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The Functional Organization and Capacity Limits of Working Memory

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Abstract

Working memory refers to keeping track of ongoing mental processes and temporary memory. One hypothesis is that this form of memory consists of multiple domain-specific components. Over four decades, experiments testing this hypothesis have yielded insight into cognitive changes from childhood to old age, selective cognitive impairments following brain damage, and on-line cognition in healthy adults. Advances in the understanding of working memory also have arisen from the discovery of associations between individual differences in working-memory capacity and a broad range of cognitive measures. These latter advances have often been interpreted as supporting the alternative hypothesis that working memory consists of a single, limited-capacity domain-general system for control of attention. Here I outline recent developments in the multiple-component perspective that address challenges derived from the attention-based hypothesis and from multivariate studies of individual differences. I argue that the multiple-component perspective and the single-attentional-system perspective are complementary, with each best suited to asking different research questions, and that many areas of contemporary debate regarding the nature of working memory reflect differences that are more apparent than real.

Keywords

working memory, multiple components of cognition, attention, online cognition, individual differences in cognition

What have you just done? What are you thinking now? What do you plan to do next? The ability to keep track of ongoing mental processes and moment-to-moment changes in the immediate environment is essential for effective everyday functioning. This ability is known as working memory, and its importance to human cognition has driven theory and research since at least the 17th Century (Logie, 1996). The last four decades have seen development of several theories that are sometimes viewed as competing. I argue that they are actually complementary, asking different questions about the nature and function of working memory.

Working Memory as Consisting of Multiple Components

The multiple-component framework for working memory has developed from almost four decades of evidence based on behavioral, developmental, neuropsychological, and neuroimaging experiments (reviewed in Baddeley, 2007). It proposes that there are multiple domain-specific cognitive functions, each having its own characteristics and capacity limit (Fig. 1). The functions are common to all healthy adults and act together to meet task demands.

One function, the visual cache (visual short-term memory), retains a temporary visual representation of a single, recently presented array. It is limited by the visual complexity of the representation—for example, the number of stimuli in an array (Luck & Vogel, 1997) or the number of cells in a visual matrix (Phillips & Christie, 1977), as illustrated in Figure 1. It stores information for several seconds after the stimulus has been removed. It does not depend on visual input but may hold a visual representation of a recent auditory-verbal description of an array or of a stimulus that recently has been explored only by touch. A second function, the "inner scribe," can retain a short sequence of movements around an array of locations, such as is illustrated to the right of the inner-scribe component in Figure 1. Visual mental imagery is associated with executive functions and temporary activation of stored experiences and knowledge in episodic and semantic long-term memory (Logie, 1995, 2003).

Temporary memory for verbal sequences involves a limited-capacity store for phonological codes coupled with subvocal rehearsal (mentally repeating the verbal sequence as "inner speech") to maintain the contents of the store. As illustrated in Figure 1, there is access to the store directly following

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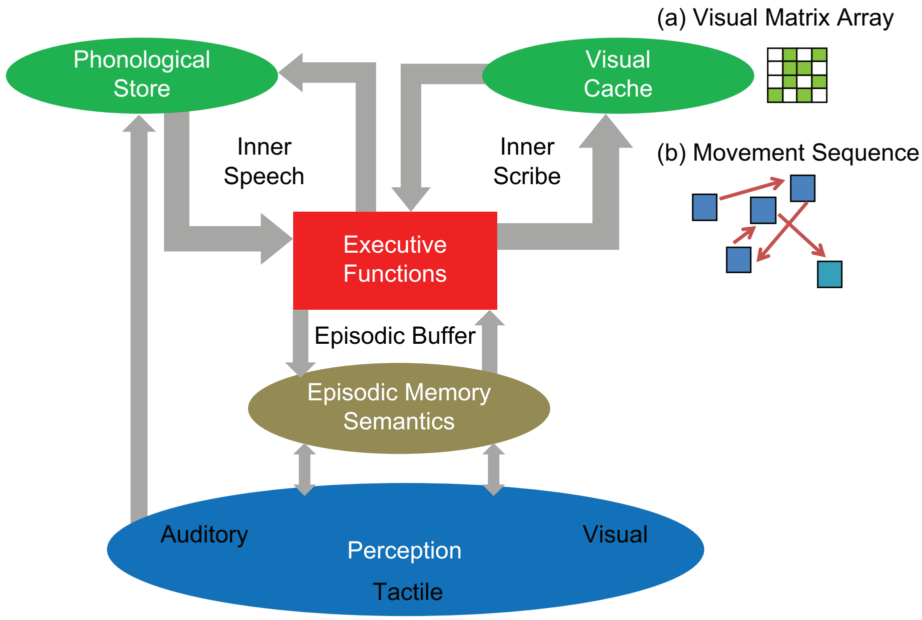

Fig. 1. Working memory as a multicomponent workspace. Information from auditory, visual and other forms of perception (e.g. tactile) activates stored knowledge (from long-term memory) about the properties of the perceived stimuli (e.g., shape and size from hearing an object name or from feeling an object shape, or word sounds from reading, or meaning of an object or sound). The activated knowledge is then held in a collection of interacting, domain-specific temporary memory systems—or components of working memory—and processed by a range of executive functions. For example, meaning, and shape and sound combinations may be held in the Episodic Buffer component. Details of recently perceived stimuli that have been seen or heard may be held as sound-based codes in the Phonological Store component or as visually based codes in the Visual Cache component. Both types of code decay within around 2 seconds, but the Inner Speech component can allow the sound-based codes to be held for longer by mentally repeating the sounds. The Inner Scribe component holds and can mentally rehearse sequences of movements and can allow visual codes to be held for longer by mentally rehearsing the codes held in the Visual Cache. On the right are illustrated (a) a visual matrix array as an example of how visual complexity may determine the storage limit of the Visual Cache component and (b) a sequence of movements between locations that may be stored in the Inner Scribe component, the storage limit of which is determined by sequence length. See main text for further explanation. Adapted from Logie, 1995.

auditory perception, as well as via activated stored knowledge. But it does not depend on auditory input and may store letter/word sounds from reading. What was originally viewed as a single central executive involved in controlling attention now is viewed as a range of executive functions that include focusing and sustaining attention, task switching, updating, inhibition, encoding, and retrieval (Baddeley, 2007).

An episodic buffer (Baddeley, 2007) is thought to store temporary, integrated, multidimensional representations rather than features of a stimulus/object specific to one sensory modality. Its contents are driven both by knowledge stored in long-term memory and by the contents of the modality-specific temporary stores. Binding features as integrated representations in the buffer does not require focused or sustained attention. Notably, multiple studies of visual-feature binding suggest that visual short-term memory holds temporary representations of bound features as integrated objects (e.g., Brockmole, 2009). This indicates that characteristics of the visual cache might overlap with functions of the episodic buffer. However, because the visual cache holds only visual codes, it cannot account for the ability to retain cross-modal binding, such as a combination of a sound and a visual stimulus. One possibility (see Fig. 1) is that the episodic buffer comprises interactions between working-memory components and with long-term memory. Recent evidence for this comes from the finding that individuals with Alzheimer's disease have a specific and severe impairment in temporary feature binding (color–shape combinations) but that they can successfully retain individual features (color or shape alone; Parra et al., 2009). Alzheimer's patients also have a very specific difficulty with concurrent performance of two diverse tasks (dual task) such as digit recall and tracking, regardless of overall task demand and regardless of their ability to perform each task individually (Logie, Cocchini, Della Sala, & Baddeley, 2004). Both types of impairment suggest that interactions (required for binding and for dual task) between different components of the working-memory system can be dissociated from the operation of each component on its own (remembering a single feature or performing a single task). With these paradigms, healthy younger and older adults show little or no cognitive cost of these forms of binding or dual-task demands. This suggests that the operations of each component and the interactions between them function seamlessly in concert in the healthy brain although, as noted below, empirical evidence for dissociations also has been found in healthy participants.

This framework differs from other working-memory theories in that on-line cognition is not solely constrained by capacity-limited attention but by the combined limited capacities of each of a range of specialist systems acting together to meet task demands. The overall capacity limit is an emergent property of the coordinated operation of the multiple components and may vary depending on which combination of components is deployed. This framework also differs from traditional perspectives of human cognition in that the working-memory system is not seen as acting as a gateway between sensory input and stored knowledge in long-term memory as suggested, for example, by Atkinson and Shiffrin (1968). Instead, it sees sensory input as being processed through the perceptual systems before the products of perception and activated long-term memory are held and manipulated within the various components of the working-memory system.

This general theoretical framework has been highly successful in accounting for a wide range of laboratory phenomena. For example, experiments have shown that most healthy adults can repeat back a random sequence of seven numbers or can reproduce from memory (draw) a recently seen 4 × 4 visual matrix pattern (Fig.1a). Experiments have also shown little or no reduction in memory for numbers or for a visual matrix when people are asked to remember a sequence of seven numbers at the same time as they are viewing and retrieving a 4 × 4 matrix. One crucial aspect of this finding is that the length of the verbal sequence and the visual complexity of the pattern are each set at or below the maximum that each individual can remember when doing each memory task on its own. But people cannot easily talk and remember a new 7-digit telephone number at the same time. These examples suggest that talking and temporary verbal memory share some cognitive resource, and hence interfere with one another, but that this resource is different from temporary memory for a visual pattern. However, when asked to remember a sequence of visually presented words, people may store the visual appearance of the letters, the word meanings, and the word sounds. In sum, people have a range of cognitive functions available, and they may deploy them in different ways and in different combinations depending on task demands. The challenge is to identify those different cognitive functions and their principles of operation.

The multiple-component framework is a conceptual and functional model, so there are no expectations that specific components will map onto specific areas of the brain. Each component might reflect the operation of a complex network in the brain that overlaps partially with networks engaged by other functional components. Therefore, demonstrations of overlapping activation patterns in brain-imaging studies do not undermine the theoretical and explanatory utility of the model. Nevertheless, a range of functional-brain-imaging studies have reported different patterns of activation associated with verbal immediate memory (typically the angular gyrus and supramarginal gyrus in the left hemisphere) and visuospatial immediate memory (typically posterior right parietal and some right prefrontal areas). Moreover, some individuals who have suffered localized brain damage, typically in the left parietal areas of the brain, suffer from severe impairments of verbal temporary memory while having completely intact ability to remember visual patterns. Conversely, individuals with damage in the right parietal and some right frontal brain areas show impaired visual immediate memory while having intact immediate verbal-memory abilities. The finding that visual working memory and verbal working memory can be damaged independently supports the idea that these different kinds of cognitive functions are supported by different networks in the brain (reviews in Baddeley, 2007; Logie, 1995, 2003).

Working Memory as Controlled Attention

Although the multiple-component model remains influential, the importance of understanding human working memory has inspired development of a range of alternative theoretical approaches. I cannot address all of the alternatives in this short article. However, one important contemporary theory views working memory as a system for controlling the focus of attention on currently activated contents of episodic and semantic memory rather than as a set of distinct systems for on-line cognition and temporary storage. Within this perspective, executive or controlled attention in working memory is thought to activate and maintain memory representations, switch attention between tasks, inhibit irrelevant information, and suppress unnecessary response tendencies (e.g., Cowan, 2005). The capacity of this working-memory system is very limited, but it is flexibly deployed and not specific to any particular domain of processing. Often viewed as a contrast to the multiple-component framework, this theory can also be considered as reflecting the operation of the central executive system within the multiple-component model; or, in light of what I discussed earlier, it may be seen as the coordinated operation of a range of cognitive resources. However, the focus of the controlled-attention theory is on questions about how the emergent capacity limit affects task performance (what are the implications of having a capacity limit?), whereas the multiple-component theory asks questions about the organization of the underlying functions that might give rise to that limit (where does it come from?). So although the theoretical assumptions initially appear to differ, the key difference may lie in the nature of the research questions being asked.

Development of the controlled-attention theory has drawn on both experimental techniques and on studies of individual differences in working-memory capacity. It draws less frequently on neuropsychological evidence than does the multiple-component framework. However, the latter asks specific questions about the functional architecture of temporary memory and on-line cognition. The controlled-attention view is less concerned with temporary memory and asks different questions about the ability to direct and sustain attention when confronted with distraction or interference. Because it asks questions about the implications of having a capacity limit, it is also the basis for theoretical approaches that ask questions about the implications of overall differences between individuals in their mental abilities and, in particular, their working-memory capacity.

Working-Memory Capacity

Working-memory capacity typically is measured by requiring some form of cognitive processing, such as reading sentences or performing simple arithmetic, coupled with remembering the final words of the sentences, arithmetic totals, or unrelated words (e.g., Daneman & Hannon, 2007; Turner & Engle, 1989). Typically, the measure of capacity is the maximum number of items correctly recalled. This measure of memory in the context of additional processing (reading or calculating) correlates more highly than does simple verbal-memory span (recalling lists of words or numbers) with other measures of complex cognition, such as language comprehension, academic performance, inhibition of automatic responses and irrelevant distracters, switching between tasks, and updating the contents of temporary memory, as well as fluid intelligence (e.g., Kane & Engle, 2002; Miyake et al., 2000). Waters and Caplan (1996) have shown that these correlations are even higher with a composite measure of both the processing task and the memory task, suggesting that processing and memory might reflect largely independent capacities that normally operate together (Daneman & Hannon, 2007; Duff & Logie, 2001; see also Unsworth, Redick, Heitz, Broadway, & Engle, 2009).

Working-memory capacity is a powerful predictor of cognitive performance inside and outside of the laboratory and is linked with frontal-lobe function. The major question is why such a simple task of reading and recalling correlates so highly with such a wide variety of mental-ability measures. Multivariate statistical methods such as factor analysis and latent variable analysis have led to contrasting conclusions, with some studies identifying a single, common factor—consistent with a single cognitive resource such as control of attention—that varies between people (e.g., Kane, Bleckley, Conway, & Engle, 2001). Other studies have identified several different factors (e.g., Miyake et al., 2000), with some factors changing more rapidly than others across the life span (e.g., Johnson, Logie, & Brockmole, 2010).

The concept and measurement of individual differences in working-memory capacity is important and extremely useful in identifying why some individuals perform more effectively than others on a wide range of cognitive tasks. However, it is not clear whether these studies yield as much insight into the functional organization of the underlying cognition as is sometimes assumed. One reason for this is that people vary in the strategies they use for performing working-memory tasks, as well as in the strengths and weaknesses of their different cognitive abilities (e.g., Chen & Cowan, 2009; Johnson et al., 2010; Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996). So statistical variation across individuals could reflect systematic variation in strategy choices rather than the functional organization of the cognitive resources available.

A further complication comes from assumptions about what can be concluded from measures of individual differences. By definition, the scores that people achieve on tests of individual differences reflect the maximum possible score that they can achieve when stretching their abilities to their limits. However, any task will require the use of some abilities at well below their maximum capacity and other abilities at their limits. For example, if we were to measure the visual acuity and the reading ability of 100 people, the correlation between visual acuity and reading would be negligible. However, it would be misleading to conclude from this low correlation that visual acuity is not required for reading. If those people were to close their eyes, reading would be impossible, showing that visual acuity is essential for reading and that the lack of a correlation comes about because most reading does not normally place demands at the limits of our visual system. The maximum capacity for visual acuity is not required for normal reading, but some minimum level of vision *is* required, and measures of individual differences would not reflect this requirement. Measures of individual differences are measures of the maximum capacity of the ability of individuals for the tests that they undertake, but this approach would be completely insensitive to the contributions from other abilities that are essential but only at some minimum level of competence. With visual acuity and reading this conclusion is obvious. With understanding cognition, and how cognitive tasks are performed, the issue is much less obvious. So even if a single statistical factor is found to contribute to maximum cognitive performance on a complex task, this does not mean that there is only one single attentional-capacity limit that governs cognitive function. There may be a range of specific cognitive functions, each performing well within its capacity limits, that are important for that task, but their contribution would be invisible in correlations between measures of individual differences on tests of those functions. In the context of the model shown in Figure 1, reading and remembering a list of seven numbers may involve a small load on the visual cache and a very heavy (at maximum capacity) load on the phonological store, but only the operation of the phonological store would be detected from correlations between measures of different mental abilities and a measure of the ability to recall the numbers. The correlation between recalling numbers and a measure of the operation of the visual cache (visual short-term memory) would be very low, so its contribution would go unnoticed. However, removal of a contribution from visual short-term memory by experimental manipulations such as loading it with different material, or as a result of focal brain damage, may result in poorer memory for the numbers. So an experimental or neuropsychological approach can yield insight into the functional organization of working memory in a situation in which patterns of correlations among individual-differences measures cannot.

It is also possible that when tasks are very demanding, they require a domain-general executive or attentional system to support performance because the task demands are beyond the capacity of domain-specific resources. For example, a task that requires more than the capacity of the phonological store in Figure 1 might also require executive functions to aid performance, and the operation of the executive functions may be detected, not the contribution of the phonological store. So, again, this kind of individual-differences approach would be insensitive to domain-specific contributions. Therefore, experimental studies that maximize cognitive demand may reflect the operation of both domain-general and domain-specific resources but be insensitive to the latter. Thus, approaches that involve people performing at their maximum ability may be crucial for asking research questions about why people differ from one another in their maximum task performance and what constrains their ability at very high levels of demand, but may be ill suited to identifying the functional organization of the cognition that supports performance. Multivariate statistical methods, manipulation of cognitive demands, experimental dissociations, and neuropsychological approaches each may be best suited to ask different kinds of research questions. Progress on understanding the functional organization of working memory and how the limits of working memory constrain cognitive performance will come from combining methods that target different but complementary questions while recognizing the research questions to which each approach is best suited (e.g. Baddeley, 2007; Cowan, 2005; Johnston et al., 2010; Unsworth et al., 2009).

Summary

The argument here is that working memory is a collection of cognitive functions. These are common to all healthy adults, but individuals can draw on them differentially for performing tasks. Researchers who focus on the control of attention, those who focus on capacity differences, and those who focus on temporary memory and on-line cognition are asking different but complementary questions. Multivariate individual-differences techniques and experimental techniques that manipulate overall task demand effectively address the impact of overall capacity limits on cognitive performance but experimental studies of healthy and impaired cognition that manipulate the type (rather than the amount) of cognitive processing and memory requirements are better suited for investigating the functional organization of cognition. This suggests that the debates are not as polarized as they might appear and that they have more to do with the different kinds of questions being asked than with fundamentally different theoretical assumptions. Research on the functions of healthy and impaired on-line cognition has come a long way in four decades of research. Converging evidence from a range of methodologies and from different research questions offers a means to make genuine new progress in theory and application of this core ability for moment-to-moment interactions between the mental and the external world.

Recommended Reading

Baddeley, A.D. (2007). *Working memory, thought and action*. Oxford, England: Oxford University Press. Provides a detailed summary of over three decades of research on working memory from when it was first investigated in 1974 by Baddeley and colleagues.

Cowan, N. (2005). *Working memory capacity*. Hove, England: Psychology Press. Covers Cowan's theoretical perspective of working memory as a limited-capacity system for controlling attention.

Kane, M.J., & Engle, R.W. (2002). The role of prefrontal cortex in working memory capacity, executive attention, and general fluid intelligence: An individual differences perspective. *Psychonomic Bulletin and Review*, *9*, 637–671. Covers the key arguments and evidence regarding the relationship between individual differences in overall working-memory capacity and a wide range of other measures of mental ability.

Logie, R.H., Osaka, N., & D'Esposito, M. (2007). Working memory capacity, control, components and theory: An editorial overview. In N. Osaka, R.H. Logie, & M. D'Esposito (Eds.), *The cognitive neuroscience of working memory* (pp. xiii–xvii). Oxford, England: Oxford University Press. Introduction summarizing a range of different perspectives on working memory that are covered in detail by the different authors of the subsequent chapters in the book.

Logie, R.H., & van der Meulen, M. (2009). Fragmenting and integrating visuo-spatial working memory. In J.R. Brockmole (Ed.), *Representing the visual world in memory* (pp. 1–32). Hove, England: Psychology Press. Summarises and comments on both theory and experimental findings on visuospatial working memory, showing the current relevance of early work in the 1980s and 1990s as well as of contemporary research.

Declaration of Conflicting Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

Atkinson, R.C., & Shiffrin, R.M. (1968). Human memory: A proposed system and its control processes. In K.W. Spence & J.T. Spence (Eds.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 2, pp. 89–195). New York, NY: Academic Press.

Baddeley, A.D. (2007). *Working memory, thought and action*. Oxford, England: Oxford University Press.

Brockmole, J.R. (2009). *The visual world in memory*. Hove, England: Psychology Press.

Chen, Z., & Cowan, N. (2009). Core verbal working memory capacity: The limit in words retained without covert articulation. *Quarterly Journal of Experimental Psychology*, *62*, 1420–1429.

Cowan, N. (2005). *Working memory capacity*. Hove, England: Psychology Press.

Daneman, M., & Hannon, B. (2007). What do working memory span tasks like reading span really measure? In N. Osaka, R.H. Logie, & M. D'Esposito (Eds.), *The cognitive neuroscience of working memory* (pp. 21–42). New York, NY: Oxford University Press.

Duff, S.C., & Logie, R.H. (2001). Processing and storage in working memory span. *Quarterly Journal of Experimental Psychology*, *54A*, 31–48.

Johnson, W., Logie, R.H. & Brockmole, J.R. (2010). Working memory tasks differ in factor structure across age cohorts: Implications for differentiation. *Intelligence*, *38*, 513–528.

Kane, M.J., Bleckley, M.K., Conway, A.R.A., & Engle, R.W. (2001). A controlled-attention view of working-memory capacity. *Journal of Experimental Psychology: General*, *130*, 169–183.

Kane, M.J., & Engle, R.W. (2002). The role of prefrontal cortex in working memory capacity, executive attention, and general fluid intelligence: An individual differences perspective. *Psychonomic Bulletin and Review*, *9*, 637–671.

Logie, R.H. (1995). *Visuo-spatial working memory*. Hove, England: Erlbaum.

Logie, R.H. (1996). The seven ages of working memory. In J.T.E. Richardson, R.W. Engle, L. Hasher, R.H. Logie, E.R. Stoltzfus, & R.T. Zacks (Eds.), *Working memory and human cognition* (pp. 31–65). New York, NY: Oxford University Press.

Logie, R.H. (2003). Spatial and visual working memory: A mental workspace. In D. Irwin & B. Ross (Eds.), *Cognitive vision: The psychology of learning and motivation* (Vol. 42, pp. 37–78). London, England: Elsevier.

Logie, R.H., Cocchini, G., Della Sala, S., & Baddeley, A.D. (2004). Is there a specific executive capacity for dual task co-ordination? Evidence from Alzheimer's disease. *Neuropsychology*, *18*, 504–513.

Logie, R.H., Della Sala, S., Laiacona, M., Chalmers, P. & Wynn, V. (1996). Group aggregates and individual reliability: The case of verbal short-term memory. *Memory and Cognition*, *24*, 305–321.

Luck, S.J., & Vogel, E.K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*, 279–281.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal Lobe" tasks: A latent variable analysis. *Cognitive Psychology*, *41*, 49–100.

Parra, M.A., Abrahams, S., Fabi, K., Logie, R., Luzzi, S. & Della Sala, S. (2009). Short term memory binding deficits in Alzheimer's disease. *Brain*, *132*, 1057–1066.

Phillips, W.A., & Christie, D.F.M. (1977). Components of visual memory. *Quarterly Journal of Experimental Psychology*, *29*, 117–133.

Turner, M.L., & Engle, R.W. (1989). Is working memory capacity task dependent? *Journal of Memory and Language*, *28*, 127–154.

Unsworth, N., Redick, T.S., Heitz, R.P., Broadway, J.M., & Engle, R.W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory*, *17*, 635–654.

Waters, G.S., & Caplan, D. (1996). The measurement of verbal working memory capacity and its relation to reading comprehension. *Quarterly Journal of Experimental Psychology*, *49A*, 51–79.