ISSN 1799-2591
Theory and Practice in Language Studies, Vol. 2, No. 2, pp. 393-397, February 2012

doi:10.4304/tpls.2.2.393-397

Analysis of Working Memory and Its Capacity Limit in Visual and Auditory Information

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***Abstract*—This study is an analysis of working memory capacity in the context of both visual and auditory information. Working memory storage capacity is important because cognitive tasks can be completed only with sufficient ability to hold information as it is processed. The ability to repeat information depends on task demands but can be distinguished from a more constant, underlying mechanism: a central memory store limited to 3 to 5 meaningful items in young adults. The purpose of this study is to use strategies that can increase the efficiency of the use of a limited capacity or allow the maintenance of additional information separate from that limited capacity. The researcher will discuss why this central limit is important, how it can be observed, how it differs among individuals, and why it may exist. The review focuses on the term nature of capacity limits, storage capacity limit, views of researchers on working memory, and evidences of both visual and auditory working memory. The results suggest a focus on central capacity limits that are beneficial in predicting which thought processes individuals can do, and in understanding individual differences in cognitive maturity and intellectual aptitude.**

***Index Terms*—working memory capacity limits, visual information, auditory information, central storage capacity limits, chunks, core capacity**

I. Introduction

When we talk about the things human beings can do, we should certainly discuss the limits to what they can do. There are severe limits in how much can be kept in mind at once (about 3–5 items). When, how, and why does the limit occur. Miller (1956) demonstrated that one can repeat back a list of no more than about seven randomly ordered, meaningful items or chunks. Some have concluded that the limit "just depends" on details of the memory task. It has been difficult to determine the capacity limit of working memory because multiple mechanisms retain information. Considerable research suggests that one can retain about 2 seconds' worth of speech through silent rehearsal (Baddeley & Hitch, 1974).

Memory cannot be limited this way alone, though; in running-span procedures, only the last three to five digits can be recalled (less than 2 seconds' worth). In such procedures, the participant does not know when a list will end and, when it does, must recall several items from the end of the list (Cowan, 2001). Working memory is used in mental tasks, such as language comprehension, problem solving, and planning. Many studies indicate that working memory capacity varies among people, predicts individual differences in intellectual ability, and changes across the life span (Cowan, 2005). The main purpose of this article is to characterize limits in the number of chunks of information individuals can retain in working memory and the importance of this chunk capacity limit in both visual and auditory working memory.

II. Definition of Working Memory

Working memory is the brain system for holding and manipulating a small amount of information temporarily and it is essential for many cognitive activities (Baddeley & Hitch, 1974). Working memory is the use of controlled attention to hold and manage information. Cowan (1999) defined working memory as the collection of mental mechanisms that hold information in a temporarily accessible form that can be of use in cognitive tasks. Working memory can be thought of as both a general cognitive construct and an individual difference measure, and is thought to be an important component of higher-level cognitive performance.

III. Nature of Working Memory Capacity Limits

Two things are important to understand the nature of working memory capacity limits: process-related and storage-specific distinction. These two distinctions have to do with whether the task under consideration prevents processing strategies that individuals adopt to maximize performance, and whether the task minimizes processes that interfere with storing information in working memory. Storage-specific capacity is a more analytic concept, and the capacity limit stays constant across a much wider variety of circumstances. Working memory ability varies widely depending on what processes can be applied to a given task. To memorize verbal materials, one can try to repeat them in one's mind. One can also try to form chunks from multiple words. To memorize a sequence of spatial locations, one can envision a pathway formed from the locations. Though we cannot yet make precise predictions about how well working memory will operate in every possible task, we can measure storage-specific capacity by preventing or controlling processing strategies. That is how one can observe a capacity limit of three to five separate items (Cowan, 2001).

With respect to rehearsal and grouping, information can be presented (a) in a brief, simultaneous spatial array; (b) in an unattended auditory channel, with attention to the sensory memory taking place only after the sounds ended; (c) during the overt, repetitive pronunciation of a single word by the participant; or (d) in a series with an unpredictable ending, as in running span. In such task conditions, one can observe that a handful of concepts can be held in the conscious mind. These boundary conditions are also of practical use to predict performance when the material is too brief, long, or complex to allow such processing strategies. Young adults can recall three to five chunks from a presented list no matter whether these are learned pairs or singletons. The most precise result was obtained by Chen and Cowan (2009). Ordinarily, the result would depend on the length of the list and of the items but, when verbal rehearsal was prevented by having the participant repeat the word "the" throughout the trial, individuals remembered only about 3 units, no matter whether those were singletons or learned pairs. With similar results across many types of materials and tasks, we believe there truly is a central working memory faculty limited to three to five chunks in adults, which can predict mistakes in thinking and reasoning.

Storage and processing capacities both make important contributions to intelligence and development. The inclusive versus central distinction has to do with whether we allow individuals to use transient information that is specific to how something sounds, looks, or feels—that is, sensory modality-specific information—or whether we structure our stimulus materials to exclude that type of information, leaving a residual of only abstract information that applies across modalities (called central information). If one is trying to remember a spoken telephone number, for example, further conversation produced by the same speaker's voice interferes with auditory sensory information and leaves intact only the abstract, central information about the digits in the telephone number.

Although it is useful for human memory that people can use vivid memories of how a picture looked or how a sentence sounded, these types of information tend to obscure the finding of a central memory usually limited to 3 to 5 items in adults. That central memory is especially important because it underlies problem solving and abstract thought. Limits to central memory can be observed better if the contribution of information in sensory memory is curtailed. An array of coloured squares was presented at the same time as an array of simultaneous spoken digits produced by different voices in four loudspeakers. The task was sometimes to attend to only the squares or only the spoken digits, and sometimes to attend to both modalities at once. The key finding was that, when attention was directed different ways, a central working memory capacity limit still held. People could remember about 4 squares if asked to attend only to squares, and if they were asked to attend to both squares and digits, they could remember fewer squares, but about 4 items in all. This fixed capacity limit was obtained, though, only if the items to be recalled were followed by a jumble of meaningless, mixed visual and acoustic stimuli (a mask) so that sensory memory would be wiped out and the measure of working memory would be limited to central memory. With an inclusive situation (no mask), two modalities were better than one (Cowan, Fristoe, Elliott, Brunner, & Saults, 2006).

IV. The Storage Capacity Limit

Cowan (2005) reviewed a variety of hypotheses about the central working memory storage limit of 3 to 5 chunks. They are not necessarily incompatible; more than one could have merit. There are two camps: (a) capacity limits as weaknesses, and (b) capacity limits as strengths. The capacity-limit-as-weakness camp suggests reasons why it would be biologically expensive for the brain to have a larger working memory capacity. One way this could be the case is if there is a cycle of processing in which the patterns of neural firing representing, say four items or concepts must fire in turn within, say, every consecutive 100-millisecond period, else not all concepts will stay active in working memory. The representation of a larger number of items could fail because together they take too long to be activated in turn or because patterns too close together in time interfere with each other. If the neural patterns for multiple concepts are instead active concurrently, it may be that more than about four concepts result in interference among them, or that separate brain mechanisms are assigned to each concept, with insufficient neurons at some critical locale to keep more than about four items active at once.

If capacity is a weakness, perhaps superior beings from another planet can accomplish feats that we cannot because they have a larger working memory limit, similar to our digital computers. The capacity-limit-as-strength camp includes diverse hypotheses. Mathematical simulations suggest that, under certain simple assumptions, searches through information are most efficient when the groups to be searched include about 3.5 items on average. A list of three items is well structured with a beginning, middle, and end serving as distinct item-marking characteristics; a list of five items is not far worse, with two added in-between positions. More items than that might lose distinctiveness within the list. A relatively small central working memory may allow all concurrently active concepts to become associated with one another (chunked) without causing confusion or distraction (Cowan, 2005).

V. Analysis of Visual Working Memory Capacity

Visual working memory experiments come up with capacities in the vicinity of 4--or less than 4 items (McElree, 2006). We briefly mention a quite different paradigm that has come up with the same number. One such paradigm involves the number of items that people and monkeys-- can effortlessly keep track of. For example, at a rhesus macaque monkey colony on a small island off of Puerto Rico, Marc Hauser and his colleagues did the following experiment. Two experimenters find a monkey relaxing on its own. Each experimenter has a small bucket and a pocket full of apple slices. The experimenters put down the buckets and one at a time, they conspicuously place a small number of slices in each bucket. Then they withdraw and check which bucket the monkey goes to in order to get the apple slices. The result is that for numbers of slices equal to or smaller than 4, the monkeys overwhelmingly choose the bucket with more slices. But if either bucket has more than 4, the monkeys choose at random. Monkeys chose the greater number in comparison of 1 versus 2, 2 versus 3 and 3 versus 4, but chose at random in cases of 4 versus 5, 4 versus 6, 4 versus 8 and, amazingly, 3 versus 8. The comparison of the 3 versus 4 cases (where monkeys chose more) and the 3 versus 8 cases (where they chose at random) is especially telling (Hauser, Carey & Hauser, 2000). The 8 apple slices simply overflowed working memory storage. Infant humans show similar results, although typically with a limit more in the vicinity of 3 rather than 4 (Feigenson, Carey, & Hauser, 2002). Using graham crackers instead of apple slices, Feigenson, et al., found that infants would crawl to the bucket with more crackers in the cases of 1 versus 2 and 2 versus 3 but were at chance in the case of 1 versus 4. Again, 4 crackers overflow memory storage. In one interesting variant, infants are shown a closed container into which the experimenter-again conspicuously-inserts a small number of desirable objects (e.g. M & Ms). If the number of M & Ms is 1, 2, or 3, the infant continues to reach into the container until all are removed, but if the number is more than 3, infants reach into the container once.

Vogel and Machizawa (2004) developed a procedure to allow measurement of a physiological marker of the maintenance of object information in visual working memory. By presenting several objects in each visual hemifield but indicating that the array in one hemifield must be retained for comparison, they were able to use electrical activity over the contralateral side of the scalp as an indicator of whether information was held in working memory. A clear signal was obtained, which increased with the number of array items in a manner closely resembling the behavioural marker-the capacity of working memory according to a formula that corrects for guessing (Cowan, 2001). Across individuals, working memory capacity correlated well with the increase in magnitude of the lateralized electrical signal between array sizes of 2 and 4 items. Many investigators of visual working memory have assumed an automatic, modality-specific memory faculty. However, the new data suggest that memory maintenance might be attention-demanding rather them automatic. Theoretically, the type of attention involved could be specific to vision.

However, other data indicate that a general, amodal type of attention is involved. A memory load of six or seven random spoken digits to be recited aloud interferes with maintenance of a visual array. This is not the result of recitation per se: unlike random digits, reciting a well-learned number has no effect (Morey & Cowan, 2005). Some studies have shown that people can recall about 4 items including a number of features of each one. However, other studies (Xu, 2002) have suggested smaller working memory capacities for more complex items. Xu and Chun (2006) have perhaps resolved this controversy by showing that there are two different systems with somewhat different brain bases. One of these systems has a capacity of about 4 spatial locations or objects at 4 different spatial locations, independently of complexity, the other a smaller capacity depending on the complexity of the representation. The upshot for our purposes is that neither visual working memory system has a capacity higher than 4.

Saults and Cowan (2007) tested a conceptual framework in a series of experiments in which arrays were presented in two modalities at once or, in another procedure, one after the other. A visual array of coloured spots was supplemented by an array of spoken digits occurring in four separate loudspeakers, each one consistently assigned to a different voice to ease perception. On some trials, participants knew that they were responsible for both modalities at once whereas, in other trials, participants knew that they were responsible for only the visual or only the acoustic stimuli. They received a probe array that was the same as the previous array or differed from the previous array in the identity of one stimulus. The task was to determine if there was a change. The use of cross-modality, capacity-limited storage predicts a particular pattern of results. It predicts that performance on either modality should be diminished in the dual-modality condition compared to the unimodal conditions, due to strain on the cross-modality store. That is how the results turned out.

Moreover, if the cross-modality, capacity-limited store were the only type of storage used, then the sum of visual and auditory capacities in the dual-modality condition should be no greater than the larger of the two unimodal capacities (which happened to be the visual capacity). The reason is that the limited-capacity store would hold the same number of units no matter whether they were all from one modality or were from two modalities combined. That prediction was confirmed, but only if there was a post-perceptual mask in both modalities at once following the array to be remembered. The post-perceptual mask included a multicolored spot at each visual object location and a sound composed of all possible digits overlaid, from each loudspeaker. It was presented long enough after the arrays to be recalled that their perception would have been completed. The mask was capable of overwriting various types of sensory-specific features in activated memory, leaving behind only the more generic, categorical information present in the focus of attention, which presumably is protected from masking interference by the attention process. The limit of the focus of attention was again shown to be between three and four items, for either unimodal visual or bimodal stimuli (Saults & Cowan, 2007).

VI. Analysis of Auditory Working Memory Capacity

Darwin et al., (1972) carried out an auditory experiment and found a limit of about four items even though the observed decay period for sensory memory was about 4s. The common four-item limit is best viewed as a capacity limit rather than a rate limit. Baddeley et al., (1975) found that lists of short words are recalled more successfully than lists of longer words. This phenomenon has been explained on the grounds that the phonological representations of some words are lost from short term storage while other words are being covertly rehearsed or overtly pronounced, with the extent of loss dependent on the duration of the articulated words. Broadbent (1975) proposed some situations in which multi-item chunk formation was not a factor, and suggested that the true capacity limit is three items. For example, although memory span is often about seven items, errors are made with seven-item lists and the error-free limit is typically three items. When people must recall items from a category in long-term memory they do so in spurts of about three items on average.

Baddeley, Thomson, and Buchanan (1975) stated that there is a fixed chunk capacity limit. They showed that a list of short (e.g., monosyllabic) words was recalled better than a list of the same number of longer (e.g., polysyllabic) words. They also found that an individual's recall was equal to the number of items that he or she could pronounce in about 2s. This led to a theory that the limit in memory was not the number of chunks, but the amount of time for which the materials had to be remembered. The theory was that items were refreshed by rehearsal in repeating loop (the phonological loop in the model of Baddeley, 1986). If a given item was not refreshed in about 2s, it was lost from the working memory representation through temporal decay. Cowan (2001) noted other such situations in which multi-item chunks cannot be formed. For example, in running memory span, a long list of items is presented with an unpredictable endpoint, making grouping impossible. When the list ends, the participant is to recall a certain number of items from the end of the list. Typically, people can recall three or four items from the end of the list, although the exact number depends on task demands. Individuals differ in capacity, which ranges from about two to six items in adults and the individual capacity limit is a strong correlate of cognitive aptitude (Cowan, 2001).

VII. Conclusion

Limitations in working memory capacity are a significant source of limitations in the performance of cognitive tasks. The magical number seven plus or minus two is constant in short term processing including list recall, absolute judgment and numerical estimation experiments. Although it is true that memory span is approximately seven items in adults, there is no guarantee that each item is a separate entity. Later studies suggested that the limit in capacity is more typically only three or four units. This means that there are strategies that can increase the efficiency of the use of a limited capacity or allow the maintenance of additional information separate from that limited capacity. Some researchers disagree on the number of items or chunks encompassed by the capacity limit, others believe instead in only a time limit, and others believe in a modality specific limit or in no special working limit at all just a single set of rules for all of memory. The concept of capacity limit; measured in meaningful chunks seems sound despite difficulties in identifying chunks. Working memory limits must be viewed as strength as well as limitation. The ability to hold ideas in mind, combine them into new ideas, and manipulate them is a basic human strength. That working memory has a small capacity seems to be a human limitation although it is possible that we would be overwhelmed with too much information to process at once if working memory capacity were unlimited. Recent work suggests that there is an underlying limit on a central component of working memory—typically 3 to 5 chunks in young adults. Central capacity limits are useful in predicting which thought processes individuals can execute, and in understanding individual differences in cognitive maturity and intellectual aptitude.

Acknowledgements

I thank Seyedeh Masoumeh Ahmadi, Alizadeh, Khazaee, and Babaei for their extensive and insightful discussions and comments on the paper.

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