information only in the sense of comprising markers; that is, by acting as small sets of simple signals, which achieve higher information capacity by playing across the ultradense spatial organization of the brain, somehow triggering and sometimes revising stored, distributed memory representations. Spatially organized brain waves are envisioned with the “binding” hypothesis [126,134] and other conceptions of EEG codes [31,33]. An alternative metaphor to “markers” or “tokens” is that of “pointers,” used by Baddeley ([17], p. 165) in discussing a function of WM chunks.

The expression pointer, although derived from computer programming, is used here without intending to imply details of mechanism that are like object-oriented languages, such as C++; (e.g., [60], pp. 159–161), but only to suggest that the dynamic neural attributes of WM need not themselves “contain” a great deal of information. It is sufficient for these dynamic properties simply to be capable of appropriately evoking activation of the systems that do contain the information, while participating in appropriate interactions. Although computer information processing is quite different in many ways from brain information processing, the situation here is somewhat analogous to a computer, insofar as a sequence of thirty-two settings of 1s and 0s in a register is informationally impoverished, in and of itself. However, such
information greatly gains in significance by virtue of the context and sequence of events of which it is a part. This matter of minimal requirements, for information-processing pointers, or markers, has been explained well by Barnden [10] and by Hummel and Holyoak [61], with particular reference to the longstanding controversy about whether neural representations tend to be localized or distributed.

A contemporary mathematical alternative to traditional Fourier analysis of waves into sinusoids is wavelet analysis. Although the widespread availability of powerful computers has fueled the growth of this form of mathematical research, wavelets may be another example of an important mathematical engineering feat that lies outside the direct access routes of biological natural selection. Wavelet analysis is highly efficient at detecting a specific complicated signal wave shape; however, wavelets require explicit scanning over locale and scale, and thus lack important properties that are unique to sinusoids [59]. As explained next, these special properties of sinusoids seem well-suited to achieve error tolerances and necessary continuities in biological information systems.

Four Advantages of Rhythmic Repetition in Biological Signaling

Many biological systems are periodic [105], but so too are many machines characterized by repetitive processes, e.g., continuously rotating wheels, reciprocating pistons, clock functions in computers. Is there a reason to expect periodicities to be a more basic and pervasive attribute of biological systems than of machines?

Continuities. At least some of the functional articulations of our soft, wet neurons seem not to be machinelike. Every system that has been studied at the single unit level shows a degree of broad tuning ([14]; [126], p. 353) and functions distributed across neuronal ensembles [4,21]. Broad tuning has the virtue of ensuring that all possibilities are covered within the realm of information processing encompassed by a neuronal set, and that there are functional adjacencies and overlaps among neuronal sets, thus extending the brain’s representational reach. Interpolations readily occur, and no new input falls into an empty “hole.” Broad tuning thereby ensures a continuous landscape of sentence upon which new associations or competencies may evolve gradually. This physiological property of the brain’s microscopic elements helps to explain the elusiveness of findings of discrete, pure localizations or competencies may evolve gradually. This property of sinusoids suggests permissiveness in cases of small errors in the relative timing of sources. Alternatively, it suggests a possible brain mechanism by which continuous variations of the phases of constant-frequency component signals might modulate amplitude.

If the most elemental process is not amplitude addition but phase addition, this can have a multiplier effect on amplitude, according to Fukai [34], who argues that continuous subthreshold signals in combination might thus yield a discrete resultant signal when a threshold is crossed. Such an effect might enable a particular frequency to act in a binary way, as “on” or “off.”

2. Sinusoidal Form Invariance with Integration or Differentiation

Responsiveness of neural elements often depends upon summations or, alternatively, on rates of change. This suggests that there is significance for neural information processing, in the fact that the integral or derivative of a sinusoid is a sinusoid of the same frequency, changed only in phase, by 90°. Usages of simple sinusoidal messages, which involve responsiveness that tracks the cumulating “power” of a wave (spatial and temporal summation, or integral) or, conversely, its rate of increase or decrease (derivative) will pass on messages packaged in the same sinusoidal form. This is a handy property for recursive systems. That is, the brain can use the same “apparatus” if such integrating or differentiating transforms recur, undergoing one or more stages of subsuming in other messages. The same neural circuits can be used repeatedly in loops mixed with convergence and divergence, without having to change their input-output characteristics for each stage of processing of a given message. This “calculus-constancy” is an unusual property for a mathematical function, and one that seems extremely useful for natural information-processing systems. Thus, sinusoids in brains may comprise a particularly useful variety of “interchangeable parts,” or dynamic modularity.

3. Reliability Maintenance

Rhythmic signals may automatically maintain reliable transmission of information as behavioral commitments are developing. A rhythmically structured signal may compensate for the natural distractibility of a biological information system, which changes commitments from one function to another at different times. And
this same mechanism that maintains reliability would also provide a foundation for competitions between different inputs. One imaginable competition is the recruitment of a mass of brain tissue to one or another frequency. Such a mechanism could underlie frequency glides and merges of harmonies, such as were hypothesized above. Evidence that processes of this general sort occur in the brain, albeit on a slower time scale, is in the "recruiting" and "augmenting" responses. These terms describe a crescendo of cortical responsiveness that occurs to a rhythmically repeated electrical stimulus to the thalamic nonspecific or specific nuclei. Such artificially elicited spindle-shaped bursts of waves are thought to reflect a normal brain function in wakefulness and sleep ([15], pp. 168–171; [64]). At the much slower temporal scale of ritualized behaviors of whole organisms, a recruitment of commitment that involves rhythmic repetition is illustrated by the gradual development of vigorous responses in certain emotional communications of animals and humans, for example in reciprocal rhythmic movements of greeting, courtship, or aggressive signaling [27], Kavanau [71] has presented a theory of the role of EEG in dynamic stabilization of neural circuitry (also [50]).

Extending a signal by the ploy of rhythmically repeating it raises the possibility of resonance. Waxing of responsiveness during the course of a number of input wave repetitions, becomes a measure of certainty or of importance. Such a view is also an aspect of the "adaptive resonance theory" of neural networks [53]. Waxing of responsiveness also requires neuronal systems to have active or passive damping characteristics, to enable activity to wane to a more neutral state of preparedness.

Such processes might work best with sinusoidal waves—with receptivity of brain systems receiving the signals limited to an octave, as explained above—because of the complications that would be caused if the rhythms emerging from waxing and waning modulation entered into the processing of information as spurious additional signals. Perhaps that is one reason why EEG waves tend shaped as spindles. Such gradual waxing and waning of the burst feathers the onset and offset of the signal, and thus "mimics" the statistical preconditioning of a periodic signal that is necessary to avoid spurious high frequency readouts when doing a computerized Fourier analysis [38].

4. Temporal Extension Achieves Simultaneity of Signals with Variable Onset Times

The pace of brain activity and the pace of behavior. Rhythmic repetition extends a signal in time, helping to ensure coordination of information converging from two or more separate sources. This is a more general kind of error tolerance than that described above under the heading of same-frequency summations. If evolution of brain rhythms occurred with the precision of some engineered artifacts, a single information-bearing EEG wave compounded from several sources might occur at the very finest temporal grain that is ever likely to be needed in behavior. However, safety factor in reliability engineering was widely prefigured in biologically evolved systems; therefore it seems likely that a minimal information-bearing wave would have to be at least a doublet or triplet [3,17,40,70]. The additional need to summate signals with somewhat imprecise onset times would seem to require additional wave repetitions. The evolution of the finest temporal grain for a compound neuroelectric event thus must determine a biophysical limit to the overall pace of behavior.

Calculating an approximation. Possible corroboration of this point is in the temporal relationship between EEG gamma waves and the pace of behavior. EEG gamma frequency, possibly involved in binding of stimulus attributes, includes 40 Hz at the low-frequency end. The single-wave duration for that frequency is 25 ms. At the behavioral level, a fast reaction-time, in a situation requiring stimulus identification and choice, is on the order of 250 ms [29]. About 50 ms of the reaction time is taken up by action potential travel time over the axonal distance from the eyes to the cortex, and then down and out to the responding hand. Thus, by allowing up to about eight wave repetitions (ca. 200 ms ÷ 25 ms) the gamma frequency may be a good "design choice." It is about an order of magnitude slower than the frequency of some of its own "building blocks" or causal factors in a high neuronal firing frequency, and an order of magnitude faster than the pace of a fast behavior, for which it might be considered to comprise "building blocks" [13]. If not gamma waves, but beta waves participate in information processing, their lower frequency would allow only half the room for error that gamma wave frequencies seem to permit, but ballpark calculations such as the preceding suggest the possibility that beta waves might also serve as chunk markers that could underlie the known pace of behavior. These considerations suggest a line of empirical research or additional literature review that seeks relationships between behavioral pace and brain wave frequencies across species, individuals, or behavioral states within individuals.

CONSEQUENCES OF INCREASING NUMBERS OF SIMULTANEOUS SIGNALS

Sensitivity to Coincident Peaking vs. Phase Transparency

In exaggeration of the phenomenon of beats (Fig. 4), sharp summation peaks, separated by intervals having an envelope of rather flattened amplitude, arise when a set of sinusoidal waves all reach maximum synchronously. This occurs with the phase relationships of the cosine form (Fig. 5A). When the phases of the very same set of waves are spread evenly over the cycle of the fundamental, the result is a more complicated-appearing waveform of fairly regular amplitude (Fig. 5B). Similarly, Pierce ([98], p. 186, Fig. 13-2) shows how different phase adjustments of summating harmonics can lead either to sharp peaks or to an increasing-frequency ramp within a fairly constant envelope of amplitude; the period of repetition of the ramp is equal to the fundamental frequency.

Perhaps such effects are sometimes exploited in EEG information processing and sometimes not—just as they are sometimes relevant to hearing and sometimes not. In hearing timber, we are quite sensitive to waveforms at lower frequencies, but for frequencies above about 200 or 400 Hz our hearing does not distinguish among phase differences ([98], p. 187). That fortunate fact allows for the possibility of music that comprises more than one line, or more than one instrument playing the same line, i.e. polyphony, harmonious chords, and accompaniment generally. Although it is easy enough for a group of skilled musicians to synchronize on the same beat on a time scale of large fractions of a second, they could never synchronize on the much finer temporal scale of the hundreds or thousandths of a second consumed by the individual sound waves produced by their instruments. Analogies in EEG information processing can be imagined either involving waveform sensitivity or its opposite, phase transparency (linear additivity and decomposability), a characteristic that takes advantage of the tendency of waves in water, air, and many other media to pass through each other unchanged ([114], pp. 38–40, 143–144; [140]). Slight phase adjustments of EEG harmonics might amplify into a waveshape code. If there are threshold effects in phase aggregations ([34]; [108], p. 45), then cosine-type, maximizing summation peaks might yield a pulse code. An additional possibility is that seizures might result from a pathology of phase adjustment that allows copresent EEG harmonics all to slip into a cosine-like relationship.
Crowding and Roughness

Simultaneous maintenance of at least two items must be necessary to integrate information in WM. But, again, why is the capacity of WM limited to no more than several items? Properties of coexisting rhythms suggest drastically diminishing returns for packing a band with simultaneous rhythms. There is a limit to how crowded a band can become before the signals become confused with each other. In hearing, a sensation of dissonance, or “roughness” occurs when two tones are closer in frequency than the so-called “critical bandwidth.” This occurs at a ratio of less than 6/5 (the “minor third” such as C–Eb, for frequencies above 500 Hz [98,113]). The critical band concept may also be relevant to the brain’s ability to discriminate among the hypothesized information-bearing EEG waves. The critical bandwidth phenomenon in audition depends to some degree upon mechanical properties of the middle ear. EEG waves do not have to drive anything like the ossicles and other masses of the the middle and inner ear, but electrical inductive or capacitive reactances of brain tissue might cause analogous distortions, leading to confusions among crowded frequencies.

Crowding and Fusion: A Tradeoff Between Harmonies and Melodies of the Brain?

It is more difficult to “hear out” two simultaneous tones that are close in frequency, that is, to hear clearly that there are two of them, than to discriminate between two successive tones. This phenomenon occurs at closer frequency intervals than the critical bandwidth, discussed above. For example, below 200 Hz, a difference of less than 15 Hz between two simultaneous tones leads to an experience of dissonant “fused tones with roughness.” In general, the difference between simultaneously sounded frequencies needed to avoid this experience of fusion is large: 7 to 30 times as great as the just noticeable difference for successive tones [114].

As in the case of critical bands, the difference between the auditory perceptual effects of simultaneous versus successive sounds has sometimes been attributed to the mechanical limitations of the cochlea. However, at least a partial analogy seems possible with electrical properties of brain tissue. Limitations of frequency response, due to inertia and restricted elasticity in mechanical systems, may have partial analogies in electrical media, due to capacitive, inductive, and resistive impedances.

Perhaps fusion of simultaneous tones sometimes involves entrainment of rhythms. When two oscillatory signals are very close in frequency, one rhythm may capture, or entrain, the other. One implication is that some pathologies of cognition may be due to misregulation of intervals between brain wave frequencies. For
example, small WM capacity within some modality or category of information, or excessively loose associative fusions of ideas, may be mediated by excessively wide fusion intervals or entrainment sinks for EEG rhythms in certain brain areas. On the positive side, entrainment might be a handy property for a system that uses a limited number of frequency-encoded messages, each having components converging from different sources. Entrainment might provide a kind of “touch-up,” or automatic correction, of slight mismatches, like frets in a dial. This remarkable property of rhythms occurs in many media and at different time scales, including mechanical clocks hanging and ticking together on a wall, biological rhythms of organisms living together [116], and many others [87].

The following consideration suggests a more basic reason why interacting simultaneous periodic signals might best be highly limited in number.

**Harmonies Comprise Simple, Quick Repetition Patterns**

If cognitive information processing does involve EEG harmonies, as hypothesized here, then inherent limits to WM capacity, and limits to the degree of parallel information processing that WM capacity entails, are implied by the periods of regularity of summed harmonious frequencies. The sums of more harmonious combinations of pure sinusoids comprise simpler compound waveforms, which have briefer periods. Figure 6 illustrates this point with graphs of six harmonious pairs of sinusoids ranging from the minor third (6/5), through the fifth (3/2). As shown, the lower-interval relationships create a compound wave that cycles with a higher frequency, or shorter wavelength. The smaller the integers in the ratio between the two frequencies, the more frequently a simple summed waveform repeats itself exactly.

The experience of hearing roughness in the presence of two audio frequencies having less than critical band separation is, indeed, phenomenologically suggestive of the lack of a short period of regularity. The somewhat “unsettled” feeling with dissonant tones may thus arise because there is a time limit, or perhaps temporal function of fundamental frequency, for the level of cognition at which settling of information into a regular pattern is experienced as a harmonious, smooth sound.

**Hypothetical numerical example.** Using the gamma band for an example, suppose there is frequency variation over an EEG octave of 40–80 Hz (gamma band) within an individual, and that at any given time, preferred values of the frequency variations bear harmony ratios. Thus, if 40 is the lowest frequency in a particular individual at a given time, an additional wave of 50 Hz would carry a 5/4 (major 3rd) ratio.

**Periods of regularity.** How long would the system have to wait to register regularity in a compound signal of 40 plus 50 Hz? These two frequencies beat at 10 Hz. Thus, the time between two beats is 0.1 s. A minimum of two complete beat cycles (in this example 0.2 s) is necessary to indicate rhythmic regularity. If this system has a typical biological safety factor of at least 2 [3,40,70], the minimal time to register stationarity reliably is 0.4 s.

Behaviorally, this duration is reminiscent of a rather long choice reaction time. The human capacity to grasp about four items simultaneously in a strong trace, as discussed earlier, would require a frequency spacing of about this magnitude if the items were, indeed, represented by frequencies that had to fit within an octave. If each frequency bore this ratio with the next, the values would be 40, 50, 62.5, and 78.125 Hz; however, this oversimplifies, and contracts the necessary range, because a set of more than two frequencies will not be harmoniously self-consistent if each frequency merely bears the same ratio, locally, with the adjacent frequency.

**Capacity of an Octave Band**

Again consider the analogy from hearing, of our greater reluctance to accept close frequencies as consonant in harmonies (simultaneous tones) than in melodies (successive tones). For example, the major scale splendidly occurs in its simple sequential eight-note pattern in Beethoven’s Egmont Overture, and about 8 min from the beginning of the second movement of his Third Piano Concerto. But only the most assertive of modern composers would dare the dissonance of sounding all eight of these notes at
the same time. Only with lesser crowding of frequencies within the octave can there be a harmonious chord of about three to five notes. These numbers are the same as the recency capacity in verbal free recall experiments, capacity for tachistoscopic perception of numbers of dots, and other lower estimates of WM capacity, as discussed earlier. Thus, the harmonic capacity of an octave is approximately of the same numerousness as the lower estimates of WM capacity, which concern how many items can be apprehended at once in the passive trace component of WM.

As noted above in the subsection on cross-cultural consistencies, although modern Western music (e.g. Stravinsky, Bartok, Webern) as well as nonwestern musical styles make use of a variety of intervals that deviate from the simpler consonances of classical (and traditional popular and folk) Western music, there is a more universal tendency to limit the permissible number of intervals within an octave that are allowed to occur within any one piece and to spread these intervals over the whole octave; for example, this is true of the seven-interval octave of the Indian raga [107].

Further Analysis of Periods of Regularity

An example of a populous harmonious set of notes, restricted to an octave, is the 5-note dominant seventh chord (with tonic doubling of the octave); an example, in the key of C is C-E-G-B^9-C' (with middle C as the lowest frequency, respectively 261.63, 329.63, 392.00, 466.16, and 523.25 Hz). By shading the highest frequency (C^9) infinitesimally less than an octave interval from the fundamental (C), our theoretical nervous system might gain the hypothesized advantages of harmonious relationships within an octave, without risk of confounding by spurious difference frequencies within this “safe zone.” The following illustration uses the simpler harmony of the four-note major triad with tonic doubling of the octave, e.g., C-E-G-C', comparing its regularity period with the less consonant, corresponding minor triad, C-E^9-G-C'.

Figure 7 is a plot of both of these sets of four summed sinusoidal waveforms, presented at two different magnifications. As the figure shows, the major triad harmonic relationship leads to a relatively brief compound cycle time of four times the fundamental frequency. The minor triad on the other hand comprises a summed waveform with less obvious symmetries and simple regularities, in which the duration of a compound cycle is fully ten times that of the lowest of the tones. The longer period of regularity suggests a reason why in hearing music most ordinary listeners experience somewhat lesser consonance with a minor chord than a major chord. Correspondingly, frequency ratios as in the minor triad would involve more sluggish registration of compound signal in the EEG information-marking system postulated here. (Although the Fig. 7 plots simply use the cosine phase relation, the respective regularity periods of any other set of phase relations, for these same sets of frequencies, would be the same.)

What is the general rule for how these compound cycle times arise? Two ways of deriving the cycle times are in terms of beat frequencies or in terms of greatest common divisors.

Beats: Implications for period of regularity. Any two waves that are within the same octave will beat against each other at a frequency that is equal to the difference in frequencies of the two waves; for example waves at the alpha frequencies of 9 Hz and 8 Hz would yield a wave at 1 Hz. To compare the major and minor triads, assume a fundamental frequency for “C” of 60 Hz, in the gamma EEG range. This value will allow us the convenience of whole numbers in thinking about the frequencies implied by different harmonic ratios. Figure 8 represents the frequencies in the major and minor triad as positions along a line. In addition to each of the source tones at the specified harmonic ratios, the beat-frequency difference tones are shown under the lines representing the major and the minor triads.

Beats are physical phenomena, appearing not only in a mathematical plot of summed waves but in any physical measurement of such waves. Therefore, beats between all source tones, in every paired combination, are additionally accompanied by higher-order beats, resulting from beat-frequencies beating against other beat frequencies. Figure 8 shows one representative frequency resulting from each such beat-combinatoric difference. In the case of the
major triad, the smallest such difference is 15, while with the minor triad the smallest difference is 6. These numbers are, respectively, \( \frac{1}{4} \) and \( \frac{1}{10} \) of the frequency of the 60 Hz fundamental, and that is the origin of the respective repetition rates of the compound waves illustrated in Fig. 7.

Inspection of Fig. 8 suggests that the smallest difference (or difference of differences) is simply the greatest common divisor of the frequencies participating in each of the two illustrated chords. The following simple algebraic analysis shows this to be true in general, and provides a rule for considering the regularity period of any set of waves. Alongside each step in the proof is an example from the preceding illustration of harmonic relationships.

**Algebra of beats: Greatest common divisor.** Consider a set of numbers that have a common divisor, \( c \):

\[
(\!cA\!), (\!cB\!), (\!cD\!), \text{ and } (\!cE\!).
\]

Look at the ratio between two of these:

\[
cA/cB = A/B \quad \text{e.g., } 75/60 = (15 \times 5)/(15 \times 4) = \frac{5}{4}
\]  

Also look at the difference between the same two terms:

\[
cA - cB = c(A - B) \quad \text{e.g., } 75 - 60 = (15 \times 5) - (15 \times 4)
\]

\[
= 15(5 - 4) = 15
\]

This shows that the difference between the two terms is a multiple of the common divisor \( c \). Since \( c \) can be any common divisor, it can be the greatest common divisor. Similarly, for another example,

\[
cD - cE = c(D - E) \quad \text{e.g., } 120 - 75 = (15 \times 8) - (15 \times 5)
\]

\[
= 15(8 - 5) = (15 \times 3) = 45.
\]

Now, by analogy with finding higher-order beats, we calculate the difference of the above differences:

\[
c(D - E) - c(A - B) = c((D - E) - (A - B))
\]

It is evident that this algebraic process (related to the Euclidian algorithm; [92], pp. 4–9) is general, with \( c \) always factoring out as a common divisor. Thus, differences of differences will come out equal to the greatest common divisor. Recall, the implication for harmonies is that the cycle duration of a compound wave, which results from (linearly) summing a set of sinusoids, is equal to the greatest common divisor of the frequency of all the sinusoids.

**Carrying too many WM chunks at once will weigh you down.** These mathematical underpinnings of the experience of roughness or dissonance in music show why crowding an octave of brain waves with more frequencies might result in diminishing returns in information processing. Packing in additional signals would mean they must be spaced more closely, leading to a longer beat cycle, or stationarity period. In music, the “just” scale tuning has the lowest-number ratios (Table 1). However, if sinusoids at all eight of these frequencies were present at once, the greatest common divisor would be 24 times the period of the tonic, a long period of

| TABLE 1 |
|-----------------|---|---|---|---|---|---|---|---|---|
| Note-Example   | C  | D  | E  | F  | G  | A  | B  | C'|
| Ratio to fund. | 1  | 9/8| 5/4| 4/3| 3/2| 5/3|15/8| 2 |
| Local ratio    | 1  | 9/8|10/9| 6/15| 9/8|10/9| 9/8|16/15|
regularity. This is 2.4 times longer than the period of the minor triad illustrated earlier and six times that of the expeditious major triad. Thus, if harmonic brain wave pointers are part of the foundation of WM, holding seven or eight chunks simultaneously, without shifting to the rapid-successive mode characteristic of rehearsal cycling, would add the burden of a long holding time before the grouping could be registered. If a gamma brain wave octave of 40–80 Hz performs the WM function, then a single compound cycle for a summation of the seven (or eight) notes of the major scale (e.g., CDEFGAB[C’]) would take 0.6 s. The need to wait for two or more such cycles to be certain of the content of one complete cycle then implies a sluggish organism, who requires a waiting time of at least 1.2 s before being able to identify the large set of information in WM. This contrasts with a waiting time for the major triad of 0.2 s for two cycles, a more behaviorally meaningful value, on the order of magnitude of a typical behavioral reaction time.

Additional Empirical Implications

Behavioral decision times. The above argument suggests a particular mathematical function, for behavioral recognition or decision times, when simple items are incrementally added to WM. Because it depends on ratios, this prediction is independent of whether the above examples, using hypothetical gamma frequencies, are correct estimates. Additional factors may have an impact; for example, the motor reaction time for indicating what was recognized may add a constant to the decision latency for each WM load. One obvious next step to pursue this implication of the present hypothesis might be to use the Sternberg paradigm, for measuring decision reaction time with scanning of short-term memory systematically loaded with between 1 and 6 items. However, much interpretive controversy has surrounded the large numbers of results obtained with variations of the Sternberg procedure, during three decades of its use in cognitive psychology experimentation and theory (e.g., [8], pp. 199–203). Reviewing that work is beyond the scope of this paper.

Spectral analysis of brain waves. The foregoing points obviously also suggest it would be worthwhile to seek empirical evidence of copresent brain waves in low-integer ratio relationships, using Fourier decomposition techniques on raw signals taken from a single site and also comparing signals taken from different brain regions at the same time. Finding empirical evidence of frequency distributions suggesting such harmonic combinations, would encourage additional theoretical and empirical efforts along the present lines. Clearly, the theory predicts a correlation between number of items in WM and number of identifiable harmonic frequencies in the EEG. Because gamma-band EEG has generally required recording directly from the brain, using animals with implanted electrodes, it would be fortunate if the beta band, easily recordable from scalp electrodes in humans, using animals with implanted electrodes, it would be fortunate if the beta band EEG has generally required recording directly from the brain, gamma-band EEG has generally required recording directly from the brain, or to sequentially cycle temporarily maintained representations, of a sequence of working memory items [42,66,77]. This paper has dealt only in the most general terms with the mathematical formal equivalence of temporal and spatial frequency functions might easily be exploited by means of sweep operations somewhat analogous to those of bar-code readers, video monitor rasters, etc. (For a mathematical review of principles of computer graphics see, e.g., [30]) In one, almost literal neurobehavioral analogy, the tactile sensitivity of monkeys as they rub a grating with a fingertip may also exploit simply coded conversions between spatial stimulus properties and a temporal function of activity in the peripheral sensorimotor neural systems, which then reconverts back to a spatially coded representation in the brain [74]. However, if there are EEG harmonies that function as hypothesized here, we need to try to understand these processes at a deeper level than raw conversion between temporal and spatial isomorphisms.

Pursuing the analogy with our musical sensibility, perhaps there are varieties of ways in which melodious transitions of harmonies might be models of rules for informational transitions within the brain. The stylized, relative simplicity of music, by comparison with speech and language, is consistent with the possibility that music is an externalized, embellished version of a more primitive “language of the brain” [102] or middle-scale processing dynamic in animals and humans, intermediate in complexity and functionally transitional, between the firing patterns of single neurons and the behavioral patterns of a whole organism.

Further Theoretical Issues

This paper has dealt only in the most general terms with the problems of how EEG markers might evoke chunks of memory selectively as they are distributed across the brain in long-term storage, and how such distributed long-term memory engrams might be updated. As suggested above, the question of how transforms are effected between the massive parallelism of long-term memory’s anatomical/chemical structure and the small degree of parallelism, together with strong sequential aspect, of WM, may lend itself to analogies with the modest parallelism of harmonies and the serialism of melodies. (A different model that associates neural patterns with music was previously proposed by Leng, Shaw, and Wright [75].)

Some empirical observations and models have been concerned with the mapping of a time series to a spatial representation; for example with hippocampal pyramidal neurons viewed as leaky integrators [109]. Troyer, Levin, and Jacobs [136] demonstrate how, in the cricket’s mechanoreception for discriminating patterns of air currents, electrical and optical activity records can be coupled with a detailed database of the anatomy of dendritic structures, leading to a complete description of an ensemble code that incorporates both spatial and brief temporal-sequence information in a spatial array. Troyer et al. refer to work by Carr and Konishi that illustrates how higher-order sensory maps may juxtapose continuous codes for more than one parameter, one of which is a spatial map of a time variable.

The mathematical formal equivalence of temporal and spatial frequency functions might easily be exploited by means of sweep operations somewhat analogous to those of bar-code readers, video monitor rasters, etc. (For a mathematical review of principles of computer graphics see, e.g., [30]) In one, almost literal neurobehavioral analogy, the tactile sensitivity of monkeys as they rub a grating with a fingertip may also exploit simply coded conversions between spatial stimulus properties and a temporal function of activity in the peripheral sensorimotor neural systems, which then reconverts back to a spatially coded representation in the brain [74]. However, if there are EEG harmonies that function as hypothesized here, we need to try to understand these processes at a deeper level than raw conversion between temporal and spatial isomorphisms.

Addendum about a recent popularization. It is not obvious whether the hypothesis developed here implies other cognitive properties of music than those discussed above. Experimental attempts to use music as a catalyst for aspects of cognitive functioning (the so-called “Mozart Effect”) have yielded mixed results [90,106,111,131]. Reliable positive results might suggest that the mystery of why there is a human affinity for auditory patterns having a musical structure has an answer in some basic property of the brain. If that is true, that hypothetical property may or may not comprise the characteristics of brain waves hypothesized in the present paper. In evaluating popularizations, such as the idea that music is good for cognition and health [18]—even when they court the “New Age” attitude—we should be neither naively accepting nor overly critical.
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