Visual and auditory working memory capacity

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A considerable amount of cognitive, behavioral research has been conducted on working memory[1]. Definitions vary, but a theory-independent definition might state that working memory is the collection of mental processes that permit information to be held temporarily in an accessible state, in the service of some mental task. The nature of the task can vary widely and can include immediate recall, reading or listening comprehension, reasoning, or problem-solving. In listening comprehension, for example, it is often the case that the intended meaning of a word within a sentence is unclear until subsequent words in the sentence are presented. It is necessary to hold words in mind in some form until their meanings can be interpreted in light of the remainder of the sentence. In reasoning, assumptions and facts must be held in mind and considered together until conclusions can be deduced from them. It has been clear that the capacity of working memory is limited ever since George Miller[2] described various research studies suggesting that people can recall at most about seven independent, meaningful items or 'chunks' at a time.

Although limits to working memory are easily observed, it is much more difficult to determine what specific mental faculties underlie the observed limits. The observed limit depends upon details of the stimuli, suggesting that it is not a single, simple limit. For example, immediate memory for lists of words is better when the lists contain words that can be pronounced relatively quickly[3], and this 'word-length effect' occurs to some extent even when the short-word and long-word sets actually comprise the same words, but with instructions to pronounce them quickly versus slowly[4]. To account for stimulus-dependent working memory limits as well as age differences in working memory, various researchers have proposed working memory systems that include multiple components. Baddeley[1] proposed a system that includes a 'central executive' process that makes use of a passive, time-limited phonological store along with a 'covert rehearsal' process for verbal recall, and a passive, time-limited 'visuospatial store', possibly with another covert rehearsal process, for visual recall. In my own theoretical writing[5,6] I have proposed that working memory is composed of a capacity-limited focus of attention, along with a temporarily activated portion of the information in permanent memory, which extends beyond the focus of attention to include some automatically activated information (see Fig. 1). When researchers use the term 'working memory', some of them seem to be referring only to the focus of attention, whereas others seem to be referring to all of the temporarily activated information. It is also likely that certain inactive portions of memory can be stored in a way that allows them to be recalled (or reactivated) quickly[2,6,7]. For example, in a reasoning problem involving rainbow colors, encoding the seven colors of the rainbow as the name 'Roy G. Biv' and keeping that name in mind makes the color names easily accessible while using up perhaps only one to three items of working memory capacity.

There have been some attempts to go beyond the observed working memory limits to glean the limits of the underlying processing components. Broadbent[8] suggested, on the basis of past evidence, that the true capacity limit is about three items (presumably when the contributions of mnemonically useful processes such as rehearsal and long-term memorization have been eliminated). For example, this is about the number of items that can be recalled without error across many trials, and about the maximum number of items that can be grouped together into a single 'chunk', although the actual limit may be closer to four. Other researchers have proposed similar capacity limits of three or four items in the number of processing channels for visual search[9], the number of items that can be enumerated quickly, without a slow, serial counting process[10], and the number of moving visual items that can be tracked at the same time[10,11]. A similar limit of about four items has been found when subjects encounter a spatial array of printed characters[12] or a spatiotemporal array of spoken characters[13] and must report them all. It is not clear if all of these similar limits are related; if so, perhaps they reflect the capacity limit of the focus of attention[6].

Recently, Luck and Vogel[14] have contributed to this area in an important way. They first presented a spatial array of colored squares or rectangles on every trial. The second presentation was another array that could differ from the first array in the color of one item. Subjects were able to carry out the task well only if the first array, the one to be held in memory, contained four or fewer items. (The same pattern was obtained in an experiment in which a single item within the second array, the one that sometimes differed from the first array, was marked with a surrounding square in order to limit the decision to that one item.) These results extend the previously observed capacity limit to nonverbal visual stimuli, and to a situation in which there was only one decision to be made (in the case when there was a single probe item). A few other results warrant special mention and discussion.

First, the observed capacity of visual working memory was not reduced when subjects had to hold in mind two digits during a visual memory trial, to be recalled immediately afterwards[14]. One might expect a reduction of visual working memory if both verbal and visual representations were held in the same capacity-limited store. However, it is possible that the two verbal items could be held entirely in the form of a passive phonological store and rehearsal process[1] without taking up space in the capacity-limited store or focus of attention[5,6]. If the verbal memory load were increased further or accompanied by a rehearsal-blocking task[1], it might well be shown to reduce the observed capacity of visual working memory.

Second, the capacity limit was found to be the same (about four items) no matter whether the discrepancy between displays occurred in one feature, two features, or four features of each object. Thus, the capacity is apparently for integrated objects, not features per se. This at first may seem curious, in view of the fact that other research[15] suggests that links between features must be perceived one object at a time rather than for all objects in parallel. Possibly, subjects read the items into working memory one at a time but are still limited to about four such items on a trial. If this is true, despite the short durations of the arrays ($\geqslant$100 ms), then items must be read out of a post-stimulus sensory memory[12] and, therefore, memory should be greatly curtailed by a pattern mask immediately following the first array in a trial.

For arrays larger than four it is not even absolutely clear whether subjects encode a specific four items from a visual array (either serially or in parallel) or do a partial encoding of all of the items (e.g. about half the features of each item in an eight-item array). In

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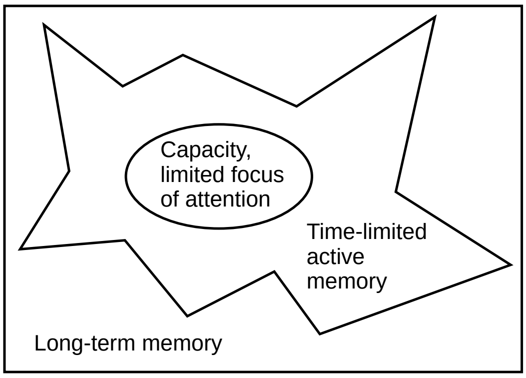

Fig. 1 An illustration of one simple theoretical model of working memory. (Modified from Refs 5,6.)

other words, the basis of the four-item limit is still unclear. Various research strategies could be of use here. For example, an item-by-item analysis could theoretically reveal that it is usually the four items closest to the fixation point that are encoded. If, instead, all items are partially encoded, then it should be possible to improve performance by changing more than one feature of the target object between presentations in the same trial, increasing the chances that at least one of the critical features had been encoded by the subject.

Working memory has also been a popular topic within recent neuroimaging studies. It is important to realize that there is still considerable behavioral work to be done before it will become clear what the behaviors are that might be explained through brain processes.

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Human abilities in cognitive tasks are clearly limited, and a central goal of cognitive science is to understand the processing restrictions that underlie limitations in the performance of these tasks. Perhaps the most thoroughly studied cognitive limitation is the highly restricted capacity of working memory. As discussed by Cowan in the preceding commentary, working memory can be defined as the temporary storage of information in an accessible state that permits the information to be used for ongoing mental operations.

Working memory is analogous to the internal memory registers of a computer's central processing unit (CPU). In standard computer architectures, the number of CPU registers is relatively small, just as the capacity of working memory is limited to a few items, and the registers are used to store the inputs and outputs of computational operations, just as working memory is used in the service of cognitive processes. In addition, many different types of data can be stored in the registers of a CPU, and this is paralleled by the ability of working memory to store information about sights, sounds, words and concepts. Moreover, just as the speed and flexibility of a computer is partially limited by the number of CPU registers, performance on cognitive tasks, such as reading and arithmetic, is correlated with an individual's working memory span[1]. Thus, it is clear that working memory plays a central role in cognitive processing and that limitations in working memory capacity are a significant source of limitations in the performance of cognitive tasks.

As discussed by Cowan, it appears that the capacity of working memory appears to be only about four items, although various 'mental tricks' can be used to retain larger sets of information[2]. Working memory capacity has been studied extensively in the context of verbal information[3], but has been addressed only rarely in the case of purely visual information. In addition, previous studies of visual working memory have primarily used letters and digits as stimuli[4], which is problematic because these stimuli could easily be encoded verbally as well as visually, and because they are relatively complex and highly overlearned visual forms. To overcome these limitations, we recently examined the capacity of visual working memory for simple features, such as color and orientation, as well as for combinations of these features[5]. This approach permits a more systematic exploration of factors such as stimulus complexity and similarity.

Our basic experimental paradigm is illustrated in Figure 1A. On each trial, subjects viewed two arrays of colored squares (called S1 and S2) and reported whether the two arrays were identical or differed in the color of one of the squares. A 900 ms gap separated S1 and S2, making it necessary for subjects to store S1 in memory so that it could be compared with S2. To assess the capacity of working memory, we varied the number of items in the stimulus arrays (the set size), assuming that performance would be nearly perfect when the displays were within the memory span and that performance would decline when the displays exceeded the memory span. Indeed, subjects were nearly perfect when the arrays contained one, two or three items, but accuracy began to decline as the set size increased to four or more items.

On the basis of an equation developed by Pashler[6], we estimated that subjects were able to hold an average of about four items in visual working memory at one time (because performance was not perfect with a set size of four items, it is likely that there was some variation from trial to trial in the number of items actually held in working memory). This estimate of working memory capacity is quite similar to the estimate derived for very different types of stimuli, as discussed in Cowan's commentary, and this is somewhat surprising because the information to be retained in this experiment was extremely simple.

To examine the role of stimulus complexity, we conducted an additional

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