Yadin Dudai

Department of Neurobiology
The Weizmann Institute of Science
Rehovot 76100
Israel

How Big Is Human Memory, or On Being Just Useful Enough

We are, in many respects, what we remember. But how much do we do? So far, science has provided only a very partial answer to this riddle. The magical number seven, plus or minus two, seems to constrain the capacity of our immediate memory (Miller 1956). But surely its constraints dissipate when memories settle in long-term stores. Yet how big are these stores? If we combine all of our factual knowledge and personal reminiscence, childhood scenes and memories of the past day, intimate experiences and professional expertise—how many items are there, that, combined together, mold us into unique individuals?

The answer is not simple, and neither is the question. For example, what is an *item* in long-term memory? And how can we measure it, being sure that we unveil memory capacity and not merely the occasional ability to tap it? Such theoretical and practical difficulties, no doubt, have contributed to the fact that the capacity of human memory is still an enigma. Yet, despite the inherent and undeniable complexities, the issue deserves to be retrieved, once in a while, from the oblivions of the collective memory of the scientific community. (For a selection of earlier discussions of the size of human long-term memory, see Galton 1879; Landauer 1986; Crovitz et al. 1991.)

Folk Psychology and Early Views

When confronted with the issue, many tend to provide an intuitive estimate of the size of their memory, based either on belief or introspection or both. These estimates vary greatly. In an informal survey among 30 adults with academic education (ages 25–72), I received estimates in the range of 10^2 – 10^7 for autobiographical episodes, 10^3 – 6×10^4 for words in mother tongue, and 10^2 – 10^6 for facts related to one's profession. Furthermore, when asked what percentage of memory is accessible at any given time, the answers ranged from 0.001 to 100. The distinction between memory that is stored and memory that can be retrieved is a critical issue that will be addressed further below. If the question relates to memory that is stored, regardless whether it is normally retrieved or not, many, including professional psychologists, tend to believe that everything we learn is permanently stored in the mind (cited in Loftus and Loftus 1980). This implies an immense number of accumulating traces.

Whereas Loftus and Loftus (1980) do not hold that view, other contemporary scholars do advocate the stand that something once committed to memory is never erased (Shiffrin and Atkinson 1969; Capaldi and Neath 1995; see also Ebbinghaus 1885; McGeoch 1932). A similar, even more radical, view was presented two centuries earlier by the German philosopher Tetens: “Each idea does not only leave a trace. . .but each of them can be stimulated—even if it is not possible to demonstrate this in a given situation” (Tetens 1777). The contrasting

view, that is, that some memories are erased forever, can be readily traced to ancient times [e.g., Plato, *Theatetus* 191].

Despite the prescientific attempts to propose concrete mechanisms of memory (Burnham 1889), only in a few cases was the actual size of memory addressed. St. Augustine, who contemplated memory so deeply and beautifully, depicted “the fields and spacious palaces of memory” as “innumerable” and “boundless” (St. Augustine 400). Almost 14 centuries later, the French philosopher Helvetius concluded that the capacity of memory far exceeds the practical needs of a thoughtful human being. “There is no one,” he argued, “whose memory cannot contain, not only all the words of a language, but also an infinity of dates, facts, names, places, and persons, and finally, a number of objects considerably more than six or seven thousand. I conclude confidently that every well-endowed man is given a capacity of memory far beyond what he can make use of for increasing his ideas. . . instead of regarding the inequality of memory in men as the cause of the inequality of their intellects, their latter inequality is entirely the result, either of attention. . . with which they observe the relations of objects, or the bad choice of objects with which they load their memories. . . This is why one is seldom a great man who has not the courage to be ignorant of an infinite number of useless things.” (Helvetius, cited in Burnham 1889). As we shall see below, Helvetius was not off track.

But probably the most detailed estimate of the capacity of human memory in premodern times emerged at about the same time in the writing of the Swiss-German physiologist Haller, who performed the first documented experiments in the timing of psychic processes and reached the conclusion that a third of a second is sufficient time for the production of one idea. On this basis and assuming only 8 mentally useful hours per day (!) it was calculated that in 50 years a person may collect up to 1,577,880,000 traces (Burnham 1889). Here, again, as in the case of Tetens above, and influenced by the notions of earlier philosophers such as Aristotle and Thomas Aquinas (Mahoney 1982; Kenny 1993), memory was regarded as a storehouse that includes not only traces of sensory perceptions but also ideas, hence, endogenously generated representations (Dudai 1989). This complicates the situation even further; for now, if we wish to consider human memory, we must take into account not only learned facts and experienced episodes but also concepts and images of the mind.

The modern era in the experimental approach to human memory capacity can be traced back to the ingenious yet controversial British anthropologist, Francis Galton (1879, 1907). Galton introspected memory while taking his daily walks and reached the conclusion that not only are most of life events “drowned in the waters of Lethe” (i.e., the mythological river in Hades whose water induced forgetfulness in those who drank it), but also that “forgetfulness appears absolute in the vast majority of cases, and our supposed recollections to a past life are, I believe, no more than that of a large number of episodes in it, to be reckoned in hundreds or thousands, certainly not in tens of thousands, which have escaped oblivion” (Galton 1879). Galton’s conclusions influenced some but not others; some modern textbooks still suggest that there are practically no limits to long-term memory (Eysenck and Keane 1990).

So do we store many millions of items in our memory, or only a few

thousand? In the absence of direct methods to measure the information capacity of a brain, a multitude of experimental approaches must be recruited to provide a heuristic estimate of the size of memory. These approaches range from neurophysiology and neuroanatomy, via information and computer sciences, to experimental and clinical psychology and anthropology.

The Domains of Discussion

Before embarking on the quest for pertinent data, it is useful to note that “memory capacity” means different things to different people. Theoreticians may construe it as referring to the overall storage capacity of an information-processing machine with the properties of brain. Those who are more biologically oriented may wish to add that the capacity of brains is constrained by deterioration with age and the finite life time of mortals. Experimental psychologists and neuropsychologists may have in mind distinct memory systems and may also ask how much of the capacity of each system is actually used. It is evident that the theoretical limit is larger than the real life overall capacity, which is larger than the capacity of specific systems, etc. (Table 1). We shall start our discussion with the theoretical limits and proceed toward the more practical constraints of ecological memory, using data and arguments from the various disciplines listed in Table 1.

Another important point that should be kept in mind is that experts from various disciplines often insist on using different conceptual units to quantify capacity. Such units range from bits in formal discussion of information processing systems to loosely defined, if at all, items in treatments of everyday (ecological) memory (Table 2). Furthermore, the conversion between the various units is not yet feasible (e.g., bits into memories), requires ad hoc analysis, or is simply ignored. At the current

Table 1: Sources of estimates of human long-term memory capacity

Estimate	Source
Theoretical limits of brain capacity	Information Science, Computational Neurosciences, Neurophysiology, Neuroanatomy
Theoretical capacity per memory system	Computational Neurosciences, Neurophysiology, Neuroanatomy
Upper limits of capacity per individual	Experimental Psychology, Studies of Exceptional Phenotypes
Actual capacity used per individual ^a	Experimental Psychology, Neuropsychology
Memory retrieved per individual ^a	Experimental Psychology, Neuropsychology
Average capacity used by the species	Cognitive Anthropology

^aIt is not yet known whether the actual capacity used differs from retrievable capacity. Some investigators hold the view that the term “storage capacity” is meaningless in the absence of retrieval; see text.

Table 2: *Conceptual units used to quantify memory capacity*

Unit	Embodied in	Example	Units used in
Bit	elementary neuronal activity	spike	Information Science, Computational Neuroscience, Neurophysiology
Pattern	neuronal populations	firing pattern in a neuronal module	Computational Neuroscience, Neurophysiology, Neuroimaging
Element	neuronal populations	a vector in motor memory; shape and color in visual memory; fact in episodic memory	Neurophysiology, Neuropsychology, Psychophysics, Experimental Psychology
Memory	neuronal circuits, interconnected assemblies	integrated sequence of motions in motor memory; episode in autobiographical memory	Neurophysiology, Neuropsychology, Experimental Psychology, Cognitive Anthropology

Units are illustrated that could be used in various disciplines (and hence at various levels of analysis) to quantify the memory capacity of the brain. The conversion between the units is either not yet feasible (e.g., bits into memory) or must be worked out ad hoc (e.g., elements into memory).

state of the art, the best one can do is to confine the use of specific conceptual units like bits or patterns to their appropriate discipline, regret the ignorance that prevents us from translating the language of one discipline into another, and take consolation in the thought that the variety of terms reflects the richness and the multidisciplinary nature of memory research.

Having said all that, and bearing in mind that no definite answers are going to be provided at the end of the journey, merely estimates—most of which rely on a multitude of heuristic assumptions and approximations—the time is ripe to sample very briefly what the theoreticians have to say.

A Message from Models, With Some Physiological Constraints

Theoreticians talk bits and patterns. The past two decades have provided us with a wealth of models that describe the collective behavior of large neural networks (Amit 1989). Such models tell us what is the maximal number of bits and patterns that can be stored in a network containing N elements. The fascination with the numbers so obtained should not blur two facts: first, that the exercise is interesting and imposes limits on what should be expected from capacity of certain networks under certain conditions; and second, that those are models only, and that the outcome of the calculation varies significantly with the assumptions. Nevertheless, the exercise is worth taking.

Table 3: *Exercises in brain capacity*

Parameter	Size	Reference
I. Storage capacity		
uncorrelated patterns in an artificial neural net ^a	$n = \alpha N$, ($\alpha = 0.14 - 2$)	Little and Shaw (1978) Hopfield (1982); Gardner (1987)
number of bits ^b	$n \times b_p$	
number of neurons in brain	10^{11}	Amit (1989)
number of synapses per neuron	10^4	Braitenberg and Schuz (1991)
number of bits stored per brain ^c	$\alpha 10^{15}$	Amit (1989)
II. Influx of information into brain		
a. sensory data		
maximal bits carried by optic nerve in 1 sec	$10^6 - 10^8$	Koch (1997)
bits per 70 years ^d	$1.5 \times 10^{15} -$ 1.5×10^{17}	
b. perception		
time per visual percept	150 msec	Thorpe et al. (1996)
percepts per 70 years ^d	10^{10}	
bits per percept	$10^3 - 10^4$	see text
total bits	$10^{13} - 10^{14}$	

^a(N) The number of units in the net.^bWhere b_p is bit per pattern.^cAssuming full connectivity; for a range of estimates, see text.^dDeducting one-third of the time for sleep.

One way to play with the numbers is to consider a model network and determine its capacity as a function of the number of units and the connectivity rules, select numbers for neurons and synapses in the brain, insert the latter data into the theoretical function, and get the capacity estimate for the brain. A typical exercise is presented in Table 3. In brief, a major class of neural net models shows that the number of uncorrelated patterns, n , that can stored in a network is proportional to the number of units, N , in the net: $n = \alpha N$ (Little and Shaw 1978). The proportionality coefficient α ranges between 0.14 in the archetype Hopfield model (Hopfield 1982) to 2 (Gardner 1987). Using different assumptions about numbers and connectivity, values obtained for networks of the size of the human brain range from 5×10^{12} bits (Palm 1982, "under a very restrictive strategy," p. 199) to $\alpha 10^{15}$ bits (Amit 1989, p. 274). The latter is the value favored in Table 3.

More recent modeling incorporates more realistic assumptions and data (e.g., Amit et al. 1994). The field is highly dynamic and fluid as far as incorporation of novel physiological findings is concerned (e.g., Koch 1997). Model neurons now tend to resemble somewhat better their natural counterparts in being capable of multiple states, connectivity is partial, and the brain is not treated as a homogeneous net but rather as a construct of multiple organs each containing multiple processing modules. Some physiological findings provide actual values that are

relevant to models and may constrain and improve them. For example, data are now available on the role, size, and number of columnar modules subserving elementary processing in cortex (1300 in the anterior inferotemporal cortex of monkey; Tanaka 1993), or on the fraction of neurons engaged in mnemonic function within a given memory task (only <2% in the above cortical area; Sakai and Miyashita 1991). Powerful combination of advanced electrophysiology, optical imaging and psychophysics (e.g., Tanaka 1993; Wang et al. 1996) are bound to generate more and more quantitative data of this kind.

STORAGE CAPACITY

Nevertheless, the road from physiological findings to the estimation of storage capacity is still so risky that not many laboratories dare to follow it publicly (examples of some that do are Treves and Rolls 1991, 1994; Amit et al. 1994). The published attempts deal with two brain areas: the hippocampus, favored by many as an organ engaged in transient storage of memories and their consolidation, and the visual cortex, regarded as the region in which visual memories are deposited (Mishkin and Appenzeller 1987). One example is the estimate for hippocampal storage capacity, published by Treves and Rolls (1991, 1994), and based on a computational analysis anchored in a selection of anatomical and physiological properties. These investigators hypothesized that CA3 pyramidal neurons operate as a single autoassociation network to store new episodic information, and on top of their basic hypothesis, made several simplifications and assumptions in their neural net modeling. Altogether this led them to propose that in the rat, the CA3 system can store ~36,000 episodic representations (admittedly, the investigators are not very clear on what these representations actually are: Spatial maps? Cheese? A grinning face of an electrophysiologist approaching with an electrode?) A similar estimate for human hippocampus is expected to yield a much larger capacity (Treves and Rolls 1991).

PERCEPTUAL CAPACITY

A larger number of teams attempted to combine experimental data with modeling to estimate the capacity of the brain to represent on-line stimulus information, that is, in *perception*, rather than the capacity to store and later retrieve information off-line, i.e. from memory. In a study combining electrophysiological data and computer simulations, the above group of investigators set out to determine the representational capacity of face encoding in the temporal lobe of the monkey (Abbott et al. 1996). The investigators came to the conclusion that in this system, N neurons can represent $\sim 3 (2^{0.4N})$ faces with 50% discrimination accuracy. Thus, even 25 neurons, according to this estimate, can encode no less than 3000 faces. Abbott et al. (1996) remark that "(this yields). . . remarkably large capacities for even modest numbers of neurons. Indeed, the capacity for faces may seem more than would be required. . . ." For a merely illustrative comparison between independent estimates of stimulus representation capacity and storage capacity, one can refer to the conclusions of Amit (1989), which is 10,000 pictures stored in a model network of 5,000–100,000 neurons, depending on the learning rules. As expected, storage thus yields smaller values but it is still highly impressive.

The perceptual representation capacity of high-order visual cortical areas was addressed by other teams of investigators as well. The major objective of these studies was to determine principles of neuronal coding

in the brain. It is generally found that there is partial redundancy between neurons in inferotemporal cortex, and that this places limits on the signaling capacity of a neuronal population (Gawne and Richmond 1993; Zohary et al. 1994). Even under these limitations, the capacity of the system as a whole is very high. Here is an example: The average value of bits per neuron in the inferotemporal cortex was estimated by independent studies to be ~ 0.3 (Gawne and Richmond 1993; Gochin et al. 1994). The amount of novel information carried by each neuron was suggested, on the basis of redundancy estimates, to follow the function $1/\sqrt{n}$, where n is the number of neurons in the population (Gochin et al. 1994). This means that in a system of 10^5 neurons, each neuron can carry ~ 0.001 bits of novel information. If one estimates the total inferotemporal output code to be subserved by 10^4 – 10^6 neurons, it means that at any given moment the system can encode between 30 and 300 bits of novel information. Because even 30 bits could in theory be used to distinguish between >1 billion shapes, the system appears to have a very large representational capacity. The investigators indeed use the term “storage” instead of “stimulus representation in perception” (Gochin et al. 1994, p. 2335), but this is probably merely an overenthusiastic statement.

MAXIMAL INFORMATION FLOW FROM THE OUTSIDE WORLD

At this point, an additional number game may prove illuminating. This involves attempts to estimate the maximal amount of information that the human brain is expected to perceive throughout a lifetime. Here, again, the assumptions and inherent uncertainties are numerous indeed (e.g. Hick 1952). A pioneer in the modern attempts to equate the brain with a machine, John Von Neuman, estimated that the input per nerve cell per second in the human brain is 14 bits, and, allowing 10^{10} nerve cells, concluded that the information accumulated over a life span of 60 years is 2.8×10^{20} bits (von Neuman 1958). In the past 20 years both life expectancy and the estimate of the number of neurons in the brain increased; therefore, using the same influx estimate one now gets 3.3×10^{21} bits per lifetime. On the other side of the spectrum stands a much more humble estimate of 1.2 bits/sec (via reading), and in this case the amount of information accumulated over a lifetime as a result of reading, viewing the world, and contemplating it was calculated to be only $\sim 10^{10}$ bits (Landauer 1986). More recent calculations, based on updated views of neuronal coding, yield values in between the aforementioned estimates: It was suggested that the human optic nerve has the potential of conveying 10^6 – 10^8 bits/sec, that is, 1.5×10^{15} – 1.5×10^{17} bits per waked lifetime (Koch 1997). Another method of calculation is based on multiplying the time needed to process a single moderately complex visual percept (Thorpe et al. 1996) by a heuristic, rough estimate of the number of bits that might be required to encode such a percept in imagery; this method yields an estimate of 10^{13} – 10^{14} bits perceived per lifetime (Table 3). For the purpose of discussion, one may assume that visual information is $\sim 50\%$ of the total information reaching the brain, and therefore the values obtained for visual perception do not differ by more than a factor of 2 from those obtained for all the modalities combined.

All in all, modeling, combined with some physiology, leads to the following conclusions:

1. Although the theoretical constructs of mathematicians, physicists, and other practitioners of artificial neural networks vary in their

assumptions and rules, the bottom line is that the human brain (or, more accurately, its artificial simplified counterparts) is capable of a storage capacity that can account for the higher-end estimates obtained by either folk or experimental psychology (see below). That is, we would not be able to astonish the current generation of modelers if we were to confront them with the views of St. Augustine or Haller; they surely would be able to come up with a model that reconciles with the data. The appreciation for this truly impressive capacity is clearly detected in various treatments of the subject in computer sciences and information theory. Moravec (1988), for example, points out that “The largest supercomputers of the late 1980s are a match for the 1 gram brain of a mouse, but at \$10 million or more apiece they are reserved for serious work.” However, the same calculations also attest to the fact that current theories are far from disclosing the whole story: The same author comes up with the conclusion that the brains of elephants and sperm whales are more powerful than ours (Moravec 1988, p. 61).

2. Highly simplified number games, such as those presented in Table 3, suggest that in theory, the human brain may be capable of storing all of the sensory information that it encounters throughout a lifetime.
3. Last, but not at all least: There is a link missing between theory and biology, without which the calculation would indeed remain number games. Even if we were to know how many bits the brain can store, this would not tell us how many memories we have because we do not know, first, how much of the system is engaged in mnemonics (see above), and second, most importantly, how specific pieces of information are encoded. An example based on Table 3 illustrates the latter problem. If we play with the numbers in parts IIa and IIb of Table 3, we may conclude that only a fraction (0.001%–10%) of the information flooding the brain at any given moment is sufficient to saturate our psychophysical perceptual capacity. Alas, an assumption made in part IIb is that 10^3 – 10^4 bits (i.e. pixels) can encode a moderately complex visual percept, which looks reasonable at a phenomenological level of analysis, but we do not know what code(s) the brain actually uses. The missing link is thus the code(s) in which internal representations are encoded and computed. The basics of brain codes are sought after eagerly in many laboratories worldwide (e.g., Abeles 1991; Bialek et al. 1991; Gawne and Richmond 1993; Gochin et al. 1994; Shadlen and Newsome 1994; Hopfield 1995; Softky 1995; Konig et al. 1996; Tsodyks and Markram 1997), but it will take a long time before we are able to translate neuronal firing patterns into bits, bits into percepts and memories, etc., etc., and vice versa. And without that, modelers, neurobiologists, and psychologists will go on talking different languages or, even worse, use the same terms to refer to different things.

Real Life Memory, and a Note on Heterogeneity

This leads us back to the realm of experimental psychology, that is, measuring the performance of brains in the real world (Table 1). Two remarks are appropriate at this stage. The first pertains to the heterogeneity of memory. Human memory is considered to be composed of multiple systems (Squire and Knowlton 1994). These are conventionally classified into declarative (alias explicit) and nondeclarative (alias implicit) memory. Declarative memory is usually further classified

into memory for facts (semantic memory) and memory for events (autobiographical memory), whereas nondeclarative memory is further classified into skills and habits (procedural memory), priming, classical conditioning, and nonassociative (reflexive) learning. As noted above, each of these systems is expected to have characteristic properties, including storage capacity.

An additional issue is how real life memory is measured. In declarative memory, two main types of situations are encountered, differing in the results they yield. These are recall and recognition (Hollingworth 1913; Bartlett 1932; Tulving 1983; Eysenck and Keane 1990; Haist et al. 1992). In recognition, sensory information directly relevant to the item in memory is present on-line. In recall, no such on-line information is available. Furthermore, recall can be performed in two variants. In cued recall, some sensory cue is provided that may relate to the item in memory by association. In free recall, no such intentional cues are presented. The performance on the above types of tasks also raises the issue of memory particularities. In recognition tasks, sometimes a sense of familiarity is evoked without emergence of unique details, raising the question how specific is encoding (Tulving 1983). These issues will be addressed further below.

Pictures and Words

Some of the aforementioned multiple memory systems were found by experimental psychologists to be more amenable to quantitative estimation than others. Two such stores deserve special attention. The first is language; the second is visual memory.

Language is intuitively realized to involve extensive memory, and yet the capacity of this memory is larger than most people think they have; frequently, educated adults tend to estimate their vocabulary at a figure that is only 1%–10% of the actual value (Seashore and Eckerson 1940). The major reason for this discrepancy is that people tend to confuse the vocabulary that they use in daily activities with the number of distinct words they recognize. Whereas the vocabulary used in routine daily activities ranges from a few hundred to a few thousand, depending on education and profession (Seashore and Eckerson 1940), and goes up to 8,000–20,000 in literary works (Shakespeare used 15,000 words, Milton 8,000, whereas Italian grand opera did rather well with 800 only; Seashore and Eckerson 1940), the number of distinct words in printed school English (excluding derivatives and compounds) is ~88,500 (Nagy and Anderson 1984); and it is estimated that an American high school graduate knows, on the average, 30%–60% of these words (Nagy and Anderson 1984). It was also estimated that an average 6-year-old English-speaking child commands no less than 13,000 words (Pinker 1995).

One picture is worth a thousand words. If this cliché were to be taken literally, the number of words at our command would amount to at least 10^7 : There is evidence that subjects can recognize many thousands of pictures several days after they have seen the pictures only once. The data talk about 6,600 pictures being recognized out of a set of 10,000, but it was proposed, on the basis of extrapolation, that even 1 million could be remembered (Standing 1987; it took a week to perform the test on 10,000 pictures!). Though the aforementioned report is unique in suggesting such a tremendous pictorial memory, other reports as well provide evidence that pictorial memory is vast and exceeds verbal memory in its capacity (e.g., Nickerson 1965; Shepard 1967).

Episodes, the Essence of Our Personality

Exciting as they are, memories of syllables or random slides, used in laboratory experiments, are usually not the kind of stuff that touches our heart. The memories that most of us care about much of the time are personal episodes. These episodes also attracted much of the efforts of psychologists striving to quantify the capacity of human long-term memory.

The intricacies of episodic memory exceed the scope of the present discussion (for a detailed treatment, see Tulving 1983 and Rubin 1986). Clearly, personal episodic memories are expected to vary in size, in vividness and accuracy, in reproducibility, and in their ability to evoke by association either additional details of the same episode or other episodes. This makes the quantification of such memories even more problematic. Nonetheless, it might be useful to heuristically consider, for the purpose of discussion, the notion of *core episode*, defined herein as the minimal chunk of a personal episodic memory that uniquely characterizes the episode and has the highest probability to surface when this episode is recalled. The core episode is an elementary narrative that may be composed of both focal elements (i.e., the salient occurrences in the episode) and setting elements [the time and the place in which the episode took place (Hollingworth 1913; Tulving 1983)]. The core episode can be appreciated intuitively by recalling personal episodes of the remote past. Often, there is a limited set of details of a given episode that comes to mind upon recalling it, and often, further concentration may bring up more details that only rarely come to mind as front elements in recall. It is convenient to think about the studies described below in terms of core episodes.

Several attempts have been made over the years to assess the capacity of autobiographical memory. These attempts could be classified according to the methodology used, as either free recall or cued recall experiments, and each of these could be classified further according to the specific method used.

The modern quantitative tradition starts, as noted above, with Galton (1879). At first he combined visual cued recall with introspection: "I walked leisurely along Pall Mall, a distance of 450 yards, during which time I scrutinized with attention every successive object that caught my eyes, and I allowed my attention to rest on it until one or two thoughts had arisen through direct association with that object; then I took very brief note of them, and passed on to the next object. I never allowed my mind to ramble. . . samples of my life had passed before me. . . . The actors in my mental stage were. . . by no means so numerous as I had imagined" (Galton 1879, p. 151–152). Galton then shifted to semantic cued recall, that is, he composed a list of words and later observed these words one at a time, recording the immediate associations evoked. He found that going over a list of 75 different words four times, under different circumstances, gave rise to 505 ideas, of which only 289 were different. He classified these associations into imagined sounds of words, other kinds of sense imagery, and finally what he defined as "histrionic representations, . . . where I either act a part in imagination, or see in imagination a part acted, or, most commonly by far, where I am both spectator and all the actors at once, in an imaginary mental theatre" (Galton 1879, p. 159). Galton found that two-fifths of his cued reminiscences dated prior to the age of 22 and also concluded that ". . . our working stock of ideas is narrowly limited" (Galton 1879, p. 162;

and see his estimate of “hundreds or thousands,” mentioned above).

Galton did not limit his associations a priori to autobiographical episodes. However, this was done 90 years later by Crovitz and his coworkers (Crovitz and Shiffman 1974). Whereas Galton used uncommon words, Crovitz and his colleagues switched to a list of very familiar words and specifically informed their subjects before the beginning of the experiment that this was a study of personal memories. The Crovitz modification of Galton's semantic cuing methodology became a major tool in the quantification of autobiographical memory (Rubin 1982; Brewer 1986). The analysis of their data led Crovitz and his colleagues to the conclusion that the dependence of autobiographical memory on age fits a function of the type $f = bt^{-a}$ (where t is time and a a forgetting coefficient; see also Wickelgren 1974). They estimated a and calculated the number of accessible personal episodes recollected from a given time-ago interval; for example, the function yielded 224 events for a period of 20 years prior to the test (Crovitz et al. 1991). “Galton's number” obtained in this way was hence at the lower end of Galton's estimate.

Techniques in addition to semantic cuing were also used in attempts to quantify autobiographical memory. The main ones are (1) open-ended recollection, (2) the diary technique, (3) interviewing, and (4) standardized questionnaires. In open-ended recollection, the subject is requested to spend a given amount of time in recollecting past events, usually also dating them (Crovitz and Harvey 1979; Rubin 1982). In the diary technique, the subject confines systematically to a diary a sample of on-going events and later attempts to recall them, scoring success by comparison of cued recall with the written record (Linton 1978; White 1982; Wagenaar 1986). Interviewing is used mainly in assessing eyewitnessing (Wells and Loftus 1984, Christianson 1992). Standardized questionnaires (Warrington and Silberstein 1970; Squire and Slater 1975) are used primarily to assess semantic recognition or cued recall, for example, of public figures or events, but can also be used to specifically tap autobiographic episodes (Bahrick et al. 1975; Brown et al. 1986).

Several conclusions may be drawn from the above investigations. First, the studies only sample memory and do not fully exploit mnemonic performance; therefore, capacity could only be assessed, if at all, by some kind of extrapolation. Second, the memories tapped in such studies are on the order of magnitude of hundreds to a few thousand controlled items (Linton 1978; Wagenaar 1986). Third, in longitudinal studies that spread over many years, there is a nonmonotonic age effect that includes a gradual time-dependent decline in the most recent years (<30 years), a “reminiscence” increase for the subject's youth (observed in >35-year-old subjects), and childhood amnesia (<4 years old) (Rubin et al. 1986). The data could also fit the notion that memory, including autobiographical memory, consolidates gradually over the years, with some old memories becoming practically invulnerable to disruption (Squire and Alvarez 1995).

All in all, the data suggest that on the one hand the function used by Crovitz and his coworkers yielded underestimation of the capacity of autobiographical memories, especially the older memories, but on the other hand show that even in tapping a controlled reservoir of a few thousand intentionally marked memories over several years, using personally designed cuing, a significant proportion becomes very difficult

to recall (Wagenaar 1986). It is safe to conclude that under laboratory recall conditions, the capacity of retrievable autobiographical memory in the adult taxes the upper limits of Galton's estimate, that is, thousands of core episodes. However, the capacity unveiled in recognition situations in normal individuals is expected to be significantly higher, possibly by an order of magnitude.

Exceptional Phenotypes

In various fields of the life sciences, the use of phenotypes that deviate from normal permits inference of function from dysfunction, by identifying those properties and mechanisms that are obligatory for the normal condition. Such deviations, for example, mutations, almost always result in defective performance. This is probably due to the fact that biological systems function at optimal but not peak performance, and therefore, aberrations in metabolic cascades are bound to shift the balance from the optimum, resulting in a defective phenotype (Dudai 1989). Nevertheless, in some cases, aberrations may lead to enhanced performance as well (for an example of molecular defects that may enhance memory in simple systems, see Carew 1996). In the case of human memory, specific mutations that enhance performance are not yet known, but neurological and behavioral phenotypes with exceptional memory do exist and may serve as "mutations" to provide hints on the possible limits of memory capacity.

The aforementioned phenotypes can be classified into two main classes, though, one must admit, the distinction between the two is not always obvious. One class is that of mnemonists, that is, otherwise normal individuals capable of impressive memory feats, and another class is that of idiot savants. The latter are individuals with exceptional abilities in a limited domain of human performance accompanied by retardation in other domains. Such individuals, for example, may produce impressive paintings or perform tantalizing calculations while at the same time achieving a very limited score on IQ tests (Winner 1996).

Feats of so-called normal mnemonists have been described repeatedly over the years in the general and scientific literature (e.g., Brown and Deffenbacher 1995). They often involve exceptional tricks of visual memory. Visual imagery was indeed the basics of the mnemonic art highly developed since ancient times and culminating in sophisticated procedures, grouped under the term "artificial memory systems", in the late middle ages (Yates 1966; Carruthers 1990). In a common class of these mnemotechnic procedures, images of physical items or loci (e.g., rooms in a complex building) are associated in memory with specific items or meanings and later used as a code to retrieve them. Expert mnemonists went to great pain to train themselves not only in coding and recoding using the same set of imagery loci, but also in mastering a great number of loci; it is said of the great mnemonist Peter of Ravena, who lived in the fifteenth century, that he memorized no less than 100,000 loci, and that "...on his travels, he does not cease to make new places in some monastery or church, remembering through them histories, or fables, or Lenten sermons. . . . He can repeat from memory the whole of the canon law, text and gloss. . .two hundred speeches or sayings of Cicero; three hundred sayings of the philosophers; twenty thousand legal points. . ." (Yates 1966). Judging by the fact that each speech or saying consists of multiple words and facts, and that each locus in an artificial memory system can in principle store multiple items

(Crovitz 1971), it appears that Peter was capable of memorizing hundreds of thousands of facts; and there is no reason to assume that he was so exceptional among the memory artists (Yates 1966).

Additional, more recent and sometimes more controlled accounts of mnemonic feats can be cited. Some of them attest to the special capabilities of experts in their respective fields of expertise. These range from impressive competence of waiters and porters (e.g., Anthony 1880), via the ability of chess players to memorize chess moves and games and the location of pieces (Chase and Simon 1973), that of traditional singers to compose from memory very long poems and sagas (Rubin 1995), or that of virtuoso mental calculators to rely on a vast store of accountable numerical equivalents (Hunter 1978), to the ability of the so-called “Shass Polaks” to visually memorize the entire Talmud, word by word, page by page (Stratton 1917). It should be noted that some of the aforementioned prodigious memories provide an estimate of the capacity of normal human memory for facts.

More bizarre are the performances of idiot savants; cases are known in which savant artists show a very remarkable and detailed visual memory of complex scenes while understanding and performance in other domains is much below normal (Winner 1996). However, perhaps the most famous mnemonist is S. (Sherashevski), a patient of the noted Russian neuropsychologist Luria (Luria 1968). He was not an idiot savant but was not entirely normal either. According to Luria’s description, S. practically forgot nothing he encountered. He excelled in visual memory and imagery, and in the case of propositional material, encoded it into images that he remembered for decades. Luria reached the conclusion that S.’s memory “had no distinct limits” (Luria 1968, p. 11). But the unlimited memory did not make S. successful in performing tasks beyond mnemonics: He was a failed musician and journalist, found it difficult to exercise abstract thoughts, and became confused by the vast amount of useless details he carried in his mind. S. was thus a pathological case with an enormous memory but limited intellectual capacity. As is with other cases mentioned above, S. demonstrated that the capacity of long-term memory can be extended much beyond that encountered in normal individuals in daily life. However, in his case, the overall cognitive profile carries a message concerning the useful limits of normal memory, which will be discussed further below.

On the Size of Orally Reliant Databases

Anthropological data sometimes illuminate the human cognition. An intriguing correlate to the magical number seven, which constrains the short-term memory capacity of individuals (Miller 1956), was indicated by Wallace, who analyzed the kinship terminology in geographically and historically remote societies (Wallace 1961). He showed that the minimum number of binary discriminations necessary for the specification of the meaning of a kinship term in societies is six. Furthermore, certain other institutionalized forms of discriminations, either in language or in common games (such as playing cards or chess), could also be described by systems requiring not more than six simultaneous binary discriminations. Similarly, the number of levels in bioethnographic hierarchical taxonomies traditionally used by non-Western societies to describe plants and animals is usually five (Berlin et al. 1973). One way to construe these findings is to assume that the human mind cannot hold more than six discriminations at a time, hence the capacity of working

memory, as indicated by the memory of societies, is rather similar to that of each individual as determined in laboratory settings (Berlin et al. 1973; see also D'Andrade 1995).

Can we learn about long-term memory from the same type of data? Possibly yes. In *The Savage Mind*, Levi-Strauss (1966) points out that the size of ethnobotanics and ethnozoologies reliant on oral traditions in primitive societies is universal and reaches up to ~600 items. Assuming that our knowledge of such traditional classifications is not complete, Levi-Strauss (1966) extrapolates to databases of up to 2000 items each. A more recent estimate of the maximum number of items that nonliterate ethnobiologists can retrieve is ~500 (Berlin 1992). Somewhat higher values, approximating those suggested by Levi-Strauss, are provided by Brown (1985). Expert databases of several hundred items may also be found in traditional medicine (Frake 1961). All in all, these anthropological observations may imply that human cultures naturally converge on orally reliant databases of several hundred items because our long-term memory finds it convenient to deal with such bodies of long-term information, but not larger ones (Berlin 1992).

Is it Forgotten?

But let us return from societies to individuals. Suppose we adapt a highly conservative attitude and assume that a normal human being experiences only a single episodal event of any kind whatsoever per day. This amounts to ~25,000 potential episodes in 70 years. An event per hour would yield ~400,000 potential episodes, deducting one-third of the time for sleep. (For a more extensive estimate see Table 3) Thus, even if we accept that a normal individual can recall thousands of core episodes, what happens to the rest? Are most personal events erased from memory or merely difficult to retrieve? This fundamental issue occupies a central position in the psychology and neuropsychology of memory (for a selection of treatments, see McGeoch 1932; Shiffrin and Atkinson 1969; Loftus and Loftus 1980; Capaldi and Neath 1995). Several points deserve attention in the present context.

Recognition vs. recall: As noted above, performance in recognition tests is usually superior to that in recall tests (Hollingworth 1913; Bartlett 1932; Tulving 1983; Eysenck and Keane 1990). This may be taken to imply that appropriate cues bring lost memories back to mind. Such clues may be provided by information related to focal ingredients of the experience, or by the setting, for example, context effect (Smith 1979).

Additional cues facilitate retrieval: Indeed, among the aforementioned autobiographical memory studies, the diary method, which includes multiple cues attached to the events-to-be-remembered by the tested subject, yields shallower forgetting curves (Rubin 1982; Wagenaar 1986). In her diary experiments, Linton (1978) deemed ~30% of her recorded events forgotten within 6 years. Wagenaar, on the other hand, raised doubts whether events were utterly forgotten and further investigated 10 events that initially were scored as completely forgotten and that involved some other persons (Wagenaar 1986). He interviewed these persons and reported that in all cases they were able to provide him with details that enabled him to retrieve the events from his memory. Wagenaar therefore concluded that “in light of this one cannot say that any event was completely forgotten” (1986, p. 235).

Special methods and hidden memories: It has been reported, mostly in the popular media, that special methods, such as drugs and hypnosis, may retrieve lost memories (Loftus and Loftus 1980). For example, in a survey, 96% of college students believed that hypnosis could help a person remember things that were not remembered without it (Orne et al. 1984, p. 175).

The system is inherently and extensively associative: Because nervous systems are densely interconnected networks, with elements being shared by multiple representations, one should expect percepts to leave marks on other representations (Amit 1989; Dudai 1989). The system can be depicted as a palimpsest (Amit 1989), in which the various strata of writing intermingle with each other. In this respect, experiences are never erased completely, though the characteristic structure of each individual item may be modified dramatically. Furthermore, the denser associability may facilitate retrieval.

The above arguments support the common experience that a forgotten memory is not necessarily obliterated; they also point to the cardinal role of retrieval processes in determining the limits of performance of a memory system. Indeed, some investigators argue that the critical issue in addressing the capacity of memory is not storage but rather retrieval (Tulving 1991). Unfortunately, the neurobiology of memory is still much in the dark as far as the mechanisms of retrieval are concerned.

Some caveats are, however, appropriate concerning the above conclusions.

People forget even important events: Whereas under certain special conditions, such as keeping a diary of events, retrieval is efficient (Rubin 1982; Wagenaar 1986), normally people display surprising forgetfulness even for personal events that should be ranked as important, ranging from salient changes in personal status (Jenkins et al. 1979) to dietary behavior (Smith 1991).

Confabulation has many roots: A substantial body of evidence points to the possibility that superfluous cues, explicit and implicit motivations, biased witnesses, goal-oriented interviews and interrogations, drugs, and hypnosis all may result in distorted memories and confabulations (Greenwald 1980; Wells and Loftus 1984; Bradburn et al. 1987; Schacter 1996).

Specificity vs. details: As noted above, often, recognition tests evoke a sense of familiarity but the details cannot be retrieved. It is thus possible that many percepts leave a very minimal trace, lacking in details and sufficient only to evoke a very general response (e.g., friend or foe).

It is therefore reasonable to conclude that whereas under certain conditions individuals may remember, or come to think that they remember, a substantial proportion of the events that they have experienced, in daily life many events practically sediment into oblivion. Any discussion of the capacity of memory must account for these normal limits of everyday performance.

Can We Improve it?

Given the practical limitations of our memory processes, can we improve it? The intuitive answer is yes; we have already encountered those experts

whose memory performance in their domain of expertise is larger than that of novices (Anthony 1880; Straton 1917; Chase and Simon 1973; Hunter 1978; Rubin 1995). Assuming that not all of these experts are mutations, one must conclude that training expanded their memory performance. However, this does not mean that they have increased their overall memory, as the improved performance appears to be related to data organization and strategies within only a given domain or task (Chase and Simon 1973; Hirst 1988).

Some methods were proposed for improving memory irrespective of a given expertise. These can be classified into two types: efficient training, and data organization. The latter type was illustrated above by the classical art of memory, in which organization of material by cues (*loci*) was claimed to enhance memory (Yates 1966; Carruthers 1990). The method was largely abandoned and is impractical for most material. Methods based on efficient training include spaced training, that is, training with intercalated rest intervals as opposed to massed training with no rest (Landauer and Ross 1977), and retrieval practice, that is, repeated tests with no intervening training (Payne and Wenger 1988). In the case of spaced training, a physiological rationale for its superiority over massed training has been suggested recently: Massed training interferes with the molecular cascades of consolidation in the synapses involved in representing the newly acquired information (Yin et al. 1995). Again, such methods may apply to certain types of material only, for example, factual learning. Furthermore, there is no evidence that they can result in overall enhancement of memory capacity.

The issue of memory improvement is illuminated from a different angle by neuroanatomical investigations in laboratory animals. Evidence is accumulating that within certain limits, the more the nervous system experiences the world, the higher is the density of its synapses (Bailey and Chen 1988; Weiler et al. 1995). The possibility that the capacity of memory is a plastic and adaptable variable should therefore be kept in mind. In birds, in which the volume of song subserving nuclei in brain has been reported to increase in season, the alteration in brain size has indeed been suggested (but not proven) to create space for further learning (Nottebohm 1981). In view of what has been said above about the mammalian brain, it is doubtful whether extra growth is required to expand the limits of its overall capacity. But it may entrench local dedicated circuits and, in an aging brain, may counterbalance deterioration.

Conclusions: How Much, What for, and Why

SO HOW MUCH IS THERE?

We cannot yet determine the capacity of human memory in formal terms, that is, bits, because we do not yet know how representations are encoded in the spatial and temporal patterns of neuronal activity. Furthermore, we should take into account the fact noted above that memory is composed of multiple memory systems, each subserved by particular brain systems, and that the faculties of our mind are themselves modular, each subserved by a tailored combination of memory systems (Fodor 1983; Gardner 1983). Different memory systems may use different encoding strategies, and without knowing the “machine language” used

Table 4: Pragmatic estimates of human long-term memory stores

Store	Size	Reference
Language (mother tongue)	25,000–50,000 words	Nagy and Anderson (1984)
Picture recognition	>10,000	Standing (1973)
Game patterns by a chess master	10,000–100,000	Chase and Simon (1973)
Facts by mnemonists ^a	100,000	Yates (1966)
Recall of core personal episodes	thousands	see text
Items in orally reliant expert databases in primitive societies (per database)	500–2,000	Levi-Strauss (1966); Berlin (1992)

From data above, the total number of retrievable items in human memory may be estimated to be on the order of $\beta 10^5$, with possibly $1 < \beta < 5$.
^aAnecdotal.

to encode information in each case, an “item” in each one of these systems is difficult to compare to another.

Nonetheless, we should note with some interest that current formal estimates of maximal information in our brain converge on $\alpha 10^{15}$ – $\alpha 10^{17}$ bits (Table 3). And from the pragmatic stand of ecological memory, one may also propose a combined, very rough estimate of the size of our memory. If we combine the words in our language, the pictures we are familiar with, the facts of our profession, and the core episodes of our life, while being aware that an item in one store is not equivalent to another, and that we are using a phenomenological, folk-psychology language, we reach an estimate of $\beta 10^5$ retrievable memories ($1 < \beta < 5$; Table 4). Of these, only a small fraction, probably a few percent, are personal, autobiographical memories. The contribution of habits, conditioned responses, and modified reflexes is not assessed here. Still, based on the theoretical, physiological, and psychological evidence and considerations brought above, and in spite of our aforementioned ignorance of brain codes, it is tempting to suggest that the overall estimated value is far below the theoretical limits of the brain as an information processing system.

HOW SHALL WE PROCEED
TO FIND MORE ABOUT IT?

The enigmatic nature of human long-term memory capacity is bound to moderate as our understanding of brain function expands. As in many other fields of science, riddles will be unraveled even as a fringe benefit of projects that do not specifically aim at solving the problem in the first place. Most items on a potential “to do” list might therefore prove superfluous. And yet some issues deserve special attention:

THE CHOICE OF EXPERIMENTAL
SYSTEMS

Although the question in mind is the capacity of human memory, it is worth turning attention to experimental systems in other vertebrates, which potentially permit analysis of memory capacity at different levels, integrating cellular electrophysiology, neuroanatomy, behavior, and modeling. A possible choice is spatial learning subserved by

	place cells and other components of the hippocampal formation in rodents (McNaughton et al. 1996).
RATIO OF INFLUX TO PERCEPTION TO STORAGE	Novel methods of cellular electrophysiology and modeling (for review, see Koch 1997), combined with experimental systems such as minimally cued spatial learning in rodents, may be used to cast light on the relationship between incidental influx of sensory information into the brain, the use of this information in generating a percept, and the amount of information required to store the essential features of that percept.
THE NEUROBIOLOGY OF RETRIEVAL	To a large extent, this is a terra incognita of current research on memory. Whereas modest insight is emerging into mechanisms of acquisition and consolidation at the cellular, circuit, and system levels, our knowledge on the mechanisms of retrieval lags behind, with the exception of data originating from brain imaging studies (e.g., Fink et al. 1996). Research on retrieval is instrumental in determining the long-term fate of items committed to memory.
INFANT MEMORY	Infancy is a period in which the capacity of selected memory systems is expected to be taxed heavily. Neuropsychological research on infant memory may provide insight into the kinetics and capacity of such systems [e.g., language (Saffran et al. 1996)].
THE SIZE OF EXPERT DATABASES	This approach to the capacity of everyday memory seems not to be sufficiently exploited. Relevant information may be gained from cognitive anthropology (D'Andrade 1995), as well as from investigation of the performance in professions that place special demands on memory in modern society, for example, psychotherapists. The same holds for exceptional phenotypes (Winner 1996).
HOW MUCH DO WE ACTUALLY NEED?	This question cannot be addressed in a unitary manner. Each memory system poses its own demands. Human societies can do with a much more limited linguistic repertoire than the tens of thousands of words mastered by a college graduate; in many societies a few hundred are enough. Most individuals do not need to recognize thousands of faces; in small societies a handful might suffice. And there are few professions that require the size of expert memory that Chess masters acquire while developing their skill. It seems that the capacity of all these faculties is not only much larger than the minimum needed for survival but also more than the size needed for normal usage. Our memory systems are clearly endowed with sufficient plasticity to accommodate to the changing needs and advantages of skills exercised in different eras of our cultural evolution. Socrates tells us that when the Egyptian God Theuth came to King Thamus to praise the newly invented art of writing, claiming that it would make the people of Egypt wiser and improve their memories, Thamus responded: "O man full of arts, to one it is given to create the things of art, and to another to judge what measure of harm and of profit they have for those that shall employ them. . . If men learn this, it will implant forgetfulness in their souls; they will cease to exercise memory because they rely on that which is written" (<i>Phaedrus</i> 274-275). Nowadays the fear is that computer power will make memory obsolete. But cultural evolution shows again and again that whereas some skills are

no more demanded others become taxed heavily. The unexploited capacity of our memory systems provides the potential.

Another issue is what is memory for? In the case of language, visual perception, or professional skills, the answer to this query is rather straightforward and the degree of accuracy required is a function of the task involved. Inaccuracy in language may create ambiguities that culminate in social friction, gross mistakes in visual recognition may disastrously confuse friend with foe, and mistakes in reproducing skills may become very costly. But should we expect a vast and faithful pool of autobiographical memories? As *Homo sapiens* with a reasonable degree of self-awareness, we assign great importance to the number and precision of our personal reminiscences and assume that something is faulty in our brain if plethoras of personal episodes are not retrieved with ease and accuracy. Is it not possible that we misconstrue the phylogenetic drive? It might be that autobiographical memory was intended primarily to serve as a vehicle for unitary personal meaning and grounding the self as an individual of a social species, for which only a few episodes are sufficient, rather than for accurate recollection (Conway 1996).

COGNITIVE CONSTRAINTS AND USEFULNESS

Ample observations combine to suggest that our mind selects and prunes the information it perceives, and combines it with internally generated representations to form its world views. Thus, only a fraction of the information that goes into short-term memory makes it into long-term stores (Squire 1987; Dudai 1989). Consolidation, the stabilization of the newly acquired internal representation and of processes that ensure its retrieval from long-term stores, is progressive and rather slow and fragile, requiring hours and days in synapses and up to months and years in brains (Dudai 1996). In declarative memory, it may involve a shift over time from hippocampally dependent to neocortical, hippocampally independent circuits (Squire and Alvarez 1995). The time-dependent maturation and the existence of complementary learning systems were suggested to permit selection, extraction of structure and categorization, and hence a more coherent, effective, and parsimonious mental construct of the world (McClelland et al. 1995).

Indeed, individuals and societies are naturally inclined to categorize the world (Harnad 1987, Berlin 1992), and our brain is capable of categorizing some stimuli even without declarative awareness (Squire and Knowlton 1995). Actually, brains of much simpler organisms are capable of categorizing (Walker 1983)—even insects seem to be able to do that (Giurfa et al. 1996). Categorization is therefore a faculty of brains that emerged at least once early in evolution. It carries several potential advantages: (1) It ensures generalization of response to types rather than tokens, which is critical to survival; (2) it may support economy in storing information; and (3) it may permit fast reaction by facilitating retrieval out of a large body of off-line information. It is likely that the relative weight of these advantages has changed in phylogeny. Small and primitive brains benefit more from 1 and 2 above. In the human brain, fast retrieval from large memory stores is likely to have endowed the species with an even greater phylogenetic edge.

A major component in our reaction to the world is subserved by working memory. This faculty must be able to retrieve, process, and make decisions on the basis of multiple inputs in a very short time (time scale of tens or hundreds of milliseconds). The ability of working memory to

deal with multiple items and to make binary discriminations simultaneously is therefore expected to be rather limited, which it is (Miller 1956; Wallace 1961). It is therefore possible that the useful size of our long-term memory stores and their organization is affected by the limited capacity of attention and working memory. Stores that cannot be sorted quickly on the basis of a small number of binary decisions may not be very useful. This might be the reason for the universal limit on the size of orally reliant expert databases in primitive societies and for the universally preserved small number of categories in these systems. This might also be a factor that contributes to the number of readily retrievable memory in other domains, for example, autobiographical reminiscences.

Our brain thus maintains a balance between details, required for accuracy, and categorization, required for meaning and prompt reaction. S., Luria's mnemonist, illustrates what happens when the balance is disrupted: He remembered every detail forever, but could not think and understand properly, concentrate, abstract, and draw conclusions (Luria 1968). The practical capacity of our memory reflects this tension between seeing the trees and seeing the forest. In nature, memory is selected for optimal, rather than bigger, size. The appropriate question is therefore not how big our memory is, but how big each human memory system should be to remain useful in performing its phylogenetically molded task.

Acknowledgments

I thank Daniel Amit, Tamar Flash, Rafi Malach, Mortimer Mishkin, Larry Squire, Misha Tsodyks, and Endel Tulving for helpful comments on drafts of this manuscript. The support of the Gorodetsky Center for Brain Research is gratefully acknowledged.

References

- Abbott, L.F., E.T. Rolls, and M.J. Tovee. 1996. Representational capacity of face coding in monkeys. *Cereb. Cortex* **6**: 498–505.
- Abeles, M. 1991. *Corticonics. Neural circuits of the cerebral cortex*. Cambridge University Press, Cambridge, UK.
- Amit, D.J. 1989. *Modeling brain function*. The world of attractor model networks. Cambridge University Press, Cambridge, UK.
- Amit, D.J., N. Brunel, and M.V. Tsodyks. 1994. Correlations of cortical Hebbian representations: Theory versus experiment. *J. Neurosci.* **14**: 6435–6445.
- Anthony, E. 1880. A feat of memory. *Nature* **21**: 562.
- Bahrack, H.P., P.O. Bahrack, and R.P. Wittlinger. 1975. Fifty years of memory for names and faces: a cross-sectional approach. *J. Exp. Psychol.* **104**: 54–75.
- Bailey, C.H. and M.C. Chen. 1988. Long-term memory in *Aplysia* modulates the total number of varicosities of single identified sensory neurons. *Proc. Natl. Acad. Sci.* **85**: 2373–2377.
- Bartlett, F.C. 1932. *Remembering*. Cambridge University Press, Cambridge, U.K.
- Berlin, B. 1992. *Ethnobiological classification*. Princeton University Press, Princeton, NJ.
- Berlin, B., D.E. Breedlove, and P.H. Raven. 1973. General principles of classification and nomenclature in folk biology. *Am. Anthropol.* **75**: 214–242.

- Bialek, W., F. Rieke, R.R. de Ruyter van Steveninck, and D. Warland. 1991. Reading a neural code. *Science* **252**: 1854–1857.
- Bradburn, N.M., L.J. Rips, and S.K. Shevell. 1987. Answering autobiographical questions: The impact of memory and inference on surveys. *Science* **236**: 157–161.
- Braitenberg, V. and A. Schuz. 1991. *Anatomy of the cortex. Statistics and geometry*. Springer-Verlag, Berlin/Heidelberg, Germany.
- Brewer, W.F. 1986. What is autobiographical memory? In *Autobiographical memory* (ed. D.C. Rubin), pp. 25–49. Cambridge University Press, Cambridge, UK.
- Brown, C.H. 1985. Mode of subsistence and folk biological taxonomy. *Curr. Anthropol.* **26**: 43–64.
- Brown, E. and K. Deffenbacher. 1995. Forgotten mnemonists. *J. Hist. Behav. Sci.* **11**: 342–349.
- Brown, N.R., S.K. Shevell, and L.J. Ripa. 1986. Public memories and their personal context. In *Autobiographical memory* (ed. D.C. Rubin), pp. 137–158. Cambridge University Press, Cambridge, UK.
- Burnham, W.H. 1889. Memory, historically and experimentally considered. *Am. J. Psychol.* **2**: 39–90.
- Capaldi, E.J. and Neath, I. 1995. Remembering and forgetting as context discrimination. *Learn. & Mem.* **2**: 107–132.
- Carew, T.J. 1996. Molecular enhancement of memory formation. *Neuron* **16**: 5–8.
- Carruthers, M. 1990. *The book of memory. A study of memory in medieval culture*. Cambridge University Press, Cambridge, UK.
- Chase, W.G. and H.A. Simon. 1973. The mind's eye in chess. In *Visual information processing* (ed. W.G. Chase), pp. 215–281. Academic Press, New York, NY.
- Christianson, S.-A. 1992. Emotional stress and eyewitness memory: A critical review. *Psychol. Bull.* **112**: 284–309.
- Conway, M.A. 1996. Shifting sands. *Nature* **380**: 214.
- Crovitz, H.F. 1971. The capacity of memory loci in artificial memory. *Psychon. Sci.* **24**: 187–188.
- Crovitz, H.F. and M.T. Harvey. 1979. Early childhood amnesia: A quantitative study with implications for the study of retrograde amnesia after brain injury. *Cortex* **15**: 331–335.
- Crovitz, H.F. and H. Schiffman. 1974. Frequency of episodic memories as a function of their age. *Bull. Psychon. Soc.* **4**: 517–518.
- Crovitz, H.F., H. Schiffman, and A. Apter. 1991. Galton's number. *Bull. Psychon. Soc.* **29**: 331–332.
- D'Andrade, R. 1995. *The development of cognitive anthropology*. Cambridge University Press, Cambridge, UK.
- Dudai, Y. 1989. *The Neurobiology of memory. Concepts, findings, trends*. Oxford University Press, Oxford, UK.
- . 1996. Consolidation: Fragility on the road to the engram. *Neuron* **17**: 367–370.
- Ebbinghaus, H. 1885. Ueber das Gedächtnis. Translated into English as "Memory, a contribution to experimental psychology" 1913. Republished 1964, Dover, New York, NY.

- Eysenck, M.W. and M.T. Keane. 1990. *Cognitive psychology. A student's handbook*. Lawrence Erlbaum Associates, Hove, UK.
- Fink, G.R., H.J. Markowitsch, M. Reinkemeier, T. Bruckbauer, J. Kessler, and W.D. Heiss. 1996. Cerebral representation of one's own past: Neural networks involved in autobiographical memory. *J. Neurosci.* **16**: 4275–4282.
- Fodor, J.A. 1983. *The modularity of mind*. MIT Press, Cambridge, MA.
- Frake, C.O. 1961. The diagnosis of disease among the Subanun of Mindanao. *Am. Anthropol.* **63**: 113–132.
- Galton, F. 1879. Psychometric experiments. *Brain* **2**: 149–162.
- . 1907. *Inquiries into human faculty and its development*. J.M. Dent & Sons, London, UK.
- Gardner, E. 1987. Maximum storage capacity in neural networks. *Europhys. Lett.* **4**: 481–485.
- Gardner, H. 1983. *Frames of mind: The theory of multiple intelligences*. Basic Books, New York, NY.
- Gawne, T.J. and B.J. Richmond. 1993. How independent are the messages carried by adjacent inferior temporal cortical neurons? *J. Neurosci.* **13**: 2758–2771.
- Giurfa, M., B. Eichmann, and R. Menzel. 1996. Symmetry perception in an insect. *Nature* **328**: 458–461.
- Gochin, P.M., M. Colombo, G.A. Dorfman, G.L. Gerstein, and C.G. Gross. 1994. Neural ensemble coding in inferior temporal cortex. *J. Neurophysiol.* **71**: 2325–2337.
- Greenwald, A.G. 1980. The totalitarian ego. Fabrication and revision of personal history. *Am. Psychol.* **35**: 603–618.
- Haist, F., A.P. Shimamura, and L.R. Squire. 1992. On the relationship between recall and recognition memory. *J. Exp. Psychol. LMC* **18**: 691–702.
- Harnad, S. ed. 1987. *Categorical perception. The groundwork of cognition*. Cambridge University Press, Cambridge, UK.
- Hick, W.E. 1952. On the rate of gain of information. *Q. J. Exp. Psychol.* **4**: 11–26.
- Hirst, W. 1988. Improving memory. In *Memory improvement* (ed. J. Herrmann, H. Weingartner, A. Searlman and C. McEvoy), pp. 219–244. Springer-Verlag, New York, NY.
- Hollingworth, H.L. 1913. Characteristic differences between recall and recognition. *Am. J. Psychol.* **24**: 532–544.
- Hopfield, J.J. 1982. Neural networks and physical systems with emergent collective computational abilities. *Proc. Natl. Acad. Sci.* **79**: 2554–2558.
- . 1995. Pattern recognition computation using action potential timing for stimulus representation. *Nature* **376**: 33–36.
- Hunter, I.M.L. 1978. The role of memory in expert mental calculations. In *Practical aspects of memory* (ed. M.M. Gruneberg, P.E. Morris and R.N. Sykes), pp. 339–345. Academic Press, Orlando, FL.
- Jenkins, C.D., M.W. Hurst, and R.M. Rose. 1979. Life changes. Do people really remember? *Arch. Gen. Psychiatry* **36**: 379–384.
- Kenny, A. 1993. *Aquinas on mind*. Routledge, London, UK.

- Koch, C. 1997. Computation and the single neuron. *Nature* **385**: 207–210.
- Konig, P., A.K. Engel, and W. Singer. 1996. Integrator or coincidence detector? The role of the cortical neuron revisited. *Trends Neurosci.* **19**: 130–137.
- Landauer, T.K. 1986. How much do people remember? Some estimates of the quantity of learned information in long-term memory. *Cognit. Sci.* **10**: 477–493.
- Landauer, T.K. and B.H. Ross. 1977. Can simple instructions to use spaced practice improve ability to remember a fact?: An experimental test using telephone numbers. *Bull. Psychon. Soc.* **10**: 215–218.
- Levi-Strauss, C. 1966. *The savage mind*. Weidenfeld and Nicolson, London, UK.
- Linton, M. 1978. Real world memory after six years: An in vivo study of very long term memory. In *Practical aspects of memory* (ed. M.M. Gruneberg, P.E. Morris and R.N. Sykes), pp. 69–76. Academic Press, Orlando, FL.
- Little, W.A. and G.L. Shaw. 1978. Analytic study of the memory storage capacity of a neural network. *Math. Biosci.* **39**: 281–290.
- Loftus, E.F. and G.R. Loftus. 1980. On the permanence of stored information in the human brain. *Am. Psychol.* **35**: 409–420.
- Luria, A.R. 1968. *The mind of a mnemonist*. J. Cape, London, UK.
- Mahoney, E.P. 1982. Sense, intellect and imagination in Albert, Thomas, and Siger. In *The Cambridge history of later medieval philosophy* (ed. N. Kretzmann, A. Kenny, J. Pinborg and E. Stump), pp. 602–622. Cambridge University Press, Cambridge, UK.
- McClelland, J.L., B.L. McNaughton, and R.C. O'Reilly. 1995. Why there are complimentary learning systems in the hippocampus and neocortex: Insights from the successes and failures of connectionist models of learning and memory. *Psychol. Rev.* **102**: 419–457.
- McGeoch, J.A. 1932. Forgetting and the law of disuse. *Psychol. Rev.* **39**: 352–370.
- McNaughton, B.L., C.A. Barnes, J.L. Gerrard, K. Gothard, M.W. Jung, J.J. Knierim, H. Kudromoti, Y. Qin, W.E. Skaggs, M. Suster, and K.L. Weaver. 1996. Deciphering the hippocampal polyglot: The hippocampus as a path integration system. *J. Exp. Biol.* **199**: 173–185.
- Miller, G.A. 1956. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychol. Rev.* **63**: 81–97.
- Mishkin, M. and T. Appenzeller. 1987. The anatomy of memory. *Sci. Amer.* **256**: 62–71.
- Moravec, H. 1988. *Mind children. The future of robot and human intelligence*. Harvard University Press, Cambridge, MA.
- Nagy, W.E. and R.C. Anderson. 1984. How many words are there in printed school English? *Read. Res. Q.* **19**: 304–330.
- Nickerson, R.S. 1965. Short-term memory for complex meaningful visual configurations: A demonstration of capacity. *Canad. J. Psychol.* **19**: 155–160.
- Nottebohm, F. 1981. A brain for all seasons: Cyclical anatomical changes in song control nuclei in the canary brain. *Science* **214**: 1368–1370.
- Orne, M.T., D.A. Soskis, D.F. Dinges, and E.C. Orne. 1984. Hypnotically induced testimony. In *Eyewitness testimony* (ed. G.L. Wells and E.F. Loftus), pp. 171–213. Cambridge University Press, New York, NY.

- Palm, G. 1982. *Neuronal assemblies. An alternative approach to artificial intelligence*. Springer-Verlag, Berlin, Germany.
- Payne, D.G. and M.J. Wenger. 1988. Improving memory through practice. In *Memory improvement* (ed. D.J. Herrmann, H. Weingartner, A. Searlman, and C. McEvoy), pp. 187–209. Springer-Verlag, New York, NY.
- Pinker, S. 1995. *The language instinct*. Harper, New York, NY.
- Plato. *The collected dialogues* (ed. E. Hamilton and H. Cairns). 1961. Princeton University Press, Princeton, NJ.
- Rubin, D.C. 1982. On the retention function for autobiographical memory. *J. Verb. Learn. Verb. Behav.* **21**: 21–38.
- , ed. 1986. *Autobiographical memory*. Cambridge University Press, Cambridge, UK.
- . 1995. *Memory in oral traditions*. Oxford University Press, New York, NY.
- Rubin, D.C., S.E. Wetzler, and R.D. Nebes. 1986. Autobiographical memory across the lifespan. In *Autobiographical memory* (ed. D.C. Rubin), pp. 202–221. Cambridge University Press, Cambridge, UK.
- Saffran, J.R., R.N. Aslin, and E.L. Newport. 1996. Statistical learning by 8-month-old infants. *Science* **274**: 1926–1928.
- Sakai, K. and Y. Miyashita. 1991. Neural organization for the long term memory of paired associates. *Nature* **354**: 152–155.
- Schacter, D.L. ed. 1996. *Memory distortion: How minds, brains and societies reconstruct the past*. Harvard University Press, Cambridge, MA.
- Seashore, R.H. and L.D. Eckerson. 1940. The measurement of individual differences in general English vocabularies. *J. Educ. Psychol.* **31**: 14–38.
- Shadlen, M.N. and W.T. Newsome. 1994. Noise, neural codes and cortical organization. *Curr. Opin. Neurobiol.* **4**: 569–579.
- Shepard, R.N. 1967. Recognition memory for words, sentences, and pictures. *J. Verb. Learn. Verb. Behav.* **6**: 156–163.
- Shiffrin, R.M. and R.C. Atkinson. 1969. Storage and retrieval processes in long-term memory. *Psychol. Rev.* **76**: 179–193.
- Smith, A.F. 1991. Cognitive processes in long-term dietary recall. Vital and health statistics, Ser. 6, no. 4, Cognition and Survey Measurement. U.S. Department of Health and Human Services, publication no. (PHS) 92-1079, National Center for Health Services, Hyattsville, MD.
- Smith, S.M. 1979. Remembering in and out of context. *J. Exp. Psychol. Hum. Learn. Mem.* **5**: 460–471.
- Softky, W.R. 1995. Simple codes versus efficient codes. *Curr. Opin. Neurobiol.* **5**: 239–247.
- Squire, L.R. 1987. *Memory and brain*. Oxford University Press, New York, NY.
- Squire, L.R. and P. Alvarez. 1995. Retrograde amnesia and memory consolidation: A neurobiological perspective. *Curr. Opin. Neurobiol.* **5**: 169–177.
- Squire, L.R. and B.J. Knowlton. 1994. Memory, hippocampus and brain systems. In *The cognitive neurosciences* (ed. M. Gazzaniga), pp. 825–837. MIT Press, Cambridge, MA.
- . 1995. Learning about categories in the absence of memory. *Proc. Natl. Acad. Sci.* **92**: 12470–12474.
- Squire, L.R. and P.C. Slater. 1975. Forgetting in very long-term memory as assessed by an improved questionnaire technique. *J. Exp. Psychol. Hum. Learn. Mem.* **104**: 50–54.

- St. Augustine. 400. *The confessions*. 1969. Image, Doubleday, New York, NY.
- Standing, L. 1973. Learning 10,000 pictures. *Q. J. Exp. Psychol.* **25**: 207–222.
- Stratton, G.M. 1917. The mnemonic feat of the “Shass Pollak”. *Psychol. Rev.* **24**: 244–247.
- Tanaka, K. 1993. Neuronal mechanisms of object recognition. *Science* **262**: 685–688.
- Tetens, J.N. 1777. *Philosophische Versuche über die Menschliche Natur and ihre Entwicklung*. Weidmanns Erben und Reich, Leipzig (translated and cited in Loftus and Loftus 1980).
- Thorpe, S., D. Fize, and C. Marlot. 1996. Speed of processing in the human visual system. *Nature* **381**: 520–522.
- Tsodyks, M.V. and H. Markram. 1997. The neural code between neocortical pyramidal neurons depends on neurotransmitter release probability. *Proc. Natl. Acad. Sci.* **94**: 719–723.
- Treves, A. and E.T. Rolls. 1991. What determines the capacity of autoassociative memories in the brain? *Network* **2**: 371–397.
- . 1994. Computational analysis of the role of the hippocampus in memory. *Hippocampus* **4**: 374–391.
- Tulving, E. 1983. *Elements of episodic memory*. Oxford University Press, Oxford, UK.
- . 1991. (Interview with). *J. Cognitive Neurosci.* **3**: 89–94.
- von Neuman, J. 1958. *The computer and the brain*. Yale University Press, New Haven, CT.
- Wagenaar, W.A. 1986. My memory: A study of autobiographical memory over six years. *Cognit. Psychol.* **18**: 225–252.
- Walker, S. 1983. *Animal thought*. Routledge and Kegan Paul, London, UK.
- Wallace, A.F.C. 1961. On being just complicated enough. *Proc. Natl. Acad. Sci.* **47**: 458–461.
- Wang, G., K. Tanaka, and M. Tanifuji. 1996. Optical imaging of functional organization in the monkey inferotemporal cortex. *Science* **272**: 1665–1668.
- Warrington, E.K. and M. Milner. 1970. A questionnaire technique for investigating very long term memory. *Q. J. Exp. Psychol.* **22**: 508–512.
- Weiler, I.J., N. Hawrylak, and W.T. Greenough. 1995. Morphogenesis in memory formation: synaptic and cellular mechanisms. *Behav. Brain Res.* **66**: 1–6.
- Wells, G.L. and E.F. Loftus. eds.. 1984. *Eyewitness testimony*. Cambridge University Press, New York, NY.
- White, R.T. 1982. Memory for personal events. *Hum. Learn.* **1**: 171–183.
- Wickelgren, W.A. 1974. Single-trace fragility theory of memory dynamics. *Mem. Cogn.* **2**: 775–780.
- Winner, E. 1996. *Gifted children. Myths and realities*. Basic Books, New York, NY.
- Woolf, T.B., G.M. Shepherd, and C.A. Greer. 1991. Local information processing in dendritic trees: Subsets of spines in granule cells of the mammalian olfactory bulb. *J. Neurosci.* **11**: 1837–1854.
- Yates, F.A. 1966. *The art of memory*. ARK Books, London, UK.
- Yin, J.C.P., Del Vecchio, H. Zhou, and T. Tully. 1995. CREB as a memory modulator: Induced expression of a dCREB2 activator isoform enhances long-term memory in *Drosophila*. *Cell* **81**: 107–115.
- Zohary, E., M.N. Shadlen, and W.T. Newsome. 1994. Correlated neuronal discharge rate and its implications for psychophysical performance. *Nature* **370**: 140–143.

How big is human memory, or on being just useful enough.

Y Dudai

Learn. Mem. 1997, **3**:

Access the most recent version at doi:[10.1101/lm.3.5.341](https://doi.org/10.1101/lm.3.5.341)

References

This article cites 78 articles, 17 of which can be accessed free at:
<http://learnmem.cshlp.org/content/3/5/341.full.html#ref-list-1>

License

Email Alerting Service

Receive free email alerts when new articles cite this article - sign up in the box at the top right corner of the article or [click here](#).