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50 years of research on working memory[1]

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Abstract: Exactly 50 years ago, the model of working memory proposed by Allan Baddeley and Graham Hitch (1974) fascinated academics and practitioners dealing with human cognition, and have permanently changed the landscape of memory research. Working memory is the ability of the human mind, that allows the creation and reception of communications, performing mental arithmetic, decision-making, and other complex cognitive activities, that require temporary storage of necessary information and its manipulation in order to perform current tasks (e.g., following the flow of a conversation). As such it is one of the most dynamically developing areas of research in cognitive psychology, cognitive science, neuropsychology, and the differential psychology (especially in the intellect diagnostics). The ongoing research dispute concerns many aspects of the working memory construct: its structure, functions, capacity limits, relationship with consciousness, long-term memory, attention, etc. (see Logie, Belletier et al., 2021). The solutions proposed by researchers are characterized by such great detail, that people who do not closely follow the literature on the subject, may have difficulty understanding their essence. The beginnings of this creative fuss date back to the proposals of Baddeley and Hitch (1974), who carefully analyzed the data on temporary memory and recognized it as a system composed of many cooperating components, that is, separate subsystems storing information in different formats (e.g. visual or auditory) and a superordinate subsystem managing the flow and use of the stored information. This article presents the context in which Baddeley and Hitch's (1974) multicomponent model of working memory was developed, as well as describes the milestones that marked the dynamic changes it underwent, and lists the research projects that prompted the refinement of the descriptions of the components within the model. Although an influential portion of the contemporary competing accounts of working memory abandon many of Baddeley's theses (Cowan, 2017; Oberauer, 2019), each of them follows the conceptual paths forged by this author and must clarify their positions on questions posed during the fifty-year journey of working memory research.
Keywords: Allan Baddeley, working memory, Multicomponent Model of Working Memory

1. The development of the concept of working memory

Without working memory, communication would not be possible. Both the deciphering of the sounds uttered by the sender and the encrypting of thoughts in the form of linguistic expressions by the recipient are preceded by this specific "work" of memory, which consists in storing and manipulating phonemes in such a way that they can be recalled in the right order in a moment and integrated with significant words and sentences containing the right meaning. Understanding and producing speech, following the flow of a conversation, weighing arguments, reasoning, maintaining ideas, mental arithmetic, making decisions and judgments – all this is done thanks to the human ability of working memory (also called operational memory). Currently, working memory is one of the most popular research areas intensively developed in cognitive sciences and diagnostic practice (Logie et al., 2021). There are many definitions of this construct (see Cowan, 2017 for review), but the essence of each one refers to holding in the mind a small amount of information currently needed for use by cognitive processes – on standby (i.e., temporarily heightened state of availability) – to perform the current task. Critical defining features are the time-limited storage of information and the continuous processing of information so that it is available for use in thinking and acting (Cowan, 2017). This can be both verbal and visual information (e.g. shapes, colours, position, sequence of movements). However, this does not have to be conscious information. Working memory includes the conscious part of

1 Article in polish language: https://www.stowarzyszeniefidesetratio.pl/fer/58P_Hara.pdf

the mind, but also memory processes that operate "in the background" of consciousness, inaccessible introspectively. It is therefore not identical with the concept of consciousness.

The concept of temporary memory was known before the creation of psychology in its present form. For example, Locke (1690/1955) in his reflections mentioned – alongside various properties of memory – contemplation, which allows one to view an idea for some time before it passes into the "storehouse of ideas" (today we would say: into long-term memory storage). Two centuries later, William James (1890) described the concept of primary memory to describe what appears as present in the mind, as opposed to what is stored in so-called secondary memory. Broadbent (1958), when describing the mechanisms of attention in various cognitive tasks, refers to temporary memory, giving it the name immediate memory. Nevertheless, the first systematic attempts to explain "working memory" appear in the work of Miller and colleagues (1960), who explore the phenomenon of chunking information into meaningful new units that facilitate the memorization of larger amounts of data. However, before the term working memory had time to settle in the minds of researchers, another important concept emerged, inspired by Broadbent's thought. It was short-term memory placed in the multiple-store model of memory by Atkinson and Schiffrin (1968) as one of the storehouses related to cognitive control processes and at the same time serving as a link between the sensory memory and long-term memory stores. The influence of this model was so great that the division into long-term memory (LTM) and short-term memory (STM) has spread beyond the circle of researchers and experts. The terminology of multi-store models shaped the thinking about the processes storing information in the mind for decades to come, although there were alternative approaches to memory architecture that abandoned the rigid division into separate blocks and emphasized the homogeneity of the entire system (Craik, Lockhart, 1972).

The term "working memory" returned to scientific discussions exactly 50 years ago, after the famous publication by Alan Baddeley and Graham Hitch (1974) entitled "Working Memory", describing temporary memory as a system composed of many components and responsible not only for storing information (like short-term memory) but also for manipulating it (e.g. Baddeley, 2012). Simultaneously with the development of Baddeley and Hitch's (1974) model, in which new components were added over the years and the scope of their functions was expanded, other theoretical approaches touching on the same part of cognition flourished. The most famous include: computational models of cognition, created in North America by researchers inspired by the concepts of Atkinson and Schiffrin (1968), e.g. ACT-R (adaptive character of thought; Anderson, 1996), SOAR (Newell, 1990), EPIC (executive-process interactive control; Meyer, Kieras, 1997), approaches exploring individual differences in working memory capacity (Daneman, Carpenter, 1980; Engle et al., 1999), or approaches that emphasize the role of already accumulated knowledge and skills in current information processing (Ericsson, Kintsch, 1995).

2. Development of Baddeley and Hitch's Multicomponent Model of Working Memory

Baddeley and Hitch (1974) stated that, in the light of available research, working memory cannot be treated as a unitary mechanism. Further empirical evidence provided by researchers has consistently pointed to the fact that people handle information more efficiently when it is encoded in different formats (e.g., visual and auditory) than in the same format. The mechanism that allows this must be a multi-component system composed of many interacting elements. Otherwise it would not be possible for it to have several separate pools of resources corresponding to different (auditory vs visual) types of information. If we assume that information of a given type, stored in the same stores, competes for the same resources, then it should be difficult for the subjects to perform competitive tasks using similar stimulus material (e.g. visual), and they should have no problem coping with simultaneous tasks of different nature (one task with visual information, the other with auditory information). Such relationships were observed many times in studies conducted at that time (1974).

At the same time, the study of memory capacity limitations has become crucial for understanding the nature of working memory. A person cannot keep an infinite amount of information in his mind on an ongoing basis, nor can he manipulate it infinitely efficiently. The question about the nature of the limitation of working memory capacity is currently one of the most pressing and is addressed differently depending on the theoretical approach. In the model of Baddeley and Hitch (1974), this capacity limitation can be "bypassed", for example, by the action of rehearsing the memorized information, that is refreshing it in working memory so that it does not degrade quickly (Baddeley, Hitch, 1974).

The exact composition of Baddeley and Hitch's (1974) multicomponent model of working memory has evolved over the years, but it has always included components responsible for passive storage of various types of information and a superordinate component that controls the processing of information from these slave systems.

More than a decade after the first publication, Baddeley (1986) refined the description of the working memory model, assuming the separation of components passively storing verbal-phonological information from visual-spatial information. These are, respectively, the visuo-spatial sketchpad and the phonological loop (formerly known as: articulatory loop). Control over the stored information (mental representations) was exercised by the superior component, that is the central executive system, strongly related to attentional processes. The original version of Baddeley's (1986) working memory model, therefore, contained three components (Baddeley, 1986, 1996).

The fourth component was added several years later (Baddeley, 2000), in response to criticism of the model that highlighted an important gap. Namely, there was no explanation of how working memory connects with long-term memory to draw on the knowledge stored therein. The answer to this problem was the so-called episodic buffer, which stores semantic information and associations regardless of the information format. Integrating information from other systems (storing visual and auditory information) within the episodic buffer makes this component responsible for the temporary storage of coherent experiences.

J. Orzechowski (2012) believes that the main innovation that the scientific world owes to Baddeley is the insightful observation that the information storage function is necessary for the information processing function and that, therefore, both – although separate – should be designed into a coherent model of working memory.

3. The Phonological Loop

In the 1960s, a phenomenon was discovered that drew researchers' attention to the influence of similarity of sounds on their memorization. In 1964, Conrad and Hull described the so-called acoustic similarity effect, showing that if written words intended to be memorized contain letters that sound similar in pronunciation (their sounds rhyme), they are more difficult to remember than lists of words with letters whose sounds do not rhyme. This is probably because sound similarity makes it difficult to store sounds in working memory as separate units. Similar conclusions were drawn by Baddeley (1966) in a study of similar-sounding words. It turned out that they are more difficult to recall from memory than words with different sounds, but the opposite phenomenon is observed when the subjects have a chance to remember the meaning of the words and use the similarity of meaning when remembering them (Baddeley, 1966b). The idea of a system for temporarily storing phonological information, separate from long-term memory, was born, as Baddeley (2012) recalls, after collecting the results from the above-mentioned studies.

The phonological loop is a component that continuously stores small amounts of information heard, that is, related to speech and other sounds. According to Baddeley (2007), it evolved primarily to enable language learning (Baddeley et al., 1998). The phonological loop consists of two parts: the phonological store and the articulatory rehearsal mechanism (or verbal rehearsal mechanism). The phonological store passively stores acoustic memory traces for a short period of time. After approximately 2 seconds, memory traces decay. The articulatory rehearsal mechanism is the more active part of the loop because it prevents the disappearance of selected memory traces from the phonological store. It does this by mentally (i.e. silently; covert verbalisation) refreshing the stored sequence of sounds (words), as if reciting them in your mind. Any sound repeated in this way will fade out again unless it is refreshed again. In this way, the articulatory rehearsal mechanism increases the capacity of the phonological loop in working memory. Its second function, according to Baddeley (1986), is the conversion of visual information into speech (verbal recoding), which involves assigning verbal labels to visual information, e.g. a picture of a cat (or the word "CAT") may be given the verbal label "cat". This transformation from a visual to a verbal format makes it easier to remember visual information because its memory trace can then be maintained in a phonological loop (unlike the image of a cat, the sound of the word "cat" can be iterated in the mind by silently repeating it). Therefore, visual information can also enter the phonological loop, provided that an effort is made to label (recode) this information into the appropriate (phonological) format (Baddeley, 1986).

Research demonstrating the existence of an articulatory rehearsal mechanism led to the discovery of a phenomenon called the word length effect (Baddeley et al., 1975). Longer words (i.e. those containing more syllables) are more difficult to recall from memory than shorter words. This is probably because silently repeating longer words in your mind takes longer, so it is more difficult to prevent them from disappearing into the phonological loop (fewer such words can fit in 2 seconds). This short storage time of the phonological loop also explains why subjects who have a faster speaking rate (and therefore mentally repeat memorized objects faster) are able to recall more words from memory than people with a slower speaking rate. In fact, research shows that people remember as much as they can read in exactly 1.8 seconds (Baddeley et al., 1975).

Since the articulatory rehearsal mechanism complicates research (the researcher can never be sure whether and which subjects use silent repetition, bypassing the limitations of working memory capacity), a procedure has been developed to block it, and it is called the articulatory suppression technique. In this procedure, subjects are instructed to say aloud various unrelated words during the experiment (e.g., one two three, one two three... etc.). Such an additional task is simple enough not to burden working memory too much, but at the same time it occupies the resources of the articulatory loop mechanism to such an extent that it cannot be used to refresh the memory trace of the test stimuli (Baddeley et al., 1984; Murray, 1968).

4. The Visuo-spatial sketchpad

The inspiration for designing a separate component processing visual information (including spatial information) came from studies on the persistence of the memory trace of a point located on a line (Posner, Konick, 1966) or in space (Dale, 1973), which persisted for up to half a minute if it was not interrupted by a competing task. To test this phenomenon, while eliminating the possibility that the memory trace was supported by the phonological loop (by naming objects), Phillips and Baddeley (1971) measured the quality of memory recall on various (randomly half-filled) 5x5 matrices, showing a deterioration in performance as the seconds passed. The Phillips and Baddeley (1971) matrices, in a modified version, were interestingly used by Della Sala et al. (1999), who compared the results concerning their memorization with the results concerning the memorization of spatial stimuli in the classic clinical Corsi blocks test. It has been found that the level of performance on both tests differs in the same subjects and that the level of performance on spatial information tasks and visual information tasks deteriorates if subjects have to perform competing information processing tasks of the same nature (Baddeley, 2012; Della Sala et al., 1999).

In Baddeley and Hitch's (1974) model of working memory, the component that stores visual and spatial information is the visuo-spatial sketchpad (Baddeley, Hitch, 1974; Baddeley, 1986). Initially, Baddeley imagined this component as being homogeneous, but the research of his colleague Robert Logie, who was fascinated by the phenomena of visual imagery and mnemonics, convinced him to change his mind (Baddeley, 2012). Logie (1986, 1995) proved that it is worth distinguishing two mechanisms in the structure of the sketchbook: the visual cache and the inner scribe. The visual cache passively stores information about the appearance of objects (color, shape, pattern). The inner scribe, on the other hand, plays a more active role, being responsible for creating images and planning sequences of movements. Both mechanisms work together because the inner scribe uses information stored in the visual cache. Many subsequent studies, also involving brain neuroimaging, confirmed this distinct functioning of visual and spatial information in working memory (Klauer, Zhao, 2004; Smith, Jonides, 1997). Some researchers go even further, arguing that it would make sense to isolate a third mechanism responsible for storing kinesthetic information (e.g. body movements during dancing; Smyth, Pendleton, 1990), and Baddeley himself also points to the ambiguity of the status of tactile information in working memory (Baddeley, 2012).

The durability of memory traces in the sketchbook is low, but there are no consistent answers to the question of how long visuospatial information persists in working memory before it fades away. Researchers disagree on whether and how the sketchbook functions to refresh (repeat) information so as to prevent degradation of the memory trace. Logie (1995, 2011) attributes this ability to the inner scribe.

5. The Episodic Buffer

The episodic buffer was the last component added to the working memory model (Baddeley, 2000). Like the previous stores of visuospatial and phonological information, the episodic buffer stores information for a short time in order to perform the current task. Unlike the other two stores, however, the buffer does not specialize in one type of stored information. It is multimodal, meaning that the information it stores comes from different senses (e.g., the appearance of a room, the sounds of conversation, smells, gestures) and is linked together to create coherent representations of entire events (e.g., the situation of a romantic dinner). To achieve such integration, the buffer works closely with the parent component – the central executive system. (Baddeley, 2000).

There are three main channels through which information can enter the episodic buffer to create such complex and meaningfully coherent representations of events. The first are the components of working memory mentioned earlier: the visuo-spatial sketchpad and the phonological loop. The second is simply perception, that is, data delivered directly from the senses. The third source is long-term memory (Baddeley, 2007). Because of this third source, the episodic buffer is a bridge between the central executive system and long-term memory and supplements the information needed for the functioning of the sketchpad and loops. The buffer enables a mind to use previously accumulated knowledge to solve current tasks.

The episodic buffer is limited in capacity by the number of events (episodes) it can store simultaneously, with information that is highly related and consistent taking up less buffer resources. Working memory's access to long-term memory, provided by the episodic buffer, facilitates the chunking of remembered items, thereby bypassing the capacity limits of working memory. This is confirmed by the results of numerous studies, including those on: remembering meaningful vs. meaningless words (Hulme et al., 1991).

Interestingly, one of the followers of Baddeley's thought – Robert Logie – while retaining the idea of a multi-component model of working memory, proposes abandoning the episodic buffer, the function of which is to be fulfilled by interactions between the remaining components (Logie et al. 2021).

6. The Central Executive

The central executive (CE) system is Baddeley's (1986) idea to capture the most complex aspects of human cognition, which are the managerial processes controlling information processing in the mind. Initially, the modest and vague descriptions of this component attributed to it responsibility primarily for coordinating the remaining – slave components – storing visual and auditory information. In his 1986 publication, Baddeley provided the first detailed description of the central executive system, explicitly using Norman and Shallice's (1986) concept of the supervisory attentional system (SAS) as a prototype. Since then, the exploration of the main functions of this most complex component of working memory has been inextricably linked to attentional processes, the role of which in various situations is to properly select important information and inhibit unnecessary information.

Ultimately, Baddeley (1996) distinguished four functions of the central executive system. The first of them is focus of attention, which deteriorates with the complexity of the task performed by the subjects. The second involves divided attention (multitasking), tested in studies involving people suffering from Alzheimer's disease, who, compared to a group of healthy people, achieved worse results in dual-task performance. The third function of the central executive system examined using the tasks switching procedure is attentional shifting. Later, with the emergence of the episodic buffer as a third system storing information in working memory, the central executive system also gained a function that linked working memory to long-term memory, involving the retrieval of necessary information from long-term memory and its manipulation (Baddeley, 1996, 2000, 2007, 2012).

Baddeley's approach to executive functions is in opposition to neuropsychological approaches that attempt to understand them by examining the functions of the frontal lobes (np. Bor i in., 2003). Baddeley opposes this, warning against the risks of confusing neuroanatomical concepts with functional explanations of psychological phenomena. According to him, we should use the discoveries provided by clinical trials, but we should not define cognitive functions using brain structures (Baddeley, 1996). Baddeley's approach can be described as psychometric, that is, related to the study of individual differences, although different from traditional approaches of this type. Traditional psychometric approaches dealing with executive functions refer to the concept of intelligence and see the possibility of monitoring the work of executive processes (or the superior executive processor, which could correspond to the central executive system as part of working memory) in the measurement of intelligence. The emphasis on measurement, which is the essence of psychometric approaches, makes the type and compilation of test items measuring different sets of cognitive processes a key issue for this approach (see section: The Broader Context).

It remains an open debate whether the central executive system is (as Baddeley proposes) a homogeneous system with different functions that, like a homunculus – a metaphorical inhabitant of the mind – manages information temporarily stored in other subsystems (e.g. Attneave, 1961; Baddeley, 1998), or rather a bundle of various independent but cooperating control processes. Particularly noteworthy in this debate is contemporary research on executive functions, which is a construct that encompasses various types of distinct abilities: planning future actions, shifting attention, inhibition, updating information in working memory, generating new information, and monitoring the progress of goal achievement (e.g. Miyake et al., 2000).

The new version of the multicomponent model of working memory proposed by Logie, Belletier, and Doherty (2021) presents a different view of the nature of executive functions. These authors maintain the idea of components that temporarily store domain-specific information (with the exception of the episodic buffer), but they abandon the central executive system altogether. According to them, control processes are the result of the interactions of individual components performing their functions, so the central executive system is rather a property that emerges from numerous simultaneous interactions of subsystems storing and processing information (Logie, Belletier et al., 2021).

7. The Broader Contexts

The Baddeley and Hitch model of working memory, first described in 1974, has been used for decades both as a basis for scientific research on working memory and for research on individual differences in the diagnostic process (e.g. measurement of working memory in the intelligence scales). Meanwhile, in the 1990s, competing, homogeneous models of working memory began to emerge, challenging the central thesis of Baddeley and Hitch's (1974) model of multicomponent nature. The most popular homogeneous models are the activation models of Cowan (1998, 2001, 2017) and Oberauer (2002, 2011), which present working memory as an activated (by attentional processes) part of long-term memory and do not distinguish separate components of information storage.

The conflict regarding the homogeneity vs. multicomponent nature of the working memory system is reflected in diagnostic practice, especially at the stage of designing diagnostic tools. If human temporary memory is composed of multiple subsystems, then test tasks should be able to measure the performance of each of them separately. However, in healthy adults it is difficult to examine the separate components because they function in an integrated manner, giving the impression of a unified system. Logie, Belletier and Doherty (2021) note that when it comes to cognitive processes, there are no tasks that measure separate constructs. While performing test tasks, the subjects use the mental resources they consider necessary. The same is true for working memory – if it is composed of multiple components, it is difficult to check which component the person being tested is using to complete the task. The same participant may even use different resources in different trials within one test (e.g. shapes or colours on the screen may be stored in visual, verbal or semantic association form).

Since the revival of the concept of working memory by Baddeley and Hitch (1974), many different approaches to it have emerged, but at the same time researchers are publishing an increasing number of attempts to synthesize findings from different academic centers (e.g., Logie, Camos, et al., 2021; Oberauer et al., 2018). The challenges facing researchers integrating the vast knowledge accumulated over 50 years on working memory revolve around the following questions: (1) What is the relationship of the structure of working memory to attentional processes, control processes, long-term memory and consciousness? (2) What functions does working memory perform in the mind and what developmental changes are they subject to? (3) How to understand the limitations of working memory and, consequently, how to effectively study differences between people in this regard? And finally (4) can we say about the neurological and neuropsychological correlates of working memory. If the synthesis of half a century of data on working memory is fruitful, these promise to be interesting times for both researchers and diagnosticians of human cognition.

Bibliography

Anderson, J.R. (1996). ACT: A simple theory of complex cognition. *American Psychologist*, *51*(4), 355-365. https://doi.org/10.1037/0003-066X.51.4.355

Atkinson, R.C., Shiffrin, R.M. (1968). *Human Memory: A Proposed System and its Control Processes,* 89-195. https://doi.org/10.1016/S0079-7421(08)60422-3

Attneave, F. (1961). In defense of homunculi. (In:) W.A. Rosenblith (ed.), *Sensory. Communication,* 777-782. Wiley.

Baddeley, A.D. (1966a). Short-term Memory for Word Sequences as a Function of Acoustic, Semantic and Formal Similarity. *Quarterly Journal of Experimental Psychology*, *18*(4), 362-365. https://doi.org/10.1080/14640746608400055

Baddeley, A.D. (1966b). The Influence of Acoustic and Semantic Similarity on Long-term Memory for Word Sequences. *Quarterly Journal of Experimental Psychology*, *18*(4), 302-309. https://doi.org/10.1080/14640746608400047

Baddeley, A.D. (1986). *Working memory*. Oxford University Press.

Baddeley, A.D. (1996). Exploring the Central Executive. *The Quarterly Journal of Experimental Psychology Section A*, *49*(1), 5-28. https://doi.org/10.1080/713755608

Baddeley, A.D. (1998). The central executive: A concept and some misconceptions. *Journal of the International Neuropsychological Society*, *4*(5), 523-526. https://doi.org/10.1017/S135561779800513X

Baddeley, A.D. (2000). The episodic buffer: a new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417-423. https://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A.D. (2007). *Working Memory, Thought, and Action*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198528012.001.0001

Baddeley, A.D. (2012). Working Memory: Theories, Models, and Controversies. *Annual Review of Psychology*, *63*(1), 1-29. https://doi.org/10.1146/annurev-psych-120710-100422

Baddeley, A.D., Gathercole, S., Papagno, C. (1998). The phonological loop as a language learning device. *Psychological Review*, *105*(1), 158-173. https://doi.org/10.1037/0033-295X.105.1.158

Baddeley, A.D., Hitch, G. (1974). Working Memory. In *Psychology of Learning and Motivation*, 47-89. https://doi.org/10.1016/S0079-7421(08)60452-1

Baddeley, A.D., Lewis, V., Vallar, G. (1984). Exploring the Articulatory Loop. *The Quarterly Journal of Experimental Psychology Section A*, *36*(2), 233-252. https://doi.org/10.1080/14640748408402157

Baddeley, A.D., Thomson, N., Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior*, *14*(6), 575-589. https://doi.org/10.1016/S0022-5371(75)80045-4

Bor, D., Duncan, J., Wiseman, R.J., Owen, A.M. (2003). Encoding strategies dissociate prefrontal activity from working memory demand. *Neuron*, *37*(2), 361-367. https://doi.org/10.1016/S0896-6273(02)01171-6

Broadbent, D.E. (1958). *Perception and Communication*. Pergamon Press.

Conrad, R., Hull, A.J. (1964). Information, Acoustic Confusion And Memory Span. *British Journal of Psychology*, *55*(4), 429-432. https://doi.org/10.1111/j.2044-8295.1964.tb00928.x

Cowan, N. (1998). *Attention and Memory*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195119107.001.0001

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, *24*(1), 87-114. https://doi.org/10.1017/S0140525X01003922

Cowan, N. (2017). The many faces of working memory and short-term storage. *Psychonomic Bulletin Review*, *24*(4), 1158-1170. https://doi.org/10.3758/s13423-016-1191-6

Craik, F.I.M., Lockhart, R.S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, *11*(6), 671-684. https://doi.org/10.1016/S0022-5371(72)80001-X

Dale, H.C.A. (1973). Short-Term Memory For Visual Information. *British Journal of Psychology*, *64*(1), 1-8. https://doi.org/10.1111/j.2044-8295.1973.tb01320.x

Daneman, M., Carpenter, P.A. (1980). Individual differences in working memory and reading. *Journal of Verbal Learning and Verbal Behavior*, *19*(4), 450-466. https://doi.org/10.1016/S0022-5371(80)90312-6

Della Sala, S., Gray, C., Baddeley, A.D., Allamano, N., Wilson, L. (1999). Pattern span: a tool for unwelding visuo–spatial memory. *Neuropsychologia*, *37*(10), 1189-1199. https://doi.org/10.1016/S0028-3932(98)00159-6

Engle, R.W., Kane, M.J., Tuholski, S.W. (1999). Individual Differences in Working Memory Capacity and What They Tell Us About Controlled Attention, General Fluid Intelligence, and Functions of the Prefrontal Cortex. (In:) *Models of Working Memory*, 102-134. Cambridge University Press. https://doi.org/10.1017/CBO9781139174909.007

Ericsson, K.A., Kintsch, W. (1995). Long-term working memory. *Psychological Review*, *102*(2), 211-245. https://doi.org/10.1037/0033-295X.102.2.211

Hulme, C., Maughan, S., Brown, G.D. A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language*, *30*(6), 685-701. https://doi.org/10.1016/0749-596X(91)90032-F

James, W. (1890). *The Principles of Psychology:* Vol. I. Henry Holt and Company.

Klauer, K.C., Zhao, Z. (2004). Double Dissociations in Visual and Spatial Short-Term Memory. *Journal of Experimental Psychology: General*, *133*(3), 355-381. https://doi.org/10.1037/0096-3445.133.3.355

Locke, J. (1690/1955). *Rozważania dotyczące rozumu ludzkiego*. Warszawa: PWN.

Logie, R.H. (1986). Visuo-Spatial Processing in Working Memory. *The Quarterly Journal of Experimental Psychology Section A*, *38*(2), 229-247. https://doi.org/10.1080/14640748608401596

Logie, R.H. (1995). *Visuo-spatial working memory*. Lawrence Erlbaum Associates, Inc.

Logie, R.H., Belletier, C., Doherty, J.M. (2021). Integrating Theories of Working Memory. (In:) *Working Memory*, 389-430. Oxford University Press. https://doi.org/10.1093/oso/9780198842286.003.0014

Logie, R.H., Camos, V., Cowan, N. (2021). *Working Memory: The state of the science*. Oxford University Press.

Meyer, D.E., Kieras, D.E. (1997). A computational theory of executive cognitive processes and multiple-task performance: Part I. Basic mechanisms. *Psychological Review*, *104*(1), 3-65. https://doi.org/10.1037/0033-295X.104.1.3

Miller, G.A., Galanter, E., Pribram, K.H. (1960). *Plans and the structure of behavior.* Henry Holt and Co. https://doi.org/10.1037/10039-000

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*(1), 49-100. https://doi.org/10.1006/cogp.1999.0734

Murray, D.J. (1968). Articulation and acoustic confusability in short-term memory. *Journal of Experimental Psychology*, *78*(4, Pt.1), 679-684. https://doi.org/10.1037/h0026641

Newell, A. (1990). *Unified theories of cognition*. Harvard University Press.

Norman, D.A., Shallice, T. (1986). Attention to Action. In *Consciousness and Self-Regulation*, 1-18. Springer US. https://doi.org/10.1007/978-1-4757-0629-1_1

Oberauer, K. (2002). Access to Information in Working Memory: Exploring the Focus of Attention. *Journal of Experimental Psychology: Learning Memory and Cognition*, *28*(3), 411-421. https://doi.org/10.1037/0278-7393.28.3.411

Oberauer, K. (2019). Working Memory and Attention – A Conceptual Analysis and Review. *Journal of Cognition*, *April*, 1-23. https://doi.org/10.5334/joc.58

Oberauer, K., Lewandowsky, S., Awh, E., Brown, G.D. A., Conway, A., Cowan, N., Donkin, C., Farrell, S., Hitch, G.J., Hurlstone, M.J., Ma, W.J., Morey, C.C., Nee, D.E., Schweppe, J., Vergauwe, E., Ward, G. (2018). Benchmarks for Models of Short-Term and Working Memory. *Psychological Bulletin*, *144*(9), 885-958. https://doi.org/http://dx.doi.org/10.1037/bul0000153

Orzechowski, J. (2012). *Magiczna liczba jeden, czyli co jeszcze zmieści się w pamięci roboczej*. Wydawnictwo Uniwersytetu Jagiellońskiego.

Phillips, W.A., Baddeley, A.D. (1971). Reaction time and short-term visual memory. *Psychonomic Science*, *22*(2), 73-74. https://doi.org/10.3758/BF03332500

Posner, M.I., Konick, A.F. (1966). Short-term retention of visual and kinesthetic information. *Organizational Behavior and Human Performance*, *1*(1), 71-86. https://doi.org/10.1016/0030-5073(66)90006-7

Smith, E.E., Jonides, J. (1997). Working Memory: A View from Neuroimaging. *Cognitive Psychology*, *33*(1), 5-42. https://doi.org/10.1006/cogp.1997.0658

Smyth, M.M., Pendleton, L.R. (1990). Space and Movement in Working Memory. *The Quarterly Journal of Experimental Psychology Section A*, *42*(2), 291-304. https://doi.org/10.1080/14640749008401223