# THE EPIC OF PERSONAL DEVELOPMENT AND THE MYSTERY OF SMALL WORKING MEMORY

### *by Robert B. Glassman*

*Abstract.* A partial analogy exists between the lifespan neuropsychological development of individuals and the biological evolution of species: In both of these major categories of growth, progressive emergence of wholes transcends inherently limited part-processes. The remarkably small purview of each moment of consciousness experienced by an individual may be a crucial aspect of maintaining organization in that individual's cognitive development, protecting it from combinatorial chaos. In this essay I summarize experimental psychology research showing that working memory capacity comprises the so-called magical number 7±2 items, not only for words and digits but for spatial items and other sorts of cognitive materials, and not only in humans but also in other species. This is so to such an extent that 7±2 may be a "constant of nature." The small quantity range 7±2 independent items, which builds upon a more elementary, instantaneous working memory capacity of three or four items, is surprisingly independent of the time duration of a cognitive task. Moreover, it is largely independent of ontogeny. Explanations of these powerful facts about working memory are offered here within both a functionalistic framework and a framework of hypothetical neural processes. At the neural level, working memory dynamics may comprise certain brain wave harmonics or topological relationships in the sheetlike cortex. Within the functionalistic framework, I suggest an additional analogy, pertaining to cultural evolution, with Tom Gilbert's work on risk analysis and "the global problematic" that follows from unforeseen consequences of the expansiveness of human ambition. Several connections are drawn with ideas presented by participants in the Chicago Religion and Science Group about how theologies and sciences try to understand the possibility of adaptive exercises of human freedom in the face of the extreme finiteness of each human individual.

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## A NEUROCOGNITIVE APPROACH TO THE GROWTH OF RELIGIOUS PERSPECTIVES

Our conscious, wondering, wandering human selves dwell approximately mid-scale in the epic of evolutionary creation, which ranges from the light-years vastness of the universe through the diverse intricacies of the world's many levels of organization down to microscopic and subatomic levels.

What *is* consciousness? What does it mean that each of us, occupying an extremely modest sector of all of space and time, is at the present moment a sentient glow at our own center of history? How does that position affect our inclination to join something larger?

A perennial enigma concerns how something as ineffable as conscious experience can make a material difference. Rather than joining the intellectual struggle to prove that consciousness is possible, using a professional philosopher's linguistic armaments, I want to slip in the back door, as it were, with a neural psychological approach. I first assume the obvious—that there is consciousness. I further assume not only that consciousness makes a difference in nature but also that in its every smallest nuance this doorway between one's personal past and future is completely bound to the material substrate that is each of our brains. My approach concerns the two essential properties of what cognitive scientists know as working memory: its small capacity and its brief duration. Better understanding of small working memory may help us to better enlarge our horizons. Working memory's small capacity is an intriguing example of a limit problem, rather different from the important limit problem that Tom Gilbert discussed at length in his presentation "The Epic of Creation: Where Does It Lead Us?" (2003), but I believe that the problem of working memory capacity is importantly related to the problem of global limits to which Gilbert points.

Among those of us who were honored to have our life stories enriched by Ralph Burhoe's understandings of how science and religion might be yoked together well, Gilbert has been developing his view of religion as the organizing factor that may continue to healthily transcend generations, if we individual humans can now somehow manage to flex and turn in good ways. Secularists are seduced by spans of the human historical drama that cover mere decades or a couple of centuries. We middle-aged adults may chuckle indulgently when youngsters reminisce about "long traditions" of years in popular music or clothing fashions or other aspects of popular culture, yet our own souls are often easily filled with grand zest at horizons of historical memory and rational planning that are of the order of magnitude of a single human lifespan.

In this regard, Gilbert wisely points us toward the need for a larger perspective on "the global problematic." While we clever humans of the world seem to have sidestepped the particular parameters of this problem that worried Thomas Robert Malthus and, more recently, the international group of thirty prominent persons who in 1968 organized an "invisible college" they called the "Club of Rome," as Gilbert explains, it is obvious that we have on our hands a difficult responsibility with regard to expansiveness of human desire and reach, in a finite world. Gilbert sees the possibility of new mass extinction occurring in the present epoch of the earth in which the primary cause is the power of unintended consequences of human action. This is a possible seamy side of our existence as what Philip Hefner calls created co-creators. I hope that something better can be achieved with better understanding of the enabling and limiting cognitive attributes in working memory that lie at the core of the human mind. Perhaps such understanding will allow us to better tap the positive generation-spanning attributes of the phenomena we know as religion.

*Metaphors, Images, and the Chicago Group Discussions.* Gilbert has spoken of the attractiveness of the metaphor of life as a *journey*. I first heard him discuss this some years ago while considering how mathematical risk analysis in physics and engineering might be applied to a broader range of human problems. The journey metaphor leads to my next several comments, based on some of the ideas shared in discussions within the Chicago Group associated with the Zygon Center for Religion and Science (ZCRS). Gilbert was one of the founders of this group in the late 1980s.

One recent Chicago Group discussion was of Hefner's Rockwell Lectures at Rice University. In Lecture #1, Hefner applied the journey metaphor hopefully in considering "a common point of contact" of Judaism, Christianity, and Islam "in Abraham, whose place as a father of faith is grounded in his willingness to devote his life to a journey, whose outcome he could not know." Antje Jackelén, in her consideration of the nature of text and truth titled "Interpretation Matters" (2002), develops this sense of Abraham's reaching out by associating his journey with the idea of a "genuine interest in the other" and even a "passion for otherness," which implies "that something is said to me that I cannot tell myself."

Paul Heltne used an alternative, visual metaphor involving gaps between circular spatial configurations in his Chicago Group discussion in March 2003. This metaphor seems related to the journey metaphor, as Heltne considers how intimately emotion and cognition participate together in an organism's ongoing choices for allocation of effort as it attempts to adapt and readapt its particular distribution of various competencies to the ever-changing, diverse environment. A connection between the journey metaphor and Heltne's spatial-allocation metaphor may be seen more clearly with reference to a biblical parable. In the Parable of the Sower (Luke

8:1),[1] the figure who distributes potential benefits (especially ideas) in diverse places does so on a journey. The various places where his seeds either take root and flourish or fail may stand for diverse human individuals or social contexts that are variously prepared, or not, for what is sown.

We might modify that interpretation a bit, taking the metaphorical seeds' various resting places more literally as environmental niches, which are then visited by diverse seekers on subsequent journeys. Then, the niches Heltne has sketched into his spatial model become graphic reifications of the opportunities visited by developing children (and developing adults) as they engage in what developmental psychologists call "niche-picking" (Berk 2003, 117, 331–32). That is, each of us has a rich, multidimensional, uniquely individual distribution of innate endowments, variously nurtured and grown during each of our lives to date. If especially effective sowers have preceded apt seekers in their respective journeys (and, under the best social conditions, an individual plays both roles, even at the same time), then we all live in an enriched ecology that has opportunities for each of us, each with an array of hungry aptitudes. We teachers always hope that our attempts to sow are successful in that way (Glassman 1980).

Although there is a degree to which "like seeks like" in such a communication process (Glassman, Packel, and Brown 1986), we all are bearers of myriad, variously fulfilled and unfulfilled, manifest and latent complexes of innate and learned characteristics. Therefore, under the best social conditions, there is a good degree of decoupling of heritages rooted in our individual sets of genes and prior cultural conditionings, wherein diverse individuals are enabled to synergize with each other, freed from excessive concern about local *quid pro quo*. Such warmly enriched conditions have been characterized by Francis Fukuyama (1999) as containing much "social capital." In them, while we care about family and friends, we do not put those close folks far, far above all others. We broadcast benefits, cast bread widely—and we also receive. That is not to say we receive in turn. It is not "in turn," and Fukuyama does a good job of associating the idea of morality with an all-important loose-coupling, long-delay property of reciprocal relationships in a well-functioning society. (Also see economist Robert Frank's [2004] insightful comments about social commitments.) It is somewhat like the folk tale "Stone Soup." Somehow, under good conditions, we do not have to worry that the externalities arising from our own well-meaning efforts are "promiscuously altruistic," as Garrett Hardin (e.g., 1999, 71) has warned. In such a bad turn of events the unintended consequences of good deeds, exploited by selfish others, wind up working more to the detriment of the sources of goodness than to the conditions that nurtured those sources.

All of this seems related to Carol Albright's monograph *Growing in the Image of God* (2002), discussed at a Chicago Group meeting in late 2002. The image of God that she proposes is one of infinite complexity (p. 72).

In our development as individuals, "complexification can occur when we ourselves bring about linkups in patterns so that they become increasingly meaningful and productive" (p. 23). Albright's theological and humanistic discussion, which includes consideration of Fowler's theory of stages of faith development, is more generally in keeping with ideas in the psychology of cognitive development that are rooted in the framework created by Swiss psychologist Jean Piaget; for example in Robbie Case's theory that automatization of simpler perceptual, motor, and cognitive schemes permits a growing child to transcend the severe, small-capacity, and brief-duration limits of his or her working memory, thus moving more, organized material through that brief present portal between one's past and future. This way of thinking of "building on building," or "parts within parts," also applies readily to the child's steady growth of proficiency in the phonological, semantic, grammatical, and pragmatic aspects of language (see Berk 2003).

*Working Memory Limit: Ground of Individuals' Mental Growth.* I believe that the severe limit of working memory may be the crucial condition for all cognitive-emotional development. Indeed, I believe that working memory capacity is a natural constant, albeit one with fuzzier edges than the natural constants that physicists and chemists have identified. As I will explain, our limit of few items held in mind at once remains remarkably constant not only across phases of an individual's lifespan development of knowledge and wisdom but even across mammalian species! Our continuous attempt to transcend that limit of working memory may be the very factor that leads to the continuing organized expansion of an individual's long-term memory and growth of personality. If working memory capacity were much larger we might have mental and neural combinatorial chaos of an intractably disorganized sort. If working memory capacity were much smaller, all of learning might be limited to piecemeal rote accumulations.

Perhaps this issue also is a key to understanding the evolution of ideas in larger groups, such as a nation—a matter the Chicago Group considered with Bill Irons's leadership of a discussion of Louis Menand's book *The Metaphysical Club* (2001). Under what conditions does our inherent narrowness of purview merely lead a group in a long, desultory meander of ideas? Are there conditions under which the members of a group may get beyond such relativistic ("romantic" or "postmodern"?) meanders, such that we genuinely complement each other and achieve real progress?

This matter connects also with two recent Chicago Group discussions, led by Don Arther, of the life and work of Paul Tillich. Central to Tillich's ideas is the matter of human partialness and finiteness, but each of us, both alone and with others, is constantly in search of something more. In his Rockwell Lecture #2, Hefner relates this matter both to the traditional Jewish notion that God deliberately made nature imperfect—thus leaving a basic task for humans to strive for greater perfection—and to the conception of Jesus as a healer. In Lecture #3, Phil summarizes Tillich's analysis of four basic characteristics of symbols, which help us to understand how human psychology grows larger connected wholes out of smaller, previously established units. A symbol (1) points beyond itself, (2) participates in the reality to which it points, (3) opens up new levels of reality, and (4) unlocks dimensions of the soul which tune into those levels of reality. In his later monograph *Dynamics of Faith* ([1957] 2001), Tillich adds a fifth and a sixth property. A symbol (5) cannot be produced intentionally; it grows out of the unconscious, and it (6) cannot be invented; like a living being it grows, but it dies when it no longer elicits a response in members of the group.

As with Albright's discussion of complexification, and related ideas in developmental psychology, Tillich's exposition of symbols is also related to the basic principle of working memory theory known as *chunking*, the automatized habitual clustering of informational items into knowledge and expertise, which I discuss later on.

To round out this perspective, before moving on to the nitty gritty of working memory, I want to quote a few passages from the 1954 Ph.D. dissertation of a late colleague, Donald E. Bartlett, on *The Concept of the End of History in the Writings of Reinhold Niebuhr and Paul Tillich*. Reading my colleague's half-century-old dissertation following his recent death is helping me give better voice to inklings of a host of perspectives that other theologians at ZCRS, and a few scientists as wise as Gilbert, already seem to know well.

> Human existence is historical existence, [Niebuhr and Tillich] say, and the meanings of history and of human existence are inseparably connected. Man's being is expressed and realized in history as he exercises his freedom and experiences the limitations and challenges of destiny. Hence the problem of history is perennial, a problem for every period. (p. 10)

> Neither the otherworldliness of traditionalism nor an optimistic faith in historical progress is adequate, for both evade the seriousness and uncertainty of history. (p. 11)

> Tillich has given the following brief definition: "History is the totality of remembered events, which are determined by free human activity, and are important for the life of human groups." Three emphases appear in this definition. (1) History as remembered is both objective and subjective, both event and interpretation. There is no history that is not told, selected, interpreted, charged with value and feeling. (2) History is concerned with the life of groups, not individuals. Nothing is in history which lacks social significance. (3) History depends on freedom, purposiveness, and the realization of value. Because history is constituted by freedom, it is characterized by production of the new; in historical events "something unique and individually significant occurs. (p. 12)

Bartlett's summary of Niebuhr and Tillich ties in with some aspects of my earlier comments on the metaphor of life as a journey and on the Parable of the Sower. The same intelligent, special quality of human existence that provides our joys in freedom also is responsible for our sometimes difficult degrees of separation from each other and from our "ground of being." Ralph Burhoe used to point out that animals almost always *know* what to do; animals' ambiguities are far rarer and smaller than in the human condition. Thus, within the extreme finiteness of each individual human's life, each of us can rarely be certain where is good to journey and sow our seeds or where to seek our individual niches in which seeds are germinating, and which we may further nurture into just rewards. We always hope for a fit with the context around us, an aspect of human learning that mid-twentieth century American behavioristic psychology failed to capture with its highly contrived laboratory circumstances, such as the Skinner box, with overdetermined outcomes.

In a subsection of his dissertation on "freedom and finitude" Bartlett adds,

> Niebuhr and Tillich make an extensive and penetrating analysis of historical existence. Central to their interpretation are the concepts of freedom and finitude, the most fundamental concepts for defining the nature of man. Tillich writes that man not only has finite freedom, he is finite freedom. Niebuhr finds the mixture of freedom and necessity expressed in the Biblical concepts of man as image of God and creature.
>
> Appreciation of the dynamic quality which human freedom gives to history marks off historical from non-historical world views, they say. Freedom, creativity, contingency, and forward movement distinguish history from the realm of nature.
>
> Freedom is defined as [the human] capacity for self-transcendence, [our] ability to rise above [our] immediate situation and [our] present self in knowledge, in self-consciousness, in moral choice and transforming action. (pp. 17–18)

With as much of the foregoing in mind as you have been able to "chunk," I want now to connect this larger perspective about memory, growth, and history with specific matters in the science of working memory. Your life's narrative evolves just a little during each moment, from infancy through every phase of maturity. How long is a cognitive moment and how much can it contain? Which aspects of our brains are most relevant to this question? I now look at the relevant area of cognitive psychology and neuroscience as "the science of partialness and finitude."

## CHARACTERISTICS OF WORKING MEMORY

*Small Capacity.* A famous 1956 review by George Miller coined the term "the magical number 7±2" concerning the puzzling persistence of this range in measurements of the numerousness of the momentary contents of consciousness. That paper is a focal point in the history of cognitive psychology. Its important summary of a great deal of prior research led to a larger body of subsequent research in the ensuing decades that concerned how many independent items (digits, letters, words or phrases, discrete ordinal positions in a rating scale judgment) may be borne in mind at once. In one part of his classic review, Miller referred to "immediate memory" as the psychological function concerned with this matter of capacity to hold only a small number of items in attention at once. Since that time, the terms *short-term memory* and *working memory* have come to be widely used, sometimes synonymously and sometimes with distinctions among different aspects, such as a subfunction devoted to storage as compared to ones devoted to executive functions, rehearsal, or intended actions (for reviews see Baddeley 1998; Richardson et al. 1996).

*Brief Duration.* The other prominent defining characteristic of working memory is its brief duration. Consideration of this issue has evolved in different ways in different experimental contexts, often simply dichotomizing short-term memory versus long-term memory. For example, in the animal neuroscience and experimental psychology literatures, working memory and short-term memory were often considered to cover a time span of as long as hours or even days (Glassman 1999a; Glassman, Leniek, and Haegerich 1998; Rosenzweig 1996). M. R. Rosenzweig therefore suggested the label *intermediate-term memory* to help distinguish among phenomena that must surely involve different neural properties. Growing knowledge of neurophysiological functions and of psychological phenomena having varied degrees of temporal persistence (for an excellent textbook see Rosenzweig, Breedlove, and Leiman 2002) further suggests the provisional, simplifying nature of such terms as working memory and long-term memory. Indeed, below I discuss a peculiar paradoxical time-elasticity of working memory, a "relativity" with context.

Studies of adults and of developing children have shown that both the capacity of working memory (WM) and intellectual capacity vary directly as a function of the speed of WM processing (see reviews in Cowan 1997; Weinert and Schneider 1995; Weiss 1992; also the excellent developmental psychology textbook by Berk 2003, 274–77).[2] This finding has been part of a theoretical controversy about whether cognitive development leads to an increase in the "number of storage slots" in WM. A more parsimonious, alternative formulation is that effectively larger WM capacity really occurs as a result of developmental progress in cognitive strategies or information-processing efficiency. The following are some possible reasons, as summarized by W. Schneider and M. Pressley (1997) and D. F. Bjorklund and R. N. Douglas (1997), why children's WM span might show an apparent increase, although these issues remain controversial.

- *Rehearsal.* Children who have completed grade school seem to spontaneously rehearse a list of items to be remembered more than do five-year-olds.
- *Grouping.* Adults tend to group items somewhat rhythmically as they rehearse them, often in sets of two, three, or four—as when trying to retain a telephone number.

- *Chunking and Organization*. As we get older we acquire more ways of seeing meanings in groupings of simpler items. This enables us to organize those items into fewer, larger items. A basic example is the way we see a written word holistically rather than as a decoupled group of letters.
- *Item Identification Efficiency.* Adults can identify items more quickly than children can. Schneider and Pressley mention a study by M. T. H. Chi in which five-year-olds took longer than adults both at a task requiring recognition of faces and at a task that had the further demand to name the faces.
- *Verbal Mediators.* Bjorklund and Douglas cite a study by J. H. Flavell and others in which older children spontaneously named sets of pictures to be recalled, thereby performing better than younger children in this task.
- *Metamemory.* With age and experience we learn how to approach a particular problem that requires memory. Cross-cultural studies show that this is especially noticeable in cultures in which there is extensive formal schooling.

Thus, this matter seems highly analogous to one arising in the study of expertise in adults, where it is found that effective WM increases greatly, but only in a specific domain for each individual (Ericsson 1996; Ericsson and Kintsch 1995). Indeed, in one study, children who were proficient in chess were able to remember natural configurations of chess pieces on a board better than adults who were novices in chess, although the adults did better than the children in a standard digit span test of WM (reviewed in Schneider and Pressley 1997, 58–59).

Radial maze findings with humans suggest a "universal constant" of WM. "The magical number 7±2" is our human WM capacity under a great variety of conditions, most often using verbal items. What is WM capacity in other species? Laboratory rats cannot be taught to speak, but it has been widely reported that rats in an eight-arm radial maze (Figure 1) regularly attain a perfect score, by traveling down each arm of the maze once and only once to obtain the single food morsel at the end of each arm, even

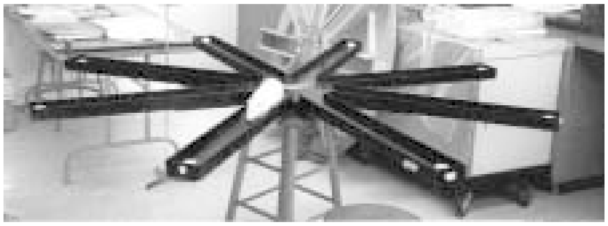


Fig. 1. Illustration of a rat in a radial-arm maze.

though their typical pattern for such foraging involves choosing arms in a random order. They do not seem to use odor trails. When the radial maze has twelve or seventeen arms, rats' performance becomes imperfect.

About a dozen years ago at Lake Forest College, we began a series of simple human behavioral experiments, in which we ask people to do analogous tasks, either with radial mazes drawn on paper or, on nice summer days, walking along the arms of a 15m-diameter radial maze painted on a large grassy area. Our participants' average scores in eight-arm or thirteen- or seventeen-arm radial mazes turned out to be the same as those of lab rats. (In these tasks, with good humor, we ask our human subjects to make it a fair contest with the rats by choosing arms in an unsystematic order. See O'Connor and Glassman 1993; Glassman et al. 1994; Glassman, Leniek, and Haegerich 1998.)

The radial maze has interesting time properties as a WM task, because it takes humans or rats some minutes to perform—much longer than the durations of typical verbal WM tasks. Moreover, during the 1980s some amazing results were reported, and replicated in several laboratories, for rats in a radial maze: If interrupted in the middle of a performance, they can complete it accurately even hours later (e.g., Beatty and Shavalia 1980). My colleagues and I found that persons in this spatial WM task have a comparable ability, at least for delays of up to fifteen minutes filled with distraction (Glassman, Leniek, and Haegerich 1998).[3] An extremely helpful anonymous reviewer of our paper offered specific references to the literature concerning the prodigious memories of bird species that cache food for the winter. Peculiarly, in laboratory tests with much shorter delays, such birds have been reported to reliably retrieve only about four to eight hidden morsels (Bednekoff and Balda 1996; Shettleworth and Krebs 1986). For a comparable task with humans, we distributed forty-two discretely marked hiding places in a large, grassy open field. People were asked to hide twelve place markers unsystematically in that situation and then to retrieve the markers after five minutes of verbal distraction. Our subjects succeeded in retrieving an average of about seven of the twelve place markers (Glassman et al. 2001).

What might it mean that there is such a small constant range for WM capacity across both situations and species? Each of us occupies only a tiny portion of space and grasps only a tiny cluster of things at any moment. Each life history is a tiny piece of world history. Indeed, in naturalistic approaches to theology, the term "Lord of History" is used in a rational way to address the proposition that evolution has naturally selected human beings to desire purposes larger than our individual knowledge provides for, so we reach (Burhoe 1975). At our best, in real life, each of us coordinates the data of past and present, progressing into the coming moment and wisely organizing intentions for the future. At such times there is clarity, a sense of encompassing a great deal at once. However, when measured under controlled laboratory conditions, the capacity of WM to hold a number of independent items is quite small. The cognitive doorway of the present remains narrow across variations in the kinds of represented items.

*Working Memory "Theory of Relativity."* During every moment of life we stoop and squeeze through the WM doorway without realizing it. Human memory can be very patchy (Neisser and Hyman 2000), yet we manage to do well enough with it. The basic trick with WM, chunking, involves automatically organizing selected material from long-term memory into the few coherent items that can be held in attention at any given moment. Such "moments" are apparently structured by task focus in addition to absolute time duration limits. Thus, the time paradox of the strangely stretched durations in the radial maze procedures mentioned earlier, as well as other time paradoxes (including "recency" recall after slowly paced list presentation, mentioned below), suggest a need for a "WM theory of relativity" (Glassman 1999a; 2000a). It looks as if a purposive thing is going on here—that our cognitive present "wants" about seven items to work with.[4]

A general question is whether WM is crudely or finely engineered by natural selection. Are the quantitative properties of WM merely the outcomes of opportunistic natural selection processes that have settled into an evolutionary "groove"? It seems more likely that WM capacity is a robust product that has "tuned in" to something deep in the logic of cognition, which concerns the fact that we are creatures living in a stream of time. In maintaining fairly constant capacity, WM may be supported by a variety of intermediate-time memory effects, known by the names *priming, implicit memory, warm-up, procedural memory,* and *figure-ground* effects (Glassman 1999a, esp. 480–84; Cowan 1997).

But is "the magical number" seven or three? Under laboratory conditions, when one is pressed to keep the same 7±2 items in mind for several seconds, about half of the set is vivid while the remainder undergoes active rehearsal. The notions of phonological loop and of sensory memory (Baddeley 1998) are among the ways this fact has been conceptualized. More effortful tests of WM capacity also suggest that at any instant only about three or four items are strongly in focus in WM.

For example, the well-known textbook phenomenon of "recency" comprises about four items, each recalled with greater than 50 percent probability, at the end of a long list of presented words (Ashcraft 2002, 171–73; Neath 1998, 67–72). Interestingly, a time paradox with recency is also cited in cognitive psychology textbooks. If a subject must try to recall the list after a twenty-second delay that is filled with an interfering task, such recall of the most recent items is lost—but not if the presentation of words was at the slow pace of one word per twelve seconds, with interfering tasks occupying those twelve-second intervals (Bjork and Whitten 1974).

Other examples of effortful tasks yielding smaller WM capacity results include continuously tracking a sequence of input items occurring every second or every four seconds (Waugh and Norman 1965); so-called sentence-span, counting-span, or speaking-span WM tasks, which require a subject to keep items in mind while using them in sentences or calculations (Hitch and Towse 1995; Lustig and Hasher 2002; Miyake 2001); and capacity for features of lines flashed at different orientations (Luck and Vogel 1997). Recently, two students in my lab replicated Irwin Pollack's (1952) finding that when the items to be remembered are musical tones played in a random sequence, immediate memory capacity is only about four tones. This seemed to be partly because, for people who are not experts in music, convenient symbols are not available to use in mental rehearsal (Glassman, McKenna and Sienkiewicz 2002). Findings supporting a conclusion that WM core capacity is only three or four items are reviewed in three earlier papers and an abstract (Glassman 1999a, b; 2000a, b) and in a more recent extensive review (Cowan 2001[5]).

Reality is not a continuous blend. "Thinghood" occurs on many scales, but not at scales in between. There are galaxies, stars, and planets, and there are organisms, organs, cells, and molecules—with big ontological gaps in between. Life occurs at a range of "middle scales" between elementary particles and the universe as a whole. These mid-scales are dense ontologically, so our scientific explorations of some levels may be insufficiently developed.

Two sets of conjectures in the following sections about temporal and spatial WM properties of the brain illustrate this point. The first concerns a hypothesis that particular EEG harmonic phenomena underlie the threes or fours of WM capacity, at intermediate scales between large cortical masses and single neuron activity. The second suggests that certain basic principles of plane topology also underlie a core capacity of WM for handling three and four independent items in the functioning of the sheetlike cortex. These two hypotheses attempt to integrate knowledge, at the neural level, both of "time and mind" and of "space and mind."

## EEG HARMONICS: TIME PROPERTIES OF WM BRAIN SIGNALS

Now being widely investigated is the hypothesis that the neural representations of mental attributes undergo *binding* into unified cognitions by means of coherent relations among spatially widespread EEG rhythms in the brain. Such electrical coherence potentially addresses the causal-linkage questions of mediation between short- and long-term memory and of how dispersed brain regions, which individually tune into the diverse properties of a psychological event, might temporarily configure and reconfigure in each succeeding moment to achieve psychological coherence (Kavanau 2002; Singer 1993; Schack et al. 2002).

However, WM contains more than a single item at a time; therefore, a single set of synchronized brain waves seems insufficient. How can the brain act as a substrate for the several conceits that are in WM at any moment? The terms *single-element binding* and *small-cluster binding* might be coined to describe two "layers" of WM.

Is "harmonious" cognition supported by literal harmonies in EEG signaling? Waveforms, in any medium, can be analyzed as summations of component sinusoidal waves, but certain wave relationships are special. The human ear, across diverse cultures, is pleased by simple musical harmonies. This fact correlates with a certain "efficiency" in the signaling properties of harmonies: Waves whose frequencies are in the low-integer ratios of harmonies (especially 3/2, 4/3) have summed waveforms that have the shortest possible wavelength (Figure 2). Harmonious frequencies also can occur in fast triplets; for example, the major triad (ratios 3/2 plus 5/4 present at once) has a wavelength only four times that of the fundamental frequency (Glassman 1999b; 2000a). This might be important if EEG has a role as a vehicle for signals at the neural level to serve working memory at the level of cognition. Working memories often have to fade within a few seconds when there is a continuing flow of information. Our ability to ignore, shelve, or discard information at an appropriate rate is as important as our ability to acquire information (Sachs 1967).[6] Pursuing the EEG harmonics hypothesis, if three items in WM were coded in a gamma EEG

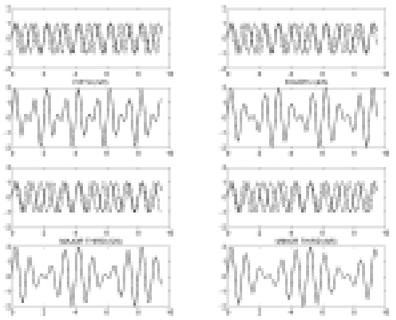


Fig. 2. Waves that are in harmony with each other have short wavelengths in their moment-by-moment summed waveforms. For example, with the harmony that is classically considered best, the "perfect fifth," there is a 3:2 ratio between wavelengths, and the summed waveform has only twice the period of either individual contributing wave. In this figure, the upper graph for each illustrated harmonic ratio shows the two contributing waves, while the lower graph shows their sum. Note that the peaks of the sum occur where the two contributing waves are closest to having synchronized peaks. Since these graphs use the sine function, perfect synchrony occurs only at the zero-crossing. (The peaks would synchronize if it were a cosine function.) The formula for the major third is y=sin[2 x]+sin[(1.25)(2 x)]. Plotted using MATLAB 6.5 software.

band “major triad,” say, of 40Hz, 50Hz, and 60Hz, a single summed wave would take 0.1 second. At least two waves are necessary to establish that there is a consistent signal, and the two-tenths of a second that this implies is, appropriately, at the brief end of the range of meaningful cognitive time intervals. (For example, it is a simple reaction time.) But how plausible is it that a sinusoidal EEG wave, as simple and low in frequency as such waves are, could be the brain-activity aspect of something as complex as a cognition in working memory? Because WM capacity is so small, at any given moment there may be a correspondingly small demand for signal differentiation in the time or frequency domain binding frequencies. As for the myriad features in long-term memory, from which a selection is tapped by WM in each moment, this differentiation must reside largely in the exquisite, dense spatial structure of the brain.

Brain wave components that are basically sinusoidal might have a certain robustness as signals, because the sinusoidal form remains constant in the face of variations in synchronization or time of arrival (i.e., phase) when waves of the same frequency undergo summation. Moreover, the sinusoidal form remains across “calculus-type transforms,” that is, when there is a mathematical extraction of their rate of change (differentiation) or of their aggregate strength over time (integration). Finally, when sinusoids of different frequencies are summed, the sinusoidal form remains implicit in the components and may be extracted by the famous analysis technique that began with Joseph Fourier in the early decades of the 1800s. Thus, it is conceivable that at any instant up to three or four different EEG frequencies could act as markers of the up to three or four items that are then most vivid in working memory. Such a pattern of brain wave harmonics would have to encompass all the regions of brain tissue whose feature-analyzing properties lead them to be called upon for those particular cognitive objects (for details see Glassman 1999b; 2000a).

Using primarily a different set of justifications than are presented here, G. L. Shaw, Mark Bodner, and colleagues have argued that there is a deep relationship between music and brain function.[7] They argue also that threeness is important and coin the term *trion* in a hypothesis about the elementary unit of neural information processing (Shaw 2000). An additional justification of their emphasis on threes, or of my own hypotheses about threes, is in a combinatorial fact long known in computer science. Namely, if it were feasible to replace the typical “yes-no,” “on-off,” or “1 vs. 0” binary fundamental structural elements of computers with *trinary* elements, each having a range of three activation levels, this would allow a more efficient simple representational system. That is, fewer elements plus states of those elements would be needed in order to represent, label, or count a number of objects. A base-3 counting system is more efficient than our decimal system, a binary system, or any other integer-base (Hayes 2001). Such an efficiency becomes meaningful when dealing with the extremely large numbers of elements in a complex information-processing machine (computer or brain) together with the extremely large number of things to be represented in a knowledge system.[8]

A hypothesized octave band restriction on brain wave signaling is part of the foregoing hypothesis about a cluster of three or four EEG harmonics. A basic algebraic principle implies that so long as two frequencies are within a single octave—that is, so long as the higher frequency is less than twice the lower frequency—no difference rhythm can occur within the same octave. This is simply to say that if you take two numbers, $x$ and $2x$, the difference $2x–x$ cannot fall between $x$ and $2x$. (This principle may be related to a theorem that is similar in form but concerns digital sampling of waves at the "Nyquist frequency"; see, e.g., Chugani, Samant, and Cerna 1998.) This suggests that if sinusoids act as simple signals in the EEG, they can engage in combinatorial play without introducing spurious, distracting aliases, so long as the three or four signal frequencies that represent WM chunks remain within a single octave. One possible EEG range that would fulfill this requirement would be a gamma band that extended, say, from 40 to 80 Hz. However, in beginning to explore this issue empirically in my lab, we are considering the full range of EEG frequencies that we are able to record, an octave at a time.[9]

## TOPOLOGY OF ACTIVE CORTICAL PATCHES: SPATIAL PROPERTIES OF WM SIGNALS

The approximately 90 percent of the human brain that is our cortex must contain virtually all of the immense quantity of information in long-term memory, which is drawn upon by the WM system, with its capacity to mobilize only a few chunks during any one moment. Strikingly, the cortex is a sheet, in humans only slightly thicker than in the mouse. V. B. Mountcastle's (1997) estimate of 2,600 cm$^2$ implies that if the cortical sheet had a square perimeter it would have almost exactly twice the linear dimensions of a typical graduation "mortarboard" cap (see Hofman 1988 for implied larger estimated area). Indeed, the mammalian cortical thickness of 2 to 3 mm is the same as the thickness of such a cap. These figures suggest the whimsical, species-centric remark that human beings are "the college graduates of biological evolution." The amazing cortical sheet comprises tens of billions of pyramidal neurons, so densely packed that there are 100,000 of them beneath each square millimeter of its outer surface (Braitenberg and Schüz 1998). Each cubic millimeter contains about a billion synapses, distributed over approximately 1–2 kilometers of axons and 456 meters of dendrites (Braitenberg and Schüz 1998; Abeles 1991; DeFelipe et al. 1999). Deliberately mixing metric and English units to describe these awe-inspiring facts about the cortex leads to the evocative alliteration "miles within millimeters" (Glassman 2002).

Although the cortex comprises about six layers, there is a unifying "vertical" organization spanning the cortex through its full 2–3 mm depth. The neurons are generally clustered as "cortical columns," typically about 300–600 mm in diameter, having much greater interconnectedness within than between columns (Braitenberg and Schüz 1998; Mountcastle 1997, 702; White 1989, 8–12, 20–29). This anatomical unity in the dimension of its thickness again implies that the cortex functionally has a sheetlike character.

Moreover, most of the commerce of the cortex, by far, is "private," an internal matter. Even in primary sensory cortex, no more than 20 percent of the synapses receive information from outside the cortex. Although 80 per cent of cortical neurons contribute axons to the white matter, overall, more than 98 percent of cortical white matter comprises connections not to subcortical areas or to the spinal cord and the body but from one cortical area to another (White 1986, cited by Braitenberg and Schüz 1998, 43). Again, this implies a sheetlike quality of the cortex's woven fabric.

It is necessary to acknowledge that the severe anatomical constraint of a thin cortex may primarily be the result of many factors. For example, it may be a necessary concomitant of ontogenetic organizing processes or of other aspects of function in a three-dimensional universe. Indeed, our bodies have many sheetlike structures, such as cell membranes and blood vessel walls. These have a variety of functions, including separation, confinement, selective transport, and uniformly ready availability for signals. Some of these functions, indeed, are metaphorically suggestive of a role of cortex as a "wall" (with a "narrow doorway" of WM) or "membrane" whose limited WM "permeability" divides a living, intelligent individual's past from his or her future.

*Combinatorial Considerations.* Returning to the "why" issue discussed earlier, perhaps the anatomical and functional features and constraints attending the sheetlike cortex yield a good compromise between combinatorial explosiveness on one hand and fecundity in the combinatorial play of associations on the other. The design of the brain must make it convenient for mind to steer between the Scylla and Charybdis of dull inertness and sheer chaos (Glassman 1999a). Related issues of degrees of retention versus forgetting have been discussed by others, at the levels of collective memory of a society (Nora 1996; Richelle 1996, 12) or the pace of life in different cultures (Helfrich 1996; Levine 1996). These matters seem related also to the issue of surface details versus meanings (and "gists") understood by individuals using language (Zangwill 1972; Ericsson and Kintsch 1995; Engle and Conway 1998; Libby and Neisser 2001) and the issue of cortical connectivity (Merker 2004).[10]

*Connectivity: Density, Sparseness, and Degrees of Separation in Graph Theory.* In spite of the extreme density of connectivity in the cortex, there is only approximately a chance in a thousand that any one pyramidal neuron within a small cortical region will synapse on any of the others within that region (Braitenberg and Schüz 1998). From a statistical point of view, the local connectivity seems random; it looks as if the synapses "rained" down (Braitenberg and Schüz 1998, 51). Thus, the extreme denseness of neural fibers should not distract us from a countermanding sparseness of local connectivity among the basal dendrites of neighboring pyramidal neurons.

In graph theory, when extremely large numbers of elements are sparsely interconnected in a random manner (rather than in a regular manner, or "lattice"), a condition readily develops in which the individual nodes have surprisingly few "degrees of separation." That is, there is a path from one node to any other node via only a few intermediate nodes (Watts and Strogatz 1998; Watts 1999; Hayes 2000). Threshold discontinuities comprise a related aspect of random graphs. Thus, the sparse, random local connectivity among pyramidal neurons within a cluster may comprise a pregnant situation, a sort of arena of productive freedom, in which cohesive dynamic patterns of neural activity are always on the threshold of creation as a result of small adjustments in the connection weights at a few synapses, while always ready to dissipate and give way to alternative patterns. One may imagine these sorts of activity fluctuations dynamically unifying the cortex as a whole, or unifying large or small subareas of cortex rather independently of each other, each in its own tightly coupled neural activity circuits, for the duration of a "WM moment." In graph theory, regions of complete internal coupling, which are loosely coupled to other such regions, within which there are also few degrees of separation, are known as "cliques" (Watts 1999, 37, 102–9). In the present context we may think of a clique, hypothetically, as the graph-theoretical aspect of single-element binding of individual WM chunks.

*Freedom to Associate.* Considering the other "layer" of WM function, small-cluster binding of threes or fours of items must also entail a kind of freedom. When we participate in laboratory experiments, working memory contents are stilted and predetermined. In real life the brain takes things as they come. Even during deliberate thinking, in solitude, thoughts emerge from preceding thoughts rather than being rehearsed. Therefore, there has to be arbitrary freedom of associations among all the chunks in WM at any moment. Thus, again, freedom of association must occur on both levels of binding. First, the brain's representational substrates for *attributes* of each chunk must be readily available to be evoked in any combination for binding together into a unified percept or concept and quickly unbinding in readiness for what comes next. Second, given the independent coalescence of up to three or four of such cognitive objects at once, all three or four must be free to associate in any combination.

*Three Topological Constraining Principles.* Three additional basic principles from mathematical graph theory and topology imply that in a planar environment (such as the cortex) information processing may be restricted to three or four independently varying items.

1. First, the four-color principle is relevant to the hypothesis of shared "subpatch" boundaries. The near two-dimensionality of the cortex suggests considering its functional regions as "patches" that are available for activation. If that makes sense, then the famous four-color principle of topology (Barr [1964] 1989; Saaty and Kainen [1977] 1986) suggests that a region that is committed to WM during some short time interval may be the scene of combinatorial play among up to four "subpatches." Such play involves both competition of psychological attributes for appropriately tuned cortical substrates and associative interactions among WM chunks.

Conceivably, even a cortical region as small as a 0.5 mm cortical column might be considered as a flat "patch," although such columns are taller than they are wide. This is because columns may well have much more rigorously homogeneous feature-analyzing properties in the vertical dimension than horizontally, where the sparse, apparently random local connectivity among basal dendrites implies looser horizontal coupling.

Element binding of a single conceit must invoke many widely distributed cortical columns. Cognitive associative activity among the pairs, triplets, or quadruplets of conceits held at one time in WM (the small-cluster level of binding) may also always involve long-distance relations as its primary feature. However, there are interesting implications if, instead, associative activity occurs largely by virtue of local interactions within each patch, while activity in the long-distance cortico-cortical axons is, hypothetically, restricted to binding within each chunk. This could happen if some significant number of the patches of activated cortical tissue *each* momentarily commit to *all* of the chunks in WM. For the duration of that WM moment, the subpatch that represents a given chunk, in each of these patches, is bound to its respective counterpart in every other patch. Such a thing might happen most readily in the fronto-limbic areas in which there is an extreme degree of convergence from all other areas and which much evidence shows to be involved in WM (Merker 2004). Each such hypothesized patch then might be divided up dynamically into as many parts as there are items in WM. If each such subpatch has a well-defined boundary, the cortical embodiment of a momentary association among simultaneously active WM chunks is in a dynamic interplay occurring at the shared boundaries of the subpatches that represent those chunks.

These hypothetical working memory patches and subpatches would have their brief moments of existence as dynamically changing amoeboid shapes, which are continually moving around each other and also denting each other with new protuberances while maintaining edge adjacencies. Again, because of global binding *within* each WM chunk, there must be closely correlated activity *among* all the subpatches, distributed over the cortex, which represent a given chunk. Topologically, mutual shared boundaries occur readily when an area is divided three ways, and only up to four "subpatches" can simultaneously freely associate, each with every other, in this way. It is impossible to add a fifth closed region in such a way that each of the regions shares a border with every other. This hypothesis about cortical subpatch associations is an apparent corollary of the famous four-color principle for geographic maps—that no more than four distinguishing markers (e.g., colors) are needed for designating subareas of any map that can be drawn on a plane in such a way that no two regions having the same marker share a boundary (Figure 3).

2. The second principle is that up to four nodes can connect exhaustively without crossings. A basic principle of graph theory leads to the same conclusion about a limit of four for contacts among freely associating local regions within a plane. This theorem is that "$K_4$ is planar" (Figure 4), while "$K_5$ is nonplanar."[11] That is, all six possible connections can be drawn among four nodes without any crossings of lines. However, if a fifth node is added, at least two of the connecting lines must cross each other in the plane. Of course, even with a mere 2–3 mm third dimension of depth, there is more than ample room in the cortex for slender axons to cross each other in order to yield differentiation of associative activity on a scale of tens of microns. However, I am here pursuing the premise that the cortex is, to a large degree, functionally a plane, in which there is cognitively significant cortical activity that requires unitary commitments on a larger scale of cortical volumes, perhaps a scale of approximately 0.1 mm horizontally, and extending through one or more cortical layers vertically. Within that scale, the dendritic trees of thousands of pyramidal neurons overlap. If such is the case, avoiding interfering crosstalk among WM chunks might require the $K_4$ restriction. It also is possible to envision an intermediate scale of connectivity in which much of the cortical columnar depth is unitarily committed in each subpatch, but an additional association might skirt these entrenched chunks via "overpass connectivity" employing the wide lateral spread of apical dendrites in the cortical molecular layer.

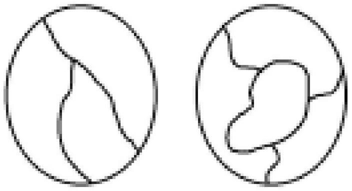


Fig. 3. Up to four discrete subareas of a plane each can make mutual contact with every other subarea.

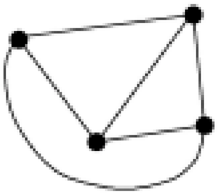
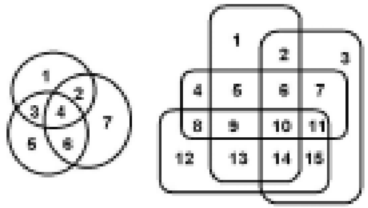


Fig. 4. Up to four nodes can be connected within a plane without any crossing of connections.

3. Third, only up to four convex Venn figures can intersect exhaustively. The topological considerations discussed above concerned edge contacts as the hypothesized mode of association among discretely bounded subpatches. Coincidentally, the same inference about a limit of four subpatches is suggested by a very different topological premise, under which the hypothetical subpatches that embody WM chunks must overlap, or interpenetrate, in order to achieve associations. Such embodiments of cognitive items can be considered as if they were like the Venn diagrams of symbolic logic. Three convex figures (having no inward bends; Yaglom and Boltyanskii 1961) easily achieve a comprehensive set of intersections, while up to four convex figures can intersect exhaustively, with some necessary stretching and squaring off (Figure 5, drawn after Barr 1964; also see Edwards 2004). Beyond that number, serpentine shapes are required (Figure 6). While such diagrams with an exhaustive set of intersections can be achieved, with effort, by a whole, intelligent person drawing intersecting figures, it seems more plausible that the level of "intelligence" of associative play among cortical subpatches must have a more primitive quality, which involves simpler, amoebalike dynamics of random exploratory expansions, contractions, and translations of convex boundaries. Greater numbers of items interacting in this way entail greater possibilities of errors (either omissions or repeats).

I develop these arguments, that applications of plane topology and of graph theory to the cortical sheet are deeply consistent with the cognitive restriction of core WM capacity to three or four items, more fully in Glassman 2003, where I also discuss some economies of time and metabolic expense that would be achieved if the main neurophysiological work, as WM chunks undergo combinatorial associative play, indeed occurs at the level of local interactions, while long-distance cortico-cortical activity plays a reduced role, limited to global binding *within* individual chunks.



**Fig, 5.** Up to four convex figures can be made to exhaustively intersect, in the manner of Venn diagrams.

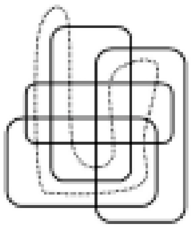


**Fig. 6.** A fifth Venn figure, which exhaustively intersects each of the others, must be concave.

## NOTES

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1. Karl Peters pointed out the relevance of this parable to related ideas in an earlier article for *Zygon* (Glassman 1980).

2. However, the role of EEG frequency in intelligence remains controversial (see Andreassi 2000, 41–60).

3. We have also found the same WM capacity in a verbal task, having a formal similarity with the radial maze, in which subjects are required to recite a sequence of eight, thirteen, or seventeen numbers or letters in random order, without repeating individual items. However, this task has less robust delay characteristics than does spatial memory in the radial maze. When we tried an eight-digit or eight-letter (A through H) random recitation task with an interference-filled thirty-second delay interposed halfway, performance was significantly poorer than without the delay (average 7 versus 7.7 items correct). It was impossible to do a standard digit-span (or letter-span) recall task, with eight items, under such a delay condition.

4. It might be interesting to systematically compare these “relativity” effects with the tendency of subjects, when explicitly judging time intervals, to be biased toward the comparison standard, whether it is longer or briefer (Eisler 1996), or to compare them with other circumstances in which intended actions have a critical relationship with time judgments, as in driving (Michon 1996).

5 . I thank both Simon Grondin and Richard Block for independently suggesting this interesting paper.

6. I thank Bjorn Merker for this interesting source.

7. It is also appropriate to cite an interesting compendium of other ideas on “biomusicology,” concerning deeper significances of music in evolution of human behavior and brain (Wallin, Merker, and Brown 2000).

8. To illustrate with approximations using small numbers, consider that two digits of our base-10 system can count from 0 to 99. With a binary system it takes between 6 and 7 digits to count or label the same 100 items ($2^6 = 64$, $2^7 = 128$; and $100\ 2^{6.644}$). And with a trinary system it takes between 4 and 5 elements ($3^4 = 81$, $3^5 = 243$; and $100\ 3^{4.192}$). The “efficiency” arises from the fact that two decimal elements have a total of 10+10=20 levels; the total number of required levels for binary and trinary counters are, respectively, 13.288 (=2X6.644) and 12.576 (=3X4.192). (Only the non-integer base *e*=2.718… is more efficient than the integer 3 as a base.)

9. A variety of additional musical phenomena, including the “fundamental bass,” difference rhythm “roughness,” and the psychological need for resolution of chord patterns (Pierce 1992; Plomp 1976; Rossing 1990) are also suggestive of possible brain wave counterparts of WM information processing (Glassman 1999b).

10. These considerations are somewhat akin to a theory that a WM capacity of seven optimizes the rapid detection of statistical correlations (Kareev 2000; I thank Nancy Brekke for pointing out this source).

11. “K” stands for “complete graph,” meaning every node is connected to every other.

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