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THEORETICAL NOTE

George Miller's Magical Number of Immediate Memory in Retrospect: Observations on the Faltering Progression of Science

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Miller's (1956) article about storage capacity limits, "The Magical Number Seven Plus or Minus Two . . .," is one of the best-known articles in psychology. Though influential in several ways, for about 40 years it was oddly followed by rather little research on the numerical limit of capacity in working memory, or on the relation between 3 potentially related phenomena that Miller described. Given that the article was written in a humorous tone and was framed around a tongue-in-cheek premise (persecution by an integer), I argue that it may have inadvertently stymied progress on these topics as researchers attempted to avoid ridicule. This commentary relates some correspondence with Miller on his article and concludes with a call to avoid self-censorship of our less conventional ideas.

Keywords: immediate memory, short-term memory, absolute judgment, scientific practices, scientific methodology

How did it come about that a widely cited work on a subject of fundamental and obvious interest could halt some areas of research rather than inspire them? I would argue that the famous article of George Miller (1956) on "the magical number seven plus or minus two" did just that. It was followed by a 40-year hiatus of work on the topic of item capacity limits in working memory. It seems a paradox for such a widely cited and esteemed source to inspire little closely related follow-up work for such a long period. I will explore the situation, partly based on published sources and partly based on my own e-mail communications in 2000 with Miller, who died in 2012 (Association for Psychological Science, 2012; Pinker, 2013; Vitello, 2012).

One of the key concepts in the field of cognitive science is that of *working memory,* often called *short-term memory* (STM) or *immediate memory*, terms that all refer to the temporarily heightened availability of information about a small number of recent events and thoughts. The terms have somewhat different connotations and detailed meanings, but these are inconsistent among investigators and unimportant for the present purposes. Google Scholar lists over 2.5 million entries for these three phrases. The concept of immediate memory was made popular by George A. Miller's (1956) article on capacity limits in information processing, suggesting that it is limited to about seven units. It is one of the best-known works in the cognitive and psychological sciences, with about 20,000 scientific citations as of this writing. Its wider popular appeal is illustrated in a Google search for the key phrase from the article's title, the *magical number seven* (or 7), which yielded about 873,000 results. Yet, for over 40 years, there was very little follow-up research on the specific processing limitations mentioned in the article. During most of that time, emphasis of the field shifted away from the item limits that Miller discussed, toward limits in the persistence or decay of items across time, and toward interference between items based on their similarity, rather than on capacity limits (following the seminal lead of Baddeley & Hitch, 1974). The investigation of item limits finally picked up again with a surge of research on visual working memory item limits after groundwork by Luck and Vogel (1997) and renewed interest based on a reappraisal of the limits in various domains (Baddeley, 2000, 2001; Cowan, 1999, 2001). Currently, research on item limits is thriving (e.g., see Cowan, Rouder, Blume, & Saults, 2012; Ma, Husain, & Bays, 2014).

During the 40-year hiatus there were, to be sure, important works that made use of an item limit in working memory in order to model the human information processing system at large (e.g., Atkinson & Shiffrin, 1968; Broadbent, 1958). Most often, though, the authors fit or explained their data by assuming a somewhat smaller capacity limit of closer to four items (for a review see Cowan, 2001). Yet, no one denies that adult humans typically can repeat, without error, lists of up to about seven items, such as random words or digits. Given such discrepancies, it has often been suggested that items capacity limits are highly task-specific or "just depend" on the circumstances.

Why did the field settle for such a vague pronouncement for so long rather than investigating the discrepancies directly? The hiatus in research on this topic may stem largely from the manner in which Miller (1956) wrote his famous article. To explain this, I will review the article briefly and then will describe his autobio-

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graphical remarks about how it was written, finally extracting some lessons from these remarks for the pursuit of science.

Description of Miller (1956)

In the 1956 article, Miller said he was persecuted by an integer: 7. He reviewed his own work along with other work in the current literature, discussing three kinds of tasks in which human abilities are shown to be limited to about seven things. (a) In absolute judgment (or absolute identification) tasks, individuals experience one stimulus at a time and must indicate the category to which the stimulus belongs. Examples of simple stimuli include tones of different frequencies (perceived as different pitches) and lines of different lengths. The response to each stimulus is to be made in terms of arbitrary category labels provided by the experimenter (e.g., 1–10) that the participant has learned in a training phase. The basic finding is that participants can effectively use only about five to nine different categories, that is, seven plus or minus two as in the article's title. The limit was thought to be expressed in binary choices or bits, in line with thinking of the day in which the conception of human processing was influenced by the blossoming field of computers (e.g., Newell & Simon, 1956). (b) A second type of task with a limit, the one remembered best by the public, was for memory span, the maximal length of a random word list that could be recalled with the items in order. Again, the answer was that roughly seven items could be recalled in normal adults, give or take a few. Here, however, it was clear that the result could not be expressed in binary choices. People can remember lists of about seven digits, letters, or words even though the response choices include 10 digits, 26 letters in English, and many thousands of words. Miller offered the concept of a *chunk* or unit of information that is coherent to the participant, suggesting that the limit of memory was about seven familiar chunks. For example, the letter string *FBICIAUSA* can be remembered without much difficulty if it is parsed into 3 chunks, each of which is an acronym representing an American agency if you know it: FBI, CIA, and USA. This idea about chunks, rather than the limit to about seven items, may be the most important specific contribution of the article. (c) In the third type of task, which is known as subitizing, it was suggested that people can quickly assess, without counting, the number of simple objects in a collection of up to about seven, but no more (e.g., a very early study in which a handful of beans was dropped in a heap onto a table to be estimated: Jevons, 1871). Miller concluded his grand review with a question as to why these limits are similar, and with the answer that the similarity is probably coincidental.

Autobiographical Account of Miller (1956)

The retrospective account offered by Miller (1989) indicates that the 1956 article was based on a public address that he had to be cajoled into giving to the Eastern Psychological Association. He did not think that his two lines of research, on absolute judgments and memory span, provided the basis for a coherent hour-long address, and initially declined the invitation. Following the organizer's persistence, he accepted the invitation when he realized that he could knit his findings into a story about their commonality: the number of bits of capacity in absolute judgment amounted to about seven categories, similar to the number of chunks making up the limit in memory span. To make the story even better, he threw in the newly awakening subitizing literature. When writing in 1989, Miller was unsure why the 1956 paper was so popular, compared to other work he had done.

When my follow-up, 2001 article on item capacity limits (Cowan, 2001) was accepted for publication, the editor, Stevan Harnad, invited Miller to write a preamble to the article, but Miller, having focused on other topics after 1956, felt unwilling (and unqualified) to make a published statement. He did, however, offer some striking observations in e-mails. On 10 January, 2000 he wrote:

> Nice to hear from you and to learn that 7 is still of interest. As you know, I have not been working on STM problems or absolute judgment for many years. I have only occasionally commented on it when someone who apparently hadn't read it overgeneralized the conclusions—I had an interesting interaction with the billboard industry during the Ladybird Johnson era, which made me revisit the topic briefly . . . More recently, Steve Malinowsky put it up on his web site and I had an excuse to read it once again. I had rather dismissed the paper, assuming that its notoriety was attributable to the amusing idea of putting a confidence interval around a magical number. But on rereading I decided that, even after all these years, it was a good piece of work. I think there is some art in it, as well as ideas.

To my further surprise and delight, after reading my in-press target article, Miller (on 11 January, 2000) magnanimously indicated that he liked it and, further, was not surprised by the discrepancy between my finding and his own in 1956. He said:

> I have now had a chance to read your BBS article. I think it is great! There were some ideas I thought you might have missed, but you didn't. A good job . . . Herb Simon used to say "George had the right idea, but the wrong number." I think Herb favored 3. I never argue with Herb Simon. I was aware, even in 1954 when I was writing my invited address, that the running memory span was only about 4, and my introspections convinced me that the 7 that was standard on the intelligence tests at that time must have been a hooking together of a rehearsed initial segment with a final segment from what Nancy Waugh used to call the "echo box." But I was stuck with 7 because of the absolute judgment results (the first half of the article that people forget).

Miller went on to explain about his autobiographical chapter (Miller, 1989), and with great humor indicated that "that is how I came to own the number 7." Continuing, he explained his perspective on the field after 1956:

> Since 1956, of course, my attention has wandered off in many other directions. As I recall it now, my interest was in the use of chunking to surmount the limits of STM, but everyone else wanted to fight about the size of the limit, or whether there was any limit at all—questions of little interest to me. I was happy to let Alan Baddeley claim the stage . . . Now I am delighted that you have slogged through the accumulated "literature" and produced a thoughtful, well-organized interpretation. I have nothing more to add to what you have said so well. Congratulations . . .

The field thus gravitated toward time limits and away from item (or chunk) limits for many years after Miller (1956). To lend further perspective to how the field changed throughout the years following Miller's article, it is interesting to examine the changing views of Herb Simon, the 1978 winner of the Nobel Prize in

economics whom Miller mentioned in his correspondence to me. Simon (1974) was one of very few early articles illustrating the limit in working memory to just several chunks regardless of their size. Simon later served as one of about eight peer reviewers of my article (Cowan, 2001) when it was first evaluated, and signed his review. Now, publication in *Behavioral and Brain Sciences* requires that the thesis be controversial enough to serve as a good basis for many following commentaries and my work met that criterion, I believe, because the reviewers radically differed. Whereas several reviewers thought that my conclusion was not newsworthy because it was already known, several others, including Simon, thought that I was wrong and that there was no clearly identifiable item limit. I was surprised that Simon seemed to be departing from the view in his 1974 article that favored fixed limits. I now wonder whether Simon might have lost enthusiasm for that view in part because his and Miller's early work was met by such a dearth of follow-up studies on capacity limits.

Why Was Miller (1956) Revered and Passed Over at the Same Time?

I have touched on at least three possible reasons why Miller's famous article did not engender a groundswell of research into item capacity limits that one might expect in the immediately following years. (a) For one thing, the limit seemed to depend on circumstances or task demands in ways that were not understood. Therefore, it was not clear that there was any fixed limit to be examined. (b) Also, the more important contribution of Miller (1956) was probably his observation that measurement of information in bits so popular in the engineering world could not explain human (as opposed to computer) working memory limits. Instead, what mattered for humans was the number of coherent, meaningful units in mind, or what has become known as chunks. This observation was clear and practically self-evident, with few researchers disputing it, so the case seemed settled. (c) Last, Miller juxtaposed descriptions of several very different item-related limits. He began with the tongue-in-cheek complaint that he was being persecuted by an integer and concluded with the coy statement that he suspected the similarity between the phenomena he discussed to be no more than "a pernicious, Pythagorean coincidence." Scientists shy away from topics that could make them the butt of a joke (e.g., cold fusion), so research on possible real commonalities between the phenomena was thereby discouraged, inadvertently I would assume.

The Case for Returning to Research on the Topics of Miller (1956)

Each of the reasons why not much research was done on the specific topics Miller described leads me to a response about how vital that endeavor actually is.

(a) First is the notion that item capacity limits just depend on circumstances. I have tried to establish that meaningful sets of boundary conditions can in fact be found (Cowan, 2001). Consider that telephone numbers around the world typically contain six to 10 digits, but consider also that the numbers are divided into groups of two to four digits. When attention must be focused on an ensemble of items all at once, the limit seems severe, in the range of about three for adults. The field now argues about whether the capacity limit is a matter of there being a fixed number of items in working memory or, instead, whether the capacity limit resembles a fluid resource that can be spread thinly over all stimulus items, sometimes too thinly to contribute to the necessary response for all items (Ma et al., 2014). Now, at least, the issue is finally seen as an intensely interesting and tractable one to investigate (largely following a groundbreaking article by Zhang & Luck, 2008).

(b) Next is the sentiment that the process of chunking is self-evident. Although that may well be the case, the issue of capacity limits cannot be solved until the actual chunks that people form and use can be consistently identified across many situations. Therefore, it can be argued that effort should be invested in trying to find out if capacity is a constant number of identified chunks (cf. Chase & Simon, 1973; Gobet & Clarkson, 2004). This generally has seemed too difficult for the field and, what is more, time limits of working memory probably have seemed simpler, to such an extent that one might believe that only time limits, without item limits, could explain working memory performance (cf. Baddeley, 1986). However, one can sometimes observe either apparent time limits or apparent item limits, depending on whether verbal rehearsal of the material has been curtailed (Chen & Cowan, 2009).

(c) Last, people were probably discouraged from exploratory research by Miller's (1956) comment that the commonality between the tasks he observed was probably due to a coincidence. In fact, though, there are good reasons to suspect that common principles may be at work across all three of the phenomena that Miller described (immediate memory of lists, absolute identification of stimuli, and estimation of small numbers of items). The reasons are as follows.

Absolute judgment is one of the simplest tasks imaginable and seems like a process that is often carried out in ordinary life. A single stimulus is delivered to the research participant, who only needs to decide to which of several pretaught categories the stimulus belongs. The apparent simplicity of the task does not, however, ensure that the mental processes are in fact that simple. Holland and Lockhead (1968) offered evidence on the absolute judgment of tone loudness indicating that these judgments are made with respect to previous trials. To judge the tone on Trial N, the tones presented on Trial N-1 had an assimilative effect: when N-1 had been more intense it made the tone on Trial N seem louder, as well; and vice versa. The previous few tones instead had a small contrast effect: when these tones had been more intense they made the tone on Trial N seem quieter and vice versa. The effect seemed to extend back to about Tone N-5, in the range of Miller's magic number. Although the mechanism of these effects is still debatable, it appears that across trials the task involves a list from the participant's point of view, and the sequential effects are subject to something akin to the usual working memory constraints. Similarly, Siegel and Siegel (1972, Figure 2) showed that when feedback was given, there was a large effect of the number of trials intervening between the stimulus on Trial N and the trial in which that same stimulus was last presented, again in the range of several items. These, however, were isolated investigations and it is only recently that a model of absolute judgment has been proposed, incorporating working memory effects (Brown, Marley, Donkin, & Heathcote, 2008). Recent research also has finally overcome the notion that absolute identification of objects on a simple continuum cannot be improved through training; it can if participants can find a way to link the judgment to some stable

frame of reference, somewhat analogous to how immediate memory can be improved through the application of knowledge for chunk formation. Several recent studies on training of absolute judgment have been quite successful (Dodds, Donkin, Brown, & Heathcote, 2011; Rouder, Morey, Cowan, & Pfaltz, 2004).

Rapid enumeration of small clusters of items, the third topic described by Miller (1956), also may rely on similar working memory mechanisms. In one version of working memory theory, the item capacity limit is identified with the capacity of the human focus of attention and how many objects can be attended at once (Cowan, 2001). The hallmark of small-set enumeration, or subitizing, is that the items must be attended and individuated—perceived as separate objects—within a short period. The typical limit in the literature is not about seven as in the suggestion of Miller, but on the order of three or four as in the literature on memory for items in an array (Luck & Vogel, 1997), and performance levels on the two tasks are highly correlated and appear to share a common limited-capacity resource (Piazza, Fumarola, Chinello, & Melcher, 2011).

The Subsistence and Revival of Chunk Capacity Limits

It would be too extreme to say that all research on item and chunk capacity limits ceased after Miller's 1956 article. As an analogy, although behaviorism had an inhibiting effect on research on mental mechanisms, such research did not totally cease during that era. There were, likewise, important studies involving item or chunk capacity limits in the years following Miller (e.g., Broadbent, 1975; Graesser & Mandler, 1978; Simon, 1974; Tulving & Patkau, 1962; Waugh & Norman, 1965; Zhang & Simon, 1985). As I (Cowan, 2001) have previously pointed out, there were also a number of other works that assumed a limited capacity as part of a larger model of cognitive processes, just without a primary focus on the assumed capacity limit and without an independent, direct evaluation of it (e.g., the seminal work of Atkinson & Shiffrin, 1968). Thus, I think that the work on chunk capacity limits was stymied, but not halted, by Miller's humorous presentation.

When it was suggested that much of working memory has a time limit (Baddeley & Hitch, 1974; Brown, 1958; Peterson & Peterson, 1959), that concept easily predominated in the field, a fact that I attribute largely to the weakness of support in that era for basic item or chunk limits. Indeed, my recollection is that for many years, sophisticated researchers tended to hold the opinion that, although the number of items in working memory is somehow limited, the limit just depends on the circumstances in a complex way that cannot easily be pinned down. Naturally, such opinions did not result in many publications articulating that view, which basically says that we don't know enough to begin to measure a capacity limit expressed in chunks. That is clearly a view that was held by a number of the initial critical reviewers of Cowan (2001), and by some of the published commentaries included in that work.

In the mid-1970s, the field rather readily adopted Baddeley's general assumption that a time limit took the place of an item limit (cf. Barrouillet, Portrat, & Camos, 2011; Case, Kurland, & Goldberg, 1982), with apparent item limits emerging indirectly, because of time limits (e.g., Schweickert & Boruff, 1986). Beginning with my graduate training starting in 1974, I, too, focused mostly on time limits, but my reading in the field led me to a nagging sense that different people were saying things that badly conflicted with one another, given the stark difference between item- and time-limited effects. The question for me was whether both kinds of limits could have validity. I thought they could, suggesting (Cowan, 1988, p. 166):

> Estimates of short-term storage capacity may be inflated by contributions of the long-term store. To obtain pure estimates of short-term storage, some investigators (e.g., Glanzer & Razel, 1974; Watkins, 1974) have subtracted out the assumed contribution of long-term storage. The resulting estimate for adults is two or three items in short-term storage. Perhaps the number of activated memory items is limited to about seven, whereas the subset of these items in awareness and voluntary attention is limited to two or three . . .. Other researchers (Baddeley, Thomson, & Buchanan, 1975; Schweickert & Boruff, 1986) have suggested that verbal STM is limited in the duration of storage as well as the number of items. When the list contains no organizing cues and rote rehearsal must he used, subjects appear able to recall as much as they can rehearse in 1.5–2.0 s. (This duration does not necessarily estimate simple memory decay, because the process of rehearsing or recalling one part of a sequence could interfere with memory for another part.) Thus, there appear to be constraints in both the number of items and the duration of pronounceable sequences in short-term storage. Although it is not clear how these two constraints work together, it might be possible to retain up to two or three chunks nonverbally while rehearsing other information (cf. Zhang & Simon, 1985). At least, some studies (Brooks, 1968; Scarborough, 1972) suggest that there are separate verbal and nonverbal components of STM that can be used together.

This kind of dual, item-plus-time-limit approach seems to have some validity (e.g., Cowan, Lichty, & Grove, 1990; Chen & Cowan, 2009), though both kinds of limits must be painstakingly disentangled from interference effects (Cowan, Saults, & Blume, 2014; Oberauer, Lewandowsky, Farrell, Jarrold, & Greaves, 2012; Ricker & Cowan, 2014).

From the 1970s through the 1990s, personally it felt all right to have item capacity limits in the background, but I sometimes felt ridiculed if these capacity limits were foregrounded in conversation. For example, the feeling of ridicule sometimes came up in conversations at a conference at the University of Colorado in 1997 that resulted in a book of conflicting theoretical viewpoints (Miyake & Shah, 1999). The conference also gave me encouragement, though, as I could see that (a) views on working memory were quite disparate, (b) some researchers agreed with me about the existence of chunk capacity limits, and (c) I was able to make some headway in convincing others and refining my own views. The conference helped in the formulation of the 2001 article in *Behavioral and Brain Sciences*, though I felt scorn from a number of reviewers. The feeling subsided when the paper was accepted, albeit by a journal that thrived upon controversy.

Baddeley (1994) correctly pointed out that Miller (1956) did have the profound effect of ending a general quest in the early formative years of cognitive psychology—a quest to explain human limits in terms of the bits (binary choices) of information theory. Miller argued that bits were not the basic units of immediate memory; meaningful chunks were. While disproving bit limits, however, item and chunk limits were not explored and pinned down nearly as much as I would have expected and hoped, until the recent research boom in that area.

Concluding Remarks: Lessons for the Progress of Science

Talk about things being pernicious (Miller, 1956); one of the most important constraints that science faces is the restriction of topics that individual scientists pursue. They place these restrictions on themselves because they do not wish to be perceived in a manner that would hurt their careers, discourage funding, or make them seem foolish or laughable. These concerns are not without a basis in reality. For example, in accounts of the career of Judah Folkman, who pioneered the well-accepted theory of the angiogenesis of tumors, he was a laughingstock whose findings were often thoughtlessly dismissed until the theory was finally accepted (Kalb, 2008). It is important for reviewers to try to be open-minded to unconventional ideas, albeit without lowering the bar for the requirement of solid evidence. George Miller was a humble man who never would have dreamed that his article would become so important, nor that the entertaining manner in which it was presented might discourage others from pursuing the basic phenomena described within.

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