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WORKING MEMORY FROM THE PERSPECTIVE OF THE MULTICOMPONENT MODEL AND EMBEDDED-PROCESSES MODEL

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ABSTRACT

In this article, we focus on working memory, the ability to store and actively manipulate information for a short period of time, and present two prominent theoretical frameworks for its study: Baddeley and Hitch's multicomponent model of working memory and Cowan's embedded-processes model. The multicomponent model assumes modality specific "slave" components for temporary storage and rehearsal of information and a central executive component that controls the entire system and determines what information enters and leaves the stores. The embedded-processes model, on the other hand, gives a more general description of the working memory system by focusing on its processes. It assumes that attention allocated to representations stored in the long-term memory underlies the short-term maintenance of information. We further describe in more detail how models conceptualize and define working memory, its components, and the processes involved, as well as factors in limiting its capacity. Finally, we describe similarities and differences between the models and present how the components of the models can be mapped to one another and to the brain systems.

KEY WORDS

working memory, multicomponent model, model of embedded-processes, representations, active maintenance

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INTRODUCTION

The aim of this article is to present the concept of working memory - the ability to store and actively manipulate information for a short period of time - from the perspective of two prominent theoretical frameworks for its study: Baddeley and Hitch's multicomponent model of working memory and Cowan's embedded-processes model. We first give a brief overview of what working memory is and how it differs from the concept of short-term memory within the scope of cognitive psychology and the functional level of the study of the cognitive system. Next, we present how the two models conceptualize and define working memory, its components, and the processes involved, as well as factors in limiting its capacity. Furthermore, we describe similarities and differences between the models and present how the components of the models might be mapped to one another. Finally, we present how the components of the two models can be related to the brain systems.

Working memory is one of the basic cognitive abilities, crucial for the successful execution of daily tasks such as remembering a telephone number, keeping up with the storyline while reading, solving math problems as well as adjusting to the ever-changing environment when driving a car. In contrast to short-term memory, which assumes simple storage of information for a short period of time [1], working memory refers to both temporary storage as well as active manipulation of information in order to achieve current task goals [2].

The term short-term memory was introduced by Atkinson and Shiffrin [1] in their multi-store model of memory, which assumes that human memory consists of three structural components: the sensory register, the short-term store and the long-term memory store. Information from the environment first enters the sensory register which is modality specific (e.g. vision, hearing) and can hold information for a brief period of time that varies across modalities from a few hundred milliseconds for visual sensory memory (also termed iconic memory) to a few seconds for auditory sensory memory (also termed echoic memory). If attention is allocated to the sensory stimulation, the information can be transferred into the unitary limited capacity short-term store in which it is present in an easily accessible state, and if rehearsed it can be further transferred into the essentially unlimited-capacity long-term memory for an indefinite period of time. By popularizing the term "working memory" a few years later, Baddeley and Hitch [3], who found Atkinson and Shiffrin's [1] model too simplistic, aimed to replace the concept of "short-term" memory by emphasizing its ability to actively manipulate information rather than only passively store it.

Active manipulation of temporarily stored information is central to cognition, as it forms the basis for higher cognitive functions such as reasoning, problem-solving and planning. Working memory correlates strongly with fluid intelligence [4] and is often impaired in diseases of the brain [5], its decline, however, is also a signature of healthy aging [6]. As such, understanding the mechanisms of working memory is of key interest in understanding human cognition.

One of the key challenges in working memory research is to understand the mechanisms of its highly limited capacity. In early research, primarily focused on verbal material, the capacity associated with the short-term memory was estimated to be roughly around 7 items or "chunks" of information of different types (words, letters, digits) [7]. It was later shown that the capacity estimate heavily depends on the type of information to be memorized (e.g. verbal, visual) as well as the complexity of the stimuli, such as phonological complexity for verbal contents, i.e. the number of phonemes or syllables [8] or complexity of visual representation (e.g. number of stimuli in a visual array) [9]. Therefore, when estimating the capacity, these and other factors affecting memory span must be taken into account, making capacity difficult to be summarized with one specific number valid within different contexts, tasks and information types [4, 10]. Cowan [11], however, proposed that working memory capacity in young adults is about four chunks of information.

Though the debate in this field has first centered on the quantification of working memory capacity, the focus has recently shifted to the question of what are the cognitive system's properties that define working memory limited capacity – are the limitations due to limited capacity of modality-specific stores or limitations in attentional processes [12, 13]? A number of models that have evolved within the framework of cognitive psychology, neuroscience and computational modelling attempt to explain its limitations by describing its structures and components as well as their processes. Two of the key theoretical frameworks for studying working memory are Baddeley and Hitch's [3, 14] multicomponent model of working memory and Cowan's [4] model of embedded-processes.

THE MULTICOMPONENT MODEL OF WORKING MEMORY

According to Baddeley and Logie [15], working memory "allows 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" [15; p.28]. In their multicomponent model of working memory, Baddeley and Hitch [3] describe working memory as a hypothetical system of limited capacity that enables temporary storage and manipulation of information needed to perform a number of cognitive activities. In their view, working memory is a system separate from long-term memory, though tightly connected with it. The model consists of several components: modality-specific temporary "slave" memory systems, which store information and refresh memory traces, and a supervisory system (the central executive) that controls, coordinates and regulates slave memory systems and activates contents from the long-term memory (Fig.1).

Initially, unlike Atkinson and Shiffrin's [1] unitary short-term store, two components for storing information were incorporated into the model [3]: a phonological loop tasked with maintenance of information in phonological form and a visuo-spatial sketchpad responsible for storing visual and spatial information. Baddeley and Hitch [3] further envisioned that the phonological loop consists of a passive 'phonological store' of limited capacity and an active 'articulatory control process' for refreshing memory traces and preventing them from temporal decay, which is the primary mechanism of forgetting in the multicomponent model working memory. By focusing on visuo-spatial working memory, Logie [9] upgraded Baddeley and Hitch's model. Analogous to the phonological loop, he envisaged that visuospatial sketch-pad also consists of a passive store for visual information (visual store) and an active system for refreshing and spatial manipulation of information (inner scribe) [9], although it is to date not entirely clear how visuo-spatial rehearsal is carried out.

In addition to the phonological loop and visuo-spatial sketch-pad, the central executive was also included in the original multicomponent model of working memory [3]. Baddeley and Hitch [3] envisioned the central executive as a supervisor, which manages the entire system and manipulates the information in the stores by determining what enters and leaves them. It is tasked with various executive functions such as focusing and switching attention, coordinating the slave systems as well as activating the contents within long-term memory. While slave systems are involved in the temporary storage of information and are of limited memory capacity, the central executive is not involved in information storage and its capacity is limited by attentional resources [2].

A fourth component, the episodic buffer, was added to the model almost 30 years later [14]. It is tasked with storing integrated information of various modalities in the form of short episodes and is tightly connected to long-term memory [14]. The initial assumption was that the storage of bound information depended on the central executive control of attention, but empirical findings confirmed that the episodic buffer – in contrast to the phonological loop and the visuo-spatial sketch-pad, which contain their own mechanisms for information rehearsal – was a passive structure, which does not need the attention of the central executive to maintain information [16, 17], but rather that the central executive is needed to defend relevant contents against disturbing stimuli [17, 18].

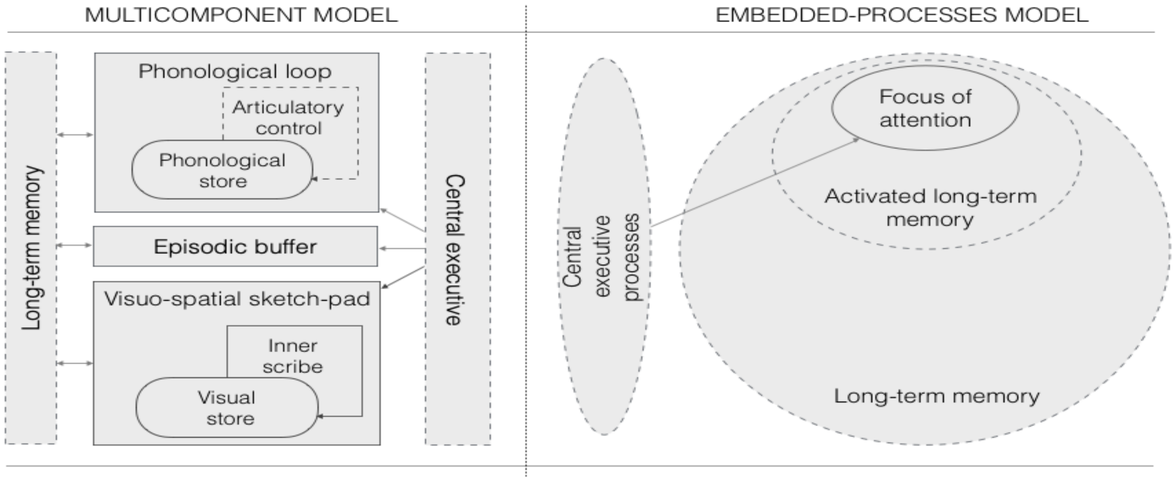

Figure 1. Comparison of the multicomponent and embedded-processes models of working memory. In the multicomponent model of working memory representations are established in modality-specific components for short-term storage of information (phonological loop, visuo-spatial sketch-pad, and episodic buffer). Active maintenance of the representations established in buffer stores is enabled through their rehearsal processes (articulatory control process, inner scribe), as well as the central executive processes that control and regulate the information flow in subsidiary systems. In the multicomponent model, the storage of items in the working memory is distinct, thought tightly connected to the contents of long-term memory. In the embedded-processes model, information in the long-term memory can be activated either automatically or voluntarily with the control of central executive processes. When the incoming sensory information is of high salience or when the information is activated by central executive processes it becomes part of the focus of attention, which enables its active maintenance. Note that solid borders denote limited working memory capacity components.

EMBEDDED-PROCESSES MODEL

According to Cowan [19] "working memory refers to cognitive processes that retain information in an unusually accessible state, suitable for carrying out any task with a mental component" [19; p.62]. The idea of Cowan's embedded-processes model [4], which is probably the most prominent representative of state-based models [20], is to give a more general description of the working memory system by describing the processes it involves rather than to divide its components based on the form of stored information, as in the multicomponent model [2]. Though Cowan [4] acknowledges that visuo-spatial and verbal memory represent two different systems, he argues that beyond verbal and visuo-spatial representations, other, equally important types of information might be stored in working memory. Cowan's [4] idea with the embedded-processes model is therefore "to describe a processing model that is exhaustive, in that nothing is left out, even at the cost of the model being vague in places" [4; p.74].

In line with this view, instead of specialized temporary storage systems and a central executive that controls them, the model of embedded-processes sees working memory as a system for controlling attention to the currently activated contents of episodic and semantic long-term memory. Within this perspective, attention allocated to internal representations that are stored either in long-term memory [4, 21] or established through sensory or motor systems [22, 23], forms the basis for short-term maintenance of information.

The embedded-processes model is a representative of unitary models of memory, as it assumes that working memory is an active part of long-term memory and identifies broader-to-more specific hierarchically organized components [4]: long-term memory, activated long-term memory and the focus of attention (Fig. 1). Activated long-term memory is a collection of long-term memory representations, that are currently activated and are as such in a particularly accessible state for a limited time. It does not have limited capacity in terms of how many representations can be activated a given moment, but is limited by time and is subject to interference effects. The second component is the capacity-limited focus of attention, which represents a subset of representations in the activated long-term memory. The focus is controlled either voluntarily by central executive processes or involuntary by orienting responses to changes in the environment. Whereas sensory representations can be activated automatically, attention is needed for integration of representations and forming new bindings in working memory.

SIMILARITIES AND DIFFERENCES BETWEEN THE MODELS

Although the models seem to differ to a great extent – the components in the multicomponent model are divided based on the properties of stored information (verbal, visuo-spatial, integrated information), while the focus of the embedded-processes model is on the components' functions – both Baddeley [2] and Cowan [4] see them as essentially complementary [9]. Baddeley [2] argues that "At a superficial level, Cowan's theories might seem to be totally different from my own. In practice, however, we agree on most issues but differ in our terminology and areas of current focus. /…/ I regard our differences as principally ones of emphasis and terminology" [2; p.21]. Cowan's [4] view is similar: "Thus the difference between the working memory model of Baddeley (2000) and the embedded-processes model is not very large and is probably best viewed as one of the level of analysis: a level of specific phonological, visuo-spatial and episodic storage properties versus a level of general principles of activated memory and attentional focus" [4; p.84].

The models can be compared in a number of ways and herein we only discuss a few. First, the models can be contrasted in how they see working memory in relation to sensory input and long-term memory. Both the multicomponent model [2] as well as embedded-processes model [19] see sensory input as separate from the contents stored in the working memory [9]. This view is similar to what was proposed by Atkinson and Shiffrin [1]. The multicomponent model assumes that sensory input is first processed by the perceptual systems and can then be transferred, manipulated and stored in the slave components with the help of attention from the central executive, and also by interacting with the long-term memory. Similarly, the embedded-processes model assumes that the sensory input that induces brief sensory afterimages first excites relevant features in the long-term memory, which can then enter the focus of attention either automatically or with the help of executive processes [4]. However, they differ in how they see a connection to long-term memory. The multicomponent model [2] assumes that working memory is distinct, though tightly connected to the contents of long-term memory, whereas the embedded-processes model sees working memory as an activated part of the long-term memory [19].

Second, the models can be compared in terms of the specific mechanisms they propose for the working memory information loss. Working memory literature proposes two main mechanisms of information loss [24]. One possibility is that if not constantly refreshed, the information decays in accuracy and distinctiveness until it cannot be reconstructed anymore. The other possibility (sometimes referred to as sudden death [24]) is that information is kept in a stable form without loss of accuracy, and the loss of information occurs instantly due to interference, e.g. interfering information replaces the existing information. Multicomponent model of working memory gives primacy to decay [2], whereas interference is more often referred to in state-based models [4].

Third, the models can be contrasted with regard to the systems and processes they involve. Both propose two systems that are involved in the maintenance of information – one is responsible for establishing and storing representations and the other for their active maintenance. The multicomponent model assumes [2] that representations are established and maintained in the slave components' stores (phonological store, visual store, episodic buffer), and that their active maintenance is enabled through their rehearsal processes (e.g. articulatory control process, inner scribe), as well as central executive processes that control and regulate the information flow in subsidiary systems [15]. In the embedded-processes model [4] representations are established within the long-term memory system, whereas central executive processes enable their active maintenance in the focus of attention.
Though the models are similar in that they both assume that two systems are involved in the maintenance of information, it is however not entirely clear whether and how their components can be mapped to one another. In Cowan's [4] view, his activated long-term memory maps onto Baddeley's temporary storage systems: "Activated memory was meant to serve the same purpose as Baddeley's two buffer stores together (phonological and visuo-spatial), plus any other buffer stores that might be posited in the future." [4; p.78]. Though no modality-specific buffer systems are specified in Cowan's [4] model, Cowan does acknowledge that activated portions of long-term memory can relate to distinct buffers. Moreover, he recognizes the role of central executive processes in focusing attention in both models, and links the role of this focus of attention to bind information to Baddeley's episodic buffer. Similarly, it can be understood that Baddeley [2] also maps his episodic buffer to Cowan's focus of attention and contents stored in the buffer stores to Cowan's activated long-term memory: "I see Cowan's model as principally concerned, in my terminology, with the link between the CE [central executive] and the episodic buffer". Cowan refers to the material on which his system works as "activated LTM [long term memory]" [2; p.20].

Another important aspect when comparing the two models is how they explain limitations in working memory capacity. In the multicomponent model, the limited capacity of the working memory is viewed as a result of an interaction between the operations of multiple components and subcomponents, and can be understood as an emergent property [9]. Multicomponent model assumes that central executive itself does not store any information, rather than its functional role is limited by attentional resources. Information storage systems are limited in terms of how much information they can store [9]. Moreover, unless refreshed by rehearsal, representations stored in phonological and visual store are subject to temporal decay, due to which information is lost in about two seconds. Though the processes for rehearsing information (i.e. articulatory control process for verbal information and inner scribe for visuo-spatial information) have no limit in terms of how many units of information they can refresh, they can only refresh information that is currently present in the buffer stores and as such depend on their capacity.

Whereas the main limitation of working memory capacity in the multicomponent model can be ascribed to the buffer store's capacities, in the embedded-processes model limitations are primarily related to the limited capacity of the focus of attention, as the central executive enables active maintenance in the focus of attention only for a limited number of representations in the activated long-term memory. On the other hand, the activated long-term memory itself has unlimited memory capacity and is limited by temporal and interference effects [4].

MODELS IN RELATION TO BRAIN SYSTEMS

The models presented here provide a conceptual description of the structure and processes of working memory at the functional level of the cognitive system. To gain a full understanding of working memory in human cognition, it is crucial to see how the functional models relate to neuroscientific findings. Although the models themselves do not provide explicit mapping to brain systems, they are consistent with the findings of neurophysiological research showing that posterior and prefrontal areas of the cerebral cortex play different roles in the short-term maintenance of visual-spatial information [25]. Studies show that the posterior areas of the cerebral cortex are involved in the formation and short-term storage of the visual, spatial and verbal representations [26], whereas prefrontal regions control allocation of attention for their active maintenance [27]. The role of prefrontal areas thus resonates with Cowan's executive processes that control what is in the focus of attention and Baddeley's rehearsal processes which refresh information from the stores to keep it active, as well as the central executive, which carries out the active work by controlling the contents in the buffer stores. Within Cowan\s model the posterior regions are associated with both activated long-term memory as well as focus of attention [4], whereas in the multicomponent model the posterior regions are associated with contents in component-specific stores, including the episodic buffer [2].

Recent findings from neuroimaging studies (for a review, see [28]) show that the posterior brain regions that are involved in temporary storage of information are not unique to working memory, but are also involved in storing long-term memory representations as well as the sensory processing of information [29, 30]. These findings are consistent with the embedded-processes model, which assumes that the focus of attention to currently activated long-term memory representations underlies working memory.

CONCLUSION

As Baddeley [2] states, the idea of the multicomponent model of working memory which also holds true for the embedded-processes model is "a relatively loose theoretical framework rather than a precise model that allows specific predictions." [2; p.7]. The models must therefore be understood as hypothetical accounts of working memory structure and function. Although the models successfully explain many of the cognitive phenomena associated with the short-term storage of information and its active manipulation, and can be in many respects meaningfully mapped onto the brain function, their purpose is not to explain all of its aspects. They can instead be understood as working platforms that need to be further developed in accordance with empirical findings.

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