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The many faces of working memory and short-term storage

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Abstract The topic of working memory (WM) is ubiquitous in research on cognitive psychology and on individual differences. According to one definition, it is a small amount of information kept in a temporary state of heightened accessibility; it is used in most types of communication and problem solving. Short-term storage has been defined as the passive (i.e., non-attention-based, nonstrategic) component of WM or, alternatively, as a passive store separate from an attention-based WM. Here I note that much confusion has been created by the use by various investigators of many, subtly different definitions of WM and short-term storage. The definitions are sometimes made explicit and sometimes implied. As I explain, the different definitions may have stemmed from the use of a wide variety of techniques to explore WM, along with differences in theoretical orientation. By delineating nine previously used definitions of WM and explaining how additional ones may emerge from combinations of these nine, I hope to improve scientific discourse on WM. The potential advantages of clarity about definitions of WM and short-term storage are illustrated with respect to several ongoing research controversies.

Keywords Short term memory · Working memory

During the past 40+ years, I have watched as working memory (WM) has become one of the most talked-about and written-about terms in the field of cognitive psychology. During that time I have noticed that many of the controversies that occur in the field are related to definitions of WM. Several times within the last decade, after having devoted much of my career to exploring WM, I have even been asked to write review papers largely to clarify what the meaning of the term WM is, and how it is different from other terms in the literature (Cowan, 2008, 2010). The alternative terms with which it can sometimes be confused include primary memory (James, 1890; Waugh & Norman, 1965), immediate memory (e.g., Miller, 1956), short-term storage (e.g., Atkinson & Shiffrin, 1968) or short-term memory, and prospective memory (Einstein & McDaniel, 2005).

It has become clearer to me that a major source of confusion is that researchers use different definitions of the malleable and useful concept of WM. We do not seem to be converging on a common definition of the term. Others also have noted this absence of clarity about definitions; see for example Postle (2015). The main purpose of this article is to delineate definitions that have been used. This could lead to better scientific discourse if researchers could qualify their statements in a convenient manner by indicating which of the following definitions, if any, they mean by WM. I will elaborate on different definitions of WM and short-term storage and say a bit about how the definitions may affect scientific debate.

On scientific definitions and WM

My sensitivity to definitions was enhanced after a conference on WM in which each participating researcher was asked to define WM, with the definitions recorded within a volume of proceedings (Miyake & Shah, 1999). Not only did the definitions differ quite a bit but many of them seemed to take on a bit too much of the detail coming from the theories of the

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chapter authors, rather than clearly converging on a common concept that we all were studying in different ways and from different perspectives. It was as if theories and definitions were merged.

What's in a definition, anyway? Shakespeare's Juliet asserted that "a rose by any other name would smell as sweet," referring to Romeo, whose Montague family name was burdened with a conflict between families. Juliet's view would not be shared by a skeptic who assumed that any person with the Montague name brought danger. If a name comes with a theory, it is not interchangeable with any other name, as Juliet hoped. So it is with terms in science, which are often defined in a theory-laden manner.

A theoretical term in science often describes a hypothetical mechanism that can be observed when a specifically prescribed set of procedures produces a particular type of result. Consider how this function relates to the theoretical term WM. One definition of WM (the generic one below, Definition 6), says WM is *the ensemble of components of the mind that hold information temporarily in a heightened state of availability for use in ongoing information processing*. According to that definition, because of the existence of WM in the mind, one can at least count on the following. If a set of several simple items is presented across a few seconds and is immediately followed by a recall task, performance will be superior to recall after a long (e.g., 1-minute) or distraction-filled delay. If two people do equally well on delayed recall, but Person A shows that immediate-recall advantage more clearly than Person B, it is reasonable to say that Person A appears to have a WM that is in some way more capable than Person B. In contrast, this empirical test would not be relevant to all definitions of WM. According to the storage-and-processing definition (Definition 5, below), WM is *a combination of temporary storage and the processing that acts upon it, with a limited capacity for the sum of storage and processing activities*. If a researcher assuming that definition heard that Person A had a more capable WM than Person B, this researcher would believe that a more complex test had been carried out, involving not only storage but also engagement of additional processing.

In the following discussion, it is important to attend carefully to the distinction between a definition and a theory. Two different theories can share a common definition, but theories sometimes alter definitions. A key tenet of this review is that theories of WM have affected the way in which the term WM has been defined and used, which tends to have the effect of making the theory underlying the definition entrenched. We must be aware of the definitions of WM being used in order to prevent confusion. When the definition is not clear, there can be apparent agreements and disagreements between investigators that are unwittingly based on different uses of the term WM rather than on a correct understanding of each other's positions.

Definitions of WM

One reason that the term WM has been so widely used is that different groups of researchers with different research agendas have adapted the term to their own uses. I have been able to identify nine different ways in which WM has been defined, as summarized in Table 1. I will explain what I see as the basis in the literature for each use of the term, going in what I perceive to be the chronological order in which these definitions first occurred in the literature. One observation that seems to make this exposition necessary is that it has taken me many years to appreciate some of the subtly different ways in which the term WM is used by different researchers, and I have noticed that many of the researchers seem to remain

Table 1 Some definitions of working memory (WM)

1. Computer WM (e.g., Laird, 2012; Newell & Simon, 1956)
A holding place for information to be used temporarily, with the possibility of many working memories being held concurrently.
2. Life-planning WM (e.g., Miller et al., 1960)
A part of the mind that saves information about goals and subgoals needed to carry out ecologically useful actions.
3. Multicomponent WM (e.g., Baddeley, 1986, 2000; Baddeley & Hitch, 1974)
A multicomponent system that holds information temporarily and mediates its use in ongoing mental activities.
4. Recent-event WM (e.g., Olton et al., 1977)
A part of the mind that can be used to keep track of recent actions and their consequences in order to allow sequences of behaviors to remain effective over time.
5. Storage-and-processing WM (e.g., Daneman & Carpenter, 1980)
A combination of temporary storage and the processing that acts upon it, with a limited capacity for the sum of storage and processing activities. When the storage component alone is measured, or the processing component alone is measured, the term WM is not applied, in contrast to the usage within multicomponent WM. Further distinguishing this definition from multicomponent WM, there is not always a clear commitment to multiple storage components, only a separation between storage and processing.
6. Generic WM (e.g., Cowan, 1988)
The ensemble of components of the mind that hold a limited amount of information temporarily in a heightened state of availability for use in ongoing information processing.
7. Long-term WM (e.g., Ericsson & Kintsch, 1995)
The use of cue and data-structure formation in long-term memory that allows the information related to an activity to be retrieved relatively easily after a delay.
8. Attention-control WM (e.g., Engle, 2002)
The use of attention to preserve information about goals and sub-goals for ongoing processing and to inhibit distractions from those goals; it operates in conjunction with short-term storage mechanisms that hold task-relevant information in a manner that does not require attention.
9. Inclusive WM (e.g., Unsworth & Engle, 2007)
The mental mechanisms that are needed to carry out a complex span task; it can include both temporary storage and long-term memory, insofar as both of them require attention for the mediation of performance.

unaware of the pitfalls of definition, sometimes creating confusion as a result. (My apologies to the extent that I may have contributed to that confusion.)

Computer WM

This definition refers to a holding place for information to be used temporarily, with the possibility of many working memories being held concurrently.

The earliest use I have found for the term WM was not in the psychological research literature, but in the early computer science literature (see Logie & Cowan, 2015). Newell and Simon (1956) developed a computer program that could solve proofs in symbolic logic, using methods depending "heavily on heuristic methods similar to those that have been observed in human problem solving activity" (p. 1). To do so, they required computer memory locations that they called "working memories," which were designed to hold information only temporarily, while certain operations were carried out; these were distinguished from "storage memories," which were more persistent locations for memory (p. 11). This notion of WM resembles a worksheet that one might use while figuring out one's taxes, not necessarily saving the worksheet afterward. This description helps to explain why the term WM seemed appropriate; there was specific work to carry out using the information in WM. The term WM was used in a manner both similar to its later use with humans, and different from that use. It was similar in that information only temporarily resided in a WM, and was used to carry out activities considered cognitive work. It was different, though, in that the computer was allowed to have various multiple WMs at the same time, constructed as necessary, whereas human WM is generally conceived as a resource of much more limited capacity. The idea of a WM containing a set of information limited not by capacity per se, but by the relevance of the information to ongoing cognitive operations, lives on in at least one well-known, computer-based model of cognition (Laird, 2012).

Life-planning WM

This definition refers to a part of the mind that saves information about goals and subgoals needed to carry out ecologically useful actions.

Although Miller (1956) presented the seminal article on capacity limitations in memory, in that article it was not termed WM but, rather, immediate memory. The term referred to a procedure called memory span, in which a list of items is presented and then is to be recalled with no imposed delay, as soon as possible. Miller, Galanter, and Pribram (1960), though, did use the term WM in their book on how activities are planned. One must retain goals on many levels: the ultimate goals (e.g., perhaps getting a good job), subgoals within them (e.g., finishing a program in college), sub-subgoals (e.g., attending class today), and sub-sub-subgoals (e.g., getting dressed and, within that, perhaps choosing the clothes and putting them on). The ones of immediate concern were said to be held in a WM to allow them to govern behavior at the appropriate times, in the appropriate ways. The emphasis was on the need to use such a WM, with little or no commitment to the mental architecture that would be needed for this WM. This kind of memory seems somewhat akin to what is now called prospective memory, the ability to remember to do something at the appropriate time (Einstein & McDaniel, 2005), but with more attention to the notion that this kind of memory depends on the representation of goals and subgoals, allowing a complex hierarchy of behaviors to take place.

Multicomponent WM

This definition refers to a multicomponent system that holds information temporarily and mediates its use in ongoing mental activities.

The book chapter of Baddeley and Hitch (1974) contained many experiments and became the seminal work that probably spread the idea of WM more than any other single work. The concept of WM described in that chapter was in contrast to the concept of a short-term store as described by Atkinson and Shiffrin (1968). An assumption of Atkinson and Shiffrin was that it was adequate, for the time being at least, to consider a short-term store to be unitary. A host of phenomena had previously been explored that underlay this concept, including, for example, findings of the loss of information from simple stimuli followed by distraction (Peterson & Peterson, 1959), and good memory for the last few items in a series (Waugh & Norman, 1965). Atkinson and Shiffrin focused on control processes that shuttled information in and out of the short-term store. Baddeley and Hitch, however, noted that the telltale signs of short-term storage did not all hang together. There appeared to be multiple types of storage (e.g., some kind of abstract semantic storage vs. phonological storage).The recency effect in the free recall of words (i.e., especially good memory for the last few items in the list) had been taken as a hallmark of short-term memory, but it seemed unaffected by other short-term memory markers. It was not affected by a secondary memory load, or by phonological characteristics of words in the list, including phonological similarity and word length. In contrast, serial recall of short lists seemed to depend on a phonological type of memory, as it was affected by a verbal memory load and by phonological characteristics of the words.

To account for the finding that different kinds of task and manipulations did not affect one another very much, Baddeley and Hitch (1974) suggested that there is a multicomponent system of stores and processes that operate together, which they termed working memory. Baddeley (1986) and Baddeley and Logie (1999) later elaborated upon the structure of the system, suggesting that it includes two stores that operate passively: a phonological store and a visuospatial store. Passive storage refers to persistence of information for a limited time, regardless of any optional, voluntary mnemonic strategies such as covert verbal rehearsal (Baddeley, Thomson, & Buchanan, 1975) or attention-based refreshment (Camos, Mora, & Oberauer, 2011; Cowan, 1992; Raye et al., 2007), in contrast to the notion of an active storage that occurs through such mnemonic processes, typically as a supplementation or extension of the passive storage mechanisms.

In Baddeley's work, the passive stores were indeed accompanied by active processes to perpetuate information within them, preventing decay: a phonological rehearsal process that combined with storage to make a phonological loop, and later an "inner scribe" that similarly reiterated the visual store. Baddeley (2000) found the system insufficient and added an "episodic buffer" that could hold associations between different kinds of information, with its active versus passive nature not quite clear to me. Regardless of the specific version of the model, its multicomponent nature came to be the hallmark of the distinction between working memory and short-term storage, as the authors used it. According to them, any such short-term storage is just one part of a larger, multicomponent system, WM.

All versions of the model included a central executive, a set of processes thought to be responsible for managing the flow of information in and out of the various stores. Inclusion of the central executive as part of WM made a lot of sense in the 1974 version of the model, given that the mechanism that controls processing was not clearly distinguished from the central storage of some information from all sources. In Baddeley's 1986 book, the storage function of the central executive was removed, but this processor was still considered part of the working memory system, given that the various components all worked together to achieve the persistence of information needed to retain information.

Note that within the system of Baddeley and Hitch (1974) and the follow-up elaborations (e.g., Conway et al., 2005), there was no short-term storage independent of WM because the multicomponent WM system was defined to include any kind of temporary storage.

Given the great reach of this model, it is likely that others have used the term WM with implicit reference to the assumptions of this model. For example, Luck and Vogel (1997) included WM in the title of their article, but began the abstract with the sentence "Short-term memory storage can be divided into separate subsystems for verbal information and visual information[1]," the note referring to Baddeley (1986). Their introduction to research on memory for items presented in a spatial array suggests that the authors were willing to assume Baddeley's definition, working within it on the nature and capacity of visuospatial storage.

Recent-event WM

This definition refers to a part of the mind that can be used to keep track of recent actions and their consequences in order to allow sequences of behaviors to remain effective over time.

At some point, animal researchers started using the term WM to refer to the ability to select which spatial location had recently been visited and which had not. More generally, according to one recent explanation of this line of research (Bratch et al., 2016),

> although there is a long history of using the term 'working memory' in animal research…working memory has been used in the animal literature in a way that is quite different from the human conceptualization of working memory. In the animal literature, working memory refers to memory for information that changes in status during the completion of a test…; thus, working memory in the animal literature is not differentiated from basic short- or long-term memory. (p. 351)

Olton and Samuelson (1976) presented a radial arm maze to test rats' ability to recall which direction of the maze had already been probed, but did not refer to that kind of memory as WM. In Olton, Collison, and Werz (1977), however, the term WM was used to describe rats' faculty for performing in that task. The key notion is that as an arm of the maze has already been checked, it must be crossed off the mental list of arms left to check, or it will be needlessly rechecked. Olton, Becker, and Handelmann (1979) distinguished between WM and reference memory (i.e., memory for the aspects of the test locale that remained the same over time).

This idea of a memory for changing information that has to be updated as the task proceeds is in line with the conception of Miller et al. (1960) of a goal-related memory, but without the concern for the mental processes allowing a complex hierarchy of goals and without a clearly identifiable contribution from long-term memory. It would allow any and all mechanisms capable of helping to retain the recent events, without a particular limit being specified.

Storage-and-processing WM

This definition refers to a combination of temporary storage and the processing that acts upon it, with a limited capacity for the sum of storage and processing activities. When the storage component alone is measured, or the processing component alone is measured, the term WM is not applied, in contrast to the usage within multicomponent WM. Further distinguishing this definition from multicomponent WM, there is not always a clear commitment to multiple storage components, only a separation between storage and processing.

When Baddeley (1992) did actually define WM apart from his own instantiation of it, he did so as follows: “Working memory may be defined as the system for the temporary maintenance and manipulation of information, necessary for the performance of such complex cognitive activities as comprehension, learning, and reasoning” (p. 281). Notice that this definition seems to include manipulation as part of working memory even though, strictly speaking, manipulation is a process other than memory retention. That aspect of the definition would have been reinforced by the work of others. In particular, Daneman and Carpenter (1980) worked within the Baddeley and Hitch (1974) framework to understand individual differences in reading ability. In the process, they ended up creating a new task that became, for many, a new gold standard for tests of WM, in the process subtly changing the definition of WM. Baddeley and Hitch created a vision of WM that included both the storage faculties and a central processing faculty, the central executive. Accordingly, Daneman and Carpenter reasoned that an adequate test of WM capability must engage both storage and processing mechanisms. To do this, they created the “reading span” and “listening span” tests in which each sentence in a series was to be read aloud or comprehended (judged true or false) and, also, in which the last word in each sentence was to be remembered. The measure of reading or listening span was the length of the series of sentences that could be both comprehended and followed by correct serial recall of the sentence-final words. It was shown that reading and listening spans predicted reading performance much better than simple digit or word spans.

To people interested in individual differences, this success of Daneman and Carpenter (1980) signaled the need for tasks that included both storage and processing components to be considered WM tests. Tasks that did not include the processing component were considered short-term memory tasks. Thus, somewhat inconspicuously, for many people the definition of WM subtly changed so that it no longer applied to measures of storage that did not include processing. In contrast, Baddeley and Hitch (1974) used the term WM for a multicomponent system for which the storage or processing components could be measured either together or separately. Moreover, in the 1974 article, it appears that the existence of multiple kinds of storage was the most important driving force for coining the term WM instead of continuing to use the term *short-term memory*; the definition and theory seem conflated, though they probably were disentangled in some later writings of these authors.

When Baddeley continued to publish on aspects of WM during this period, he did continue to use the short-term memory construct when discussing recall immediately or after a short delay (e.g., Salamé & Baddeley, 1982; Vallar & Baddeley, 1982). However, it was still viewed as part of the WM system. For example, Salamé and Baddeley’s article title was *Disruption of short-term memory by unattended speech: Implications for the structure of working memory.* Although Daneman and Carpenter did not necessarily fall into the habit of defining WM and short-term memory distinctly on the basis of the reading- and listening-span versus simple span tasks, as opposed to viewing short-term memory as a subset of the WM system, many others since then have at least given the appearance of doing so. As just one example of many, Aben, Stapert, and Blokland (2012) stated that “there is a crucial role for the tasks that are used to measure STM or WM (simple and complex span tasks, respectively)” (p. 1).

A storage-and-processing formulation is convenient to the extent that one is primarily interested in the processes involved in WM. Barrouillet, Portrat, and Camos (2011) described the fruits of a program of research on the use of attention-based refreshment of representations in short-term storage that otherwise would decay. To study that system, the availability of time to refresh items in storage is controlled, so a storage-and-processing definition of WM is highly convenient. The definition becomes less convenient when it is found that certain types of immediate memory tasks that do not include both storage and processing still correlate well with cognitive aptitudes. Cowan et al. (2005) suggested that tasks that do not allow covert verbal rehearsal correlate well with aptitude measures, even if they do not include separate storage and processing components. One such task was running memory span, in which a list of items stops at an unpredictable point, after which the participant is to recall a certain number of items from the end of the list. (In Cowan et al., the list comprised digits presented rapidly at four items per second.) The assumption is that the unpredictable endpoint makes it difficult to know how and what to rehearse, and that rehearsal does not seem possible in running span when the list is presented too rapidly (Elosúa & Ruiz, 2008; Hockey, 1973; Postle, 2003). Moreover, in children too young to rehearse usefully, Cowan et al. found that simple digit spans correlated well with aptitudes. Running span was later further verified as a good predictor of aptitudes in adults at presentation rates of 500 ms or 2,000 ms per item (Broadway & Engle, 2010). This kind of finding challenges the popular assumption that a dual, storage-and-processing type of task is necessary to observe a strong relation between WM and cognitive aptitudes.

One problem with a storage-and-processing definition of WM is that, allowed to blossom, it can include so much of cognition that, taken at face value, the definition may admit all active, complex thought processes as WM. For example, Baddeley and Logie (1999) defined WM as

> those functional components of cognition that allow humans to comprehend and mentally represent their immediate environment, to retain information about their immediate past experience, to support the acquisition of new knowledge, to solve problems, and to formulate, relate, and act on current goals. (pp. 28–29)

Those are important roles that WM may play but, if WM is to remain a useful concept, a line must be drawn to keep out of WM many of the other processes that "allow humans to comprehend and mentally represent," and so on.

Generic WM

This definition refers to the ensemble of components of the mind that hold a limited amount of information temporarily in a heightened state of availability for use in ongoing information processing.

I call this definition generic because it cautiously avoids a statement about the mechanism or about functions other than retention of information (i.e., memory). The only assertions are that this memory is limited in amount, that this limited information is more available than the rest of the contents of memory, and that it is useful in information processing. Many researchers probably subscribe to this kind of definition, but it is hard to find in print because such investigators tend not to provide the definition. Stating the definition is important because it appears to be overshadowed in the literature by Definition 5. For example, as of this writing, the Wikipedia page for working memory says that it is a cognitive system with a limited capacity that is responsible for the transient holding, processing, and manipulation of information, a conception that labels more of processing as working memory.

Good candidates for use of the generic definition of working memory would seem to include studies that only examine the temporary retention of information, for example studies using briefly presented visual arrays. Even then, however, researchers have often tended to adhere to Definition 5. For example, Ma, Husain, and Bays (2014), reviewing visual array memory procedures, stated that "working memory refers to the short-term storage and manipulation of sensory information lasting on the order of seconds" (p. 347). Such examples provided in contexts in which manipulation is not really under consideration may simply indicate that researchers often do not care a great deal about the definition and are content to go with whatever the main stream of research literature seems to offer.

Although it is unclear who used Definition 6 first, something like it appeared early on in the field, in Definition 1 for computer memory (but without including the notion that the information must be limited in amount as opposed to being available in whatever quantity it is needed) and in Definition 2 for life planning (but without the memory having to be short-lived).

There may be various sources of the generic definition, but when one looks closely they are hard to find in the research literature. This definition is at least consistent with what was offered by Cowan (1988), as part of an explicit attempt to rethink the structure of the information processing system more broadly than in conceptions of the time. The thought was that we do not yet know enough to fill in a complete taxonomy of what WM modules might exist. There might be a nonverbal auditory module, a haptic module, a semantic module, an orthographic module, and so on. It was also unclear (and remains unclear) how modular the system must be in order to account for various dissociations between different kinds of memory. If verbal and spatial stimuli interfere little with one another in WM, this might be accounted for by separate storage modules, or else by storage of many kinds of features in such a way that there is interference between items based on the amount of similarity between their features (e.g., physical, phonological, orthographic, and semantic similarities). For this reason, Cowan sought to characterize the information processing system on a more general level without filling in putative modules. Within this system, the activated portion of long-term memory was said to be subject to decay over time, and subject to limits based on interference between concurrently-activated items. Within that activation, at most three or four items at a time were said to be available in a better-integrated, highly analyzed form, within a subset of activated memory termed the focus of attention. Within this scheme of processing, WM was said to be a composite concept. It was said to be composed of any information held temporarily in any form, the suggested forms comprising activated long-term memory and the focus of attention. Oberauer (2002) extended the Cowan (1988) model to include three levels: the activated portion of long-term memory, a region within it limited to several items, and a single-item focus of attention within that. Nee and Jonides (2013) similarly did so, on the basis of neuroimaging data. The model still fits the generic definition of WM inasmuch as all storage components are temporary, assuming that the activation of long-term memory is considered to be temporary.

The generic definition does not have to include these specific conceptions of how working memory operates; this overall definition of WM as an ensemble of mechanisms temporarily holding information in a state of heightened accessibility could apply to anyone's information processing theory. For example, applied to Baddeley's (2000) conception, the phonological, visuospatial, and episodic buffers and possibly the concomitant rehearsal processes would be parts of working memory; the central executive could be considered so when it functions to preserve information in working memory, but not when it functions to manipulate the information or change its form.

It is worth mentioning that there are gray areas when applying a definition, including this one. For example, Cowan (1988, 1995) was aware that it is not always possible to know what information is temporarily in an activated state. What makes it difficult is that there is information that is in long-term memory and is not activated, yet is easier to recover than some other information. This may be the case, for example, with knowledge of where one parked the car in the morning.

Cues from the day often lead to recollection at the end of the work day of where one parked when going to work that morning, but it becomes more difficult to recall where one parked when going to work on previous days. Cowan (1995) proposed a "virtual" short-term memory that was not part of WM, but was a part of long-term memory that did hold cues allowing easy retrieval of some information. This was considered to be analogous to the use of virtual memory by a computer to hold information that does not fit within random-access memory, the equivalent of short-term storage or WM. Virtual short-term memory was not considered active, but was said to be stored in a way that allows it to be retrieved easier than most other parts of long-term memory.

Something like this generic definition would presumably be appealing to researchers (e.g., Colom, Chuderski, & Santarnecchi, 2016) with a psychometric, individual-differences approach who find that the important aspects of WM are highly correlated across storage and processing and account well for general intelligence, even in tasks that emphasize the storage component without additional processing, so long as that storage function is adequately measured. Although a generic definition might not be offensive to anyone, it is common for the term WM to be imbued with additional meaning when discussed by researchers who see a special place for processing and executive function in individual differences in WM.

Long-term WM

This definition refers to the use of cue and data-structure formation in long-term memory that allows the information related to an activity to be retrieved relatively easily after a delay.

Ericsson and Kintsch (1995) independently described a form of memory that was in principle similar to Cowan's (1995) virtual short-term store, in that it too was said to be a part of long-term memory. One difference is in conception: Cowan attempted to protect the term WM from being used for parts of memory that did not have either a capacity limit or a time limit, whereas the "long-term working memory" of Ericsson and Kintsch did not include these limits. They described an organization of memory cues that allowed retrieval of relevant information from information-rich domains, with episodic memory cues constructed during ongoing activity that allow an individual to switch attention away from an activity and back to it subsequently. For example, if you are reading a novel and are interrupted by a 10-minute phone call, long-term working memory is the mechanism whereby you "pick up where you left off" in your memory of what was going on in the novel. Using the term WM in this way is consistent with Definition 2 (the life-planning memory of Miller et al., 1960), Definition 4 (the recent-event memory of Olton and others), and perhaps Definition 9 (the inclusive WM of Unsworth & Engle, 2007), but seems inconsistent with all the other definitions of WM. It is most similar to recent-event memory except for the emphasis on an elaborate data structure to support memory for both recent stimuli and recent events, and it may apply over a longer time period than what was intended by recent-events conceptions.

Attention-control WM

This definition refers to the use of attention to preserve information about goals and subgoals for ongoing processing and to inhibit distractions from those goals; it operates in conjunction with short-term storage mechanisms that hold task-relevant information in a manner that does not require attention.

Engle and his colleagues extended the work of Daneman and Carpenter over the years (e.g., Engle, Cantor, & Carullo, 1992), varying the nature of the storage and processing components of the tasks to invent, more generically, what have come to be known as *complex span tasks*. There already was a task in which counting items on a screen was a process combined with memory for the sums obtained on several screen counts in a row (Case, Kurland, & Goldberg, 1982). In fact, Daneman and Carpenter (1980) refer to what appears to be a related unpublished paper by Case and colleagues presented in 1979. Engle and colleagues extended the approach to include other combinations, the most widely used being a combination of arithmetic problems with a separate word or letter presented as a memorandum after every arithmetic problem, called *operation span*; and they and others have combined spatial processing with verbal memory.

The outcome of all of these types of complex span tasks is relevant to the question of how the results are to be interpreted, and that interpretation has subtly influenced the assumed definition of WM. Daneman and Carpenter (1980) provided data compatible with the suggestion that all of the mental work involved in their processing-and-storage span tasks could be occurring in domain-specific verbal WM mechanisms. Given that the successful prediction of cognitive aptitudes (with special emphasis on fluid intelligence) held up even when the storage and processing tasks were presented in different domains (Engle, Tuholski, Laughlin, & Conway, 1999; Kane et al., 2004), the WM mechanisms involved seemed to be general across domains, as one might well expect from attention mechanisms (inasmuch as attention to music interferes with attention to a work of visual art, etc.).

Technically, the concepts of Engle et al. (1999) are quite consistent with the definition of WM by Baddeley and colleagues (Definition 3, multicomponent WM). Domain-specific passive buffers for the storage of information were coupled with attention-related central executive processes that allowed the intelligent use of information in those buffers or short-term stores, and the findings of Engle et al. suggested that central executive processes accounted for many of the individual differences in intelligence. There was, however, a tendency of these researchers to describe a WM system that was less hierarchical than the multicomponent conception. Specifically, it appeared to equate WM with the attention-control processes that were apparently most critical in accounting for individual differences in cognitive ability, without regard for the short-term storage processes. Thus, a test of short-term storage would be considered a WM test according to the multicomponent definition, but not according to the attention-control definition. This reinterpretation is understandable, inasmuch as simple concepts on an equal level (WM and short-term storage) are easier to explain and discuss than a hierarchical system (WM and, within it, short-term stores). Nevertheless, omitting mention of the hierarchical concept may have caused some confusion. For example, Engle et al. (1999) summed up their approach with the following statement: "We argue that WM or controlled attention is not modality specific, whereas STM [short-term memory] is" (p. 329). Reinforcing this way of speaking was Engle's (2002) review article entitled "Working memory capacity as executive attention." Others, as well, have expressed similar views that if the attention-control aspect of WM is the key for understanding what is interesting in the system, then that system might be better termed "working attention" (Baddeley, 1993; Beaman, 2010). It is precisely that sentiment that makes it necessary to depict attention-control WM as a separate definition of WM. Holders of this definition seem to use the term WM exclusively for the attention-control part of the storage system and its uses.

Inclusive WM

This definition refers to the mental mechanisms that are needed to carry out a complex span task; it can include both temporary storage and long-term memory, insofar as both of them require attention for the mediation of performance.

Jacoby (1991) remarked that one cannot interpret the results of a measure unless it is pure with regard to the factors or processes that one is using it to measure. A final definition of WM emanates from a situation in which a kind of measure that has been taken by many people as the gold standard for WM, the complex span measure that combines storage and processing, turns out not to be factor pure. Unsworth and Engle (2007) thus found that performance on complex span tasks relates not only to individual differences in attention-related processing but also to individual differences in the cue-dependent search of long-term memory. The further implication, borne out in subsequent work (e.g., Unsworth & Spillers, 2010), was that the contribution of complex span tasks to intelligence came from a combination of attention-related and memory-retrieval-related components.

One response to this discrepancy would be to pronounce that complex span tasks cannot be taken to index a theoretical component called WM capacity. Given that authors do not like to make statements that damn their favorite tasks, it appears that instead they just lived with the definitional problems. For example, Unsworth and Engle (2007) titled their paper "The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory" and, similarly, Unsworth and Spillers (2010) titled theirs "Working memory capacity: Attention control, secondary memory, or both? A direct test of the dual-component model." Taken literally, these titles indicate that the concept of WM must now include long-term memory retrieval and, to accommodate that inclusivity, I have simply named this definition inclusive WM.

Additional definitions?

This might be a good time to remember that we are not listing theories of WM, but definitions. There are times when one might suspect that the term WM is being used differently by different investigators, but without being certain that it is the case. One example is when investigators see WM as a fluid resource of limited capacity (e.g., Just & Carpenter, 1992; more recently, Ma et al., 2014). It is possible that these investigators would include the fluid and divisible nature of the resource in the definition, either explicitly or implicitly, but it seems just as likely that they would use the term WM according to an existing definition, perhaps one like the generic definition (Definition 6), given that the fluid and divisible nature of the resource is the key empirical statement that they want to make about WM.

Another example of a point of view about WM that may or may not imply a different definition occurs for researchers who use as the main evidence for WM persistent neural firing, as a reviewer brought up. Here, again, it is not clear that researchers who use neural evidence do not implicitly or explicitly still think of WM in behavioral terms suitable to an existing definition. For example, Fuster and Bressler (2012) discussed WM in predominantly neural terms but still stated that WM is "the temporary retention of an item of information for the prospective attainment of a goal" (p. 211), consistent with the life-planning definition (Definition 2). The same might be the case for other neural researchers, though the definition is sometimes not made clear. In a recent review from a neural perspective, D'Esposito and Postle (2015) did not seem to offer their own definition per se but reviewed the way in which the term WM has most often been used, highlighting a cognitive perspective in which "attentional selection of mental representations brings them into working memory," such that "the consequences of attentional prioritization explain such properties as capacity limitations, proactive interference from no-longer-relevant items, etc." (p. 117). This view seems amenable to the generic definition of WM.

Compound definitions?

To avoid multiplying definitions of WM unnecessarily, it is helpful to recognize that some researchers might use multiple definitions conjointly. The WM of the ACT-R computer model of cognition appears to be a combination of Definitions 1 (computer WM), 2 (life-planning WM, and 8 (attention-control WM). Regarding this model, Anderson, Reder, and Lebiere (1996) stated:

> As Baddeley (1992) notes there are several senses in which the term working memory has been used. The paper will be concerned with two of these senses. One is associated with the tradition that defines working memory in terms of paradigms which require the subject to maintain a memory load while performing a task (e.g., Baddeley & Hitch, 1974; Daneman & Carpenter, 1980). The second is associated with production system theories (e.g., Newell, 1991) where working memory is taken to be the currently available information against which production rules match. We are interested in relating these two senses because the ACT theory…is associated with both. The ACT theory is associated with the first because of its strong roots in the human memory literature. It is associated with the second because it is a production system theory. ACT is a bit peculiar as a production system theory in that it does not have a working memory as that term is usually understood in production systems. Rather, the concept of capacity limitations is carried by the concept of activation. (p. 221)

Production systems seem like technical implementations of the kinds of goal pursuits described under the life-planning definition, but the limits in the activation needed to carry out memory retrievals are closely tied to the concept of attention.

Summary of distinctions

There are a number of features that appear to distinguish between the definitions of WM as used by various authors. There is room to quibble about some of these distinctions, but, to summarize the way I perceive the works, Table 2 summarizes the characteristics in which the definitions differ. Some, but not all, of the definitions refer to true WM components in that they exclude any contributions of long-term memory to the task. Some are limited in capacity, but there are two kinds of exceptions. Computer memory includes WMs that are created and eliminated without any capacity limit beyond the total processing limit of the computer. Definitions of human WM that allow a long-term memory contribution circumvent any limit through that contribution. Some definitions include the multicomponent nature of the system, as emphasized by Baddeley and Hitch (1974). Also as in that article, some of the definitions include the processing that takes place on temporarily held information as part of WM, viewing storage and processing apparently as an inseparable combination. All of the definitions allow the contribution of passive storage to count as part of WM, except for the attention-control concept of WM that seems to distinguish WM from short-term memory as a separate construct. Additional flavors of WM can be built through combinations of these definitions, as in the work of Anderson et al. (1996).

The flip side of the coin: Definitions of temporary-memory concepts

It is important to note the implication that the definition of short-term memory (most often tied to the procedure used) or short-term storage (for the underlying brain mechanism) depends on the definition of WM. When WM was a term that entered psychology only in the life-planning sense, the term *short-term storage* was to be taken on a more fine-grained level of analysis, to refer to the brain mechanism that held information temporarily, regardless of its use in processing. Some of the early terminology is still in use, but some has shifted.

Still-used terminology

The case of time limits Researchers differed in their terminology in part because of a difference in what was thought to make memory temporary: a time limit or an item limit. In the work of Peterson and Peterson (1959), the label *short-term retention* appears in the title and carries the implication that it is time that limits temporary memory. Brown (1958) also used this label, short-term retention, as well as *immediate memory*, with the implication that it refers to a time-limited kind of memory. In both cases, one important assumption was that rehearsal tends to obscure the time-limited nature of the memory, unless rehearsal is prevented.

The case of item limits Broadbent (1954) observed an item limit in memory rather than just a time limit but, like Brown (1958), he termed the immediate serial recall task *immediate memory*. This term was also used by Miller (1956). The numerical limit in performance in both cases was termed *memory span*. Waugh and Norman (1965) chose different terminology, setting their work apart from most others. They carried out an experiment in which a running list of digits was presented, and whenever a digit was presented for the second time, the task was to indicate what digit had followed it when

Table 2 Comparison of the distinctive features of different definitions of working memory (WM)

Type of WM	WM includes long-term memory	WM has limited capacity	WM must have multiple storage components	WM includes processing & storage	WM includes passive storage[c]
1. Computer	no	no[b]	no	no	yes
2. Life-planning	yes	no	no	no	yes
3. Multicomponent	no	yes	yes	yes	yes
4. Recent-event	no	yes	no	no	yes
5. Storage-and-processing	no	yes	no	yes	yes
6. Generic	no[a]	yes	no	no	yes
7. Long-term	yes	no	no	no	yes
8. Attention-control	no	yes	no	yes	no[d]
9. Inclusive	yes	no	no	yes	yes

Note It is assumed in each case that there is implicit (if not explicit) acceptance of the notion that goals are represented in WM along with data, even when it is not mentioned in the exposition of the model by relevant sources

[a] This definition still allows for temporarily activated portions of long-term memory to be part of WM, but not a broad retrieval of information from long-term memory as part of WM

[b] Ultimately computer memory is limited but this limit is large enough to be removed from this definition because the limit is much larger than what researchers needed for working memories

[c] Passive" implies temporary persistence of storage even without rehearsal or reactivation

[d] Passive storage is characterized as a short-term storage separate from WM in this definition

it was presented the first time. To control rehearsal, participants were asked to think of only the current digit, not previous digits, except during the probed-recall test. The rate of presentation was varied and the findings indicated to the authors that the main factor limiting performance was not the time since the probed digit had been presented, but the number of intervening items. This content-based limit was thought related to the trailing edge of the conscious present that James (1890) described, and thus the authors adopted his label for it, *primary memory*. Their link to the more-often-used terminology was evident as well, however, as the first sentence in their abstract states, “A model for short-term memory is described and evaluated” (Waugh & Norman, 1965, p. 89).

Historical shifts in terminology

The meaning of short-term storage Time- and item-based limits generally share a terminology without confusion, but, if one reads the early literature, an important discrepancy in usage pops out. Broadbent (1958) used the term *short-term store* not in the way we think of it today, but rather to describe a quickly decaying sensory trace, which we now call sensory memory. For a categorized store limited by the number of objects it could hold, he referred instead to the *limited-capacity channel*. Sperling (1960) similarly used the term *short-term memory* for a decaying sensory trace, and referred to the limit in the number of items that could be remembered as the “span of attention, apprehension, or immediate-memory” (p. 1). Alas, the terminology apparently shifted notably by the time of the seminal paper by Atkinson and Shiffrin (1968). They referred to the sensory memory as the *sensory register*, and shifted the meaning of the short-term store so that it now referred to the same kind of thing as Broadbent’s limited-capacity channel.

The relation of short-term storage to WM Atkinson and Shiffrin (1968) explained that “the short-term store is the subject’s working memory; it receives selected inputs from the sensory register and also from long-term store” (p. 90). This was done without reference to Miller et al. (1960) or any other source I could find for the term WM; that term was apparently just “in the air” at the time. Atkinson and Shiffrin also cautioned that the short- and long-term stores were theoretical mechanisms not to be equated with short- and long-term memory, the latter referring to the test situations. Thus, in a short-term memory experiment, both short- and long-term stores could play a role.

Baddeley and Hitch (1974), to make a point, distinguished between the short-term store of Atkinson and Shiffrin (1968) and WM, saying that the evidence connecting the two is “remarkably sparse” (p. 48) and adopting the term WM for their multicomponent system that replaced the short-term store. Short-term storage seems to have gained its independence from WM over time, according to some series of definitions. It went from (1) a component identified with WM (Atkinson & Shiffrin) to (2) a component that is only part of a complex WM system (Baddeley & Hitch), to (3) a separate short-term storage component that is not part of WM, according to the parlance of researchers who wish to narrow the concept of WM to focus on the attention-control aspect (the current Definition 8, e.g., Engle et al., 1999).

Engle and colleagues (1999) do maintain the belief of Baddeley and Hitch (1974) that there are domain-specific short-term stores rather than a single one. It should be noted that even Atkinson and Shiffrin (1968) were not set on there being a single short-term store that combined information across modalities; they just felt they had insufficient evidence to indicate whether visual information was retained in a visual form or recoded into a verbal form for short-term storage. Thus, the existence of passive stores (see Definition 3, multi-component WM) has been accepted for a long time, but its relation to other WM processes has been transformed several times. The label of short-term storage retains its meaning from Atkinson and Shiffrin referring to passive storage mechanisms holding a limited amount of postsensory, typically categorically encoded information.

Definition-based miscommunication

To read the literature regarding various controversies adequately, it may help to bear in mind the difficulty or adversity that people demonstrate when asked to formulate abstract definitions. Thus, one must be aware that researchers with the same point to make might discuss their point differently. For example, consider researchers who deny that there is temporal decay of unrehearsed memories in WM. Some of them seem to suggest basically that WM or short-term memory does not exist (e.g., Crowder, 1982; Nairne, 2002) so that there is no need to use those terms as opposed to, for example, "memory in the short term." Others seem to accept that something like working memory exists, but redefine it to exclude reliance on decay (e.g., Oberauer & Lewandowsky, 2008). Someone reading these sources in the future might not realize that they fundamentally agree that there is no decay, given their very different uses of terminology when they refer to similar kinds of studies, such as immediate serial recall.

One way to dramatize the purpose of the present paper is to imagine a conference spanning different eras with representatives of each definition of WM. Imagine further that Ericsson and Kintsch (1995) are now presenting for the first time their concept of long-term WM. At this conference, Miller et al. (1960) nod their heads knowingly because the concept fits comfortably with their idea of life-planning WM, in which the goal-relevant information in WM can very well be part of long-term storage. Newell and Simon (1956) like the goal-oriented aspect but wonder why the information is called long-term, given that it is eliminated when it is no longer needed. Cowan (1995) fundamentally agrees with Ericsson and Kintsch on the empirical points, having seen the need for a similar concept and having called it "virtual short-term storage," but worries about the confusing terminology of long-term WM. Many others sit uneasily, making puzzled faces because they have always defined WM as separate from long-term memory. This group at first seems to include Engle, but his work with Unsworth reminds him that they have incorporated long-term memory retrieval into the new account of WM task performance (Unsworth & Engle, 2007). Finally, theorists who suspect that there is no kind of distinct short-term memory or WM (e.g., Crowder, 1982; Jalbert, Neath, & Surprenant, 2011; Nairne, 2002) find the endeavor to be misguided because if there is no regular WM, all alleged WM is actually part of long-term memory, so that the term long-term WM is superfluous and distracting; better just to speak of recent retrieval cues. Nairne and Neath (2001) seem to agree with Ericsson and Kintsch inasmuch as they described "long-term memory span," but actually they did so as a reductio ad absurdum argument against the existence of a distinct short-term memory. Because little of this set of disparate concerns can be communicated easily, considerable confusion at the conference ensues.

It seems important to strive for definitions general enough that an empirical investigation is unlikely to overturn the definition itself any time soon. For example, if an airplane is defined as a means of transportation operating in the air on the basis of wings and multiple engines, that definition would be overthrown by the finding that an object generally considered an airplane had only a single engine. The definition should only contain guidelines that are expected to be useful, regardless of new research findings. For example, the decision to include wings in the definition of airplanes is helpful only if it is for some reason considered useful to call wingless airborne vehicles something else (e.g., rockets or missiles instead of airplanes). It is important to realize, though, that these are value-laden judgment calls, like the recent controversy about whether Pluto is a planet.

Conclusion

Many researchers outside of the field of WM have described to me confusion about its definition, and many researchers inside the field of WM often have appeared to talk past one another, in part because of discrepancies between their definitions of WM. By delineating various definitions and showing how they may fit together historically and in current usage, I hope to diminish the confusion and improve communication. The hope is that this review will provide a convenient way for researchers to specify a definition and will lead to a more thoughtful use of technical language to improve communication in the field and help to guide future progress.

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