Chapter 21
Working Memory Capacity and Individual Differences in Higher-Level Cognition

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Introduction

Let's start with a riddle: what are the Authors referring to?

> "[It] *is one of the greatest accomplishments of the human mind; it makes possible planning, reasoning, problem solving, reading, and abstraction*." (Conway, Jarrold, Kane, Miyake, & Towse, 2007, p. 3)

> "*This concept* [of it] *and its limits is a key part of human condition.* [...] *We need* [it] *to in language comprehension,* [...]*; in arithmetic,* [...]*; in reasoning,* [...]*; and in most other types of cognitive tasks.*" (Cowan, 2005a, p. 2)

If it was not for the names of the authors of the above quotes, which no doubt for majority of readers indicate unambiguously the context of "it," one could think that they are referring to terms like consciousness, abstract thinking, or the *g* factor. It is even more interesting that these quotes come from first pages of multipage books, where – in accordance with the rule "from the general to the particular" – one gives basic information about one's subject matter. However, as Nęcka (in print) felicitously says in a paper concerning this concept: "[...] *for some 2,500 years of psychology as a branch of philosophy, and then for almost 100 years of its independent development* [...], *it was not considered necessary to use* [this] *term*." Thus, it is a concept of equal importance in psychology as consciousness, thinking, and intelligence, but much younger.

It is truly interesting that psychology could do without the concept of working memory (WM) for such a long time; today, it would be unthinkable. But the idea of working memory is not as new as it seems. The concept of working memory was used for the first time fourteen years before the seminal article by Baddeley and Hitch (1974), in perhaps equally famous work by Miller, Galanter, and Pribram (1960).

Working Memory

Working memory has been recently defined as a "*temporary storage system under attentional control that underpins our capacity for complex thought*" (Baddeley, 2007, p. 1), or as the "*ability to mentally maintain information in active and readily accessible state, while concurrently and selectively processing new information*" or – more simply – as the "*ability to simultaneously maintain*

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and process goal-relevant information" (Conway et al., 2007, p. 3). An analysis of various definitions of WM shows that the differences among them are quite fundamental. Even in the above quoted descriptions, there is no agreement whether WM is a system, or an ability, or perhaps a process. Moreover, there is a serious fear that "*working memory is not memory system in itself, but a system for attention to memory* […]" (Oberauer, Süß, Wilhelm, & Sander, 2007, p. 50). This fear comes from activation theories of WM (e.g., Cowan, 1988, 1995), where its function consists in making representations encoded in LTM available for intentional information processing. Diversity of WM definitions goes together with diversity of WM theories (see a review: Miyake & Shah, 1999). It seems, however, that WM researchers agree on at least several issues.

Firstly, almost everyone agrees that WM is a capacity-limited system,[1] although it is not clear how large this limitation is. Compared to the capacity of long-term memory, it is so huge, however, that WM capacity could be ignored in that context. But the problem is that if WM capacity was ignored by evolution, we would have probably lost our abilities to perform any complex cognitive tasks, or these abilities would have been seriously constrained. We can have some idea of possible effects of such omission from examining patients with frontal lobe pathology. These patients display deficits in execution of such tasks as Wisconsin Card Sorting test (Berman, Ostrem, Randolph, & Gold, 1995) or Tower of London test (Baker, Rogers, Owen, & Frith, 1996). These tasks are behavioral tests of frontal lobe damage, and at the same time are considered to be good measures of working memory, particularly of its executive functions.

So, WM is a system of a rather small capacity but of enormous importance for our minds. Unfortunately, WM researchers do not agree about the nature of the limitation of WM capacity. Initially, following the example of STM models, this limitation was understood more structurally as resulting from the capacity limitations within each of memory buffers (Baddeley & Hitch, 1974). At present, even Baddeley (2007) does not emphasize so strongly the structural separateness of WM subsystems. But only the activation theories allowed us to interpret the capacity limitations of WM in processual instead of structural terms, i.e., as the effect of individual differences in general executive abilities or attentional control (Conway & Engle, 1994; Engle, Kane, & Tuholski, 1999; Kyllonen & Christal, 1990). The factors limiting the amount of information that can be stored and processed in WM have been identified as the amount of available activation resources (Engle, Cantor, & Carullo, 1992), processing speed (Salthouse, 1996), resistance to interference (Oberauer et al., 2004), efficiency of inhibitory mechanism (Stoltzfus, Hasher, & Zacks, 1996), or time-related decay of information stored in working memory (Portrat, Barrouillet, & Camos, 2006). There are also some attempts to integrate the above (and other) mechanisms into one model. For instance, Barrouillet and his collaborators (Barrouillet, Bernardin, & Camos, 2004) define the capacity of WM in terms of the ability to allocate temporarily attentional resources to the pieces of information stored or being processed in WM. And thus, small capacity of WM is not resulting from any structural limitations but from the processual limitations of information processing speed with regard to allocating the limited resources. The more effective is the temporal allocation of resources; thanks to quick movement of focus of attention from one item to another, the more items are available for information processing. Another problem is the source of so radical limitation of WM capacity. But it is difficult to say whether this limitation results from the upper limit of nervous system capabilities (e.g., Miller, 1956), developmental limitations (Daneman & Merikle, 1996; Gathercole, Pickering, Ambridge, & Wearing, 2004), or optimal evolutionary adaptation to cope with particular problems (Elman, 1993; Mac Gregor, 1987).

[1] According to Cowan (2007), however, this is not a universal assumption. There are theories that do not share this view. As examples, one can point to the long-term working memory theory by Ericsson and Kintsh (1995), and to the theory of task conflict by Meyer and Kieras (1997a, 1997b).

Secondly, vast majority of WM models incorporate a control mechanism, usually an attentional one. But unfortunately, there is no agreement about a detailed list of control processes carried out by WM control system. Miyake and Shah (1999; see also Miyake et al., 2000), having analyzed research results and various theories of WM, distinguished three basic control functions of WM, i.e., inhibition, task-switching, and updating the content of working memory. However, the updating function does not correlate with other control functions; therefore, Oberauer (Oberauer et al., 2007) suggests that it should be excluded from the list, at least until new cognitive tasks are elaborated, because the existing tasks for updating (e.g., n-back task) engage simultaneously storage and processing, and that is why they are measures rather of capacity than pure updating. Moreover, accepted measures of cognitive control, such as switching of task-set, seem to be unrelated to WM capacity (Oberauer, Süß, Wilhelm, & Wittman, 2003), which shows immaturity of the concept of executive functions in WM models, because one can hardly expect functions of a single cognitive system not to be related to one another. Oberauer et al. (2003) named three a little bit different than Miyake and Shah executive functions: simultaneous storage and processing, supervision, and coordination. The first of these functions consists in simultaneous and short-term retention of information available in a given moment and in transformation or derivation of new information. The second function – supervision – involves continuous monitoring of current cognitive processes, in selective activation of representation and in suppression of irrelevant information in a given moment. And the third function – coordination – consists in integrating active elements in working memory into larger structures. Other researchers are inclined to assume the existence of many, sometimes very detailed, control functions (see Friedman & Miyake, 2004); so we do not have an unambiguous platform to analyze control functions.

Another problem concerning cognitive control within working memory is that behind this seemingly modern concept lies the problem of homunculus (see Conway et al., 2007; Miyake & Shah, 1999). All versions of the central executive, which is responsible for control (planning, monitoring) of processes going on in WM, seem to be burdened with a tacit assumption that there is “someone” in our mind, who is performing this control. WM researchers put a lot of effort trying to solve this problem; for instance, they treat this control as a property of a self-contained dynamic interactive network (Munakata, Morton, & O’Reilly, 2007). At this moment, however, the problem cannot be regarded as having been satisfactorily solved. There is also a purely theoretical problem of the relation between memory and attention, which eventually should be cleared, because at present the boundaries between the two concepts seem to be unclear. And it definitely should be resolved, because data gathered in research conducted with the use of neuroimagining technique seem to show that execution of some tasks for spatial memory and spatial attention engages the same parts of brain (Corbetta, Kincade, & Shulman, 2002). There are strong arguments that it is not a random coincidence, but there exists a common neural mechanism (see Awh, Vogel, & Oh, 2006). Perhaps, we will have to abandon one of these concepts, at least in the context of processes investigated by WM researchers. It is also important what is being controlled, because these are not only processes related to the short-term maintenance of data. The latter are important but only in the context of goal-directed processing. Many researchers (see Oberauer et al., 2007) clearly emphasize the distinction between primary cognitive processes, performed on representations currently stored in memory subsystems (e.g., Baddeley) or encompassed by the focus of attention (e.g., Cowan, Engle, McErlee, & Oberauer), and executive processes aiming to initiate and monitor the correctness of primary processes in the context of an overarching goal.

Thirdly, researchers seem to agree that working memory plays a key role for effective performance of higher-level cognition processes, such as reasoning, problem solving, decision making, and – more generally – abstract thinking. A list of issues that WM researchers could agree on is certainly longer, but the other issues would certainly be more difficult to agree on.

Despite the key and superior role of cognitive control for WM effectiveness and increasing interest in the relation between control functions and intelligence, the results of many studies show that working memory capacity (WMC) is the best single predictor of reasoning ability (Kyllonen & Christal, 1990; Süß, Oberauer, Wittmann, Wilhelm, & Schulze, 2002) and of – related to it – general fluid intelligence (Ackerman, Beier, & Boyle, 2002; Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Engle, Tuholski, Laughlin, & Conway, 1999). While the control mechanisms attributed to WM seem to be highly hypothetical, and their list is still under construction, the capacity of WM refers to the observable limitation of temporary storing and processing information. And although the foundation of this limitation is at least equally hypothetical as the control functions, this limitation is a fact.

This chapter contains a short review of the most recent hypotheses, research results, and theoretical discussions concerning the relation between WMC and higher-level cognition. The fundamental question posed by the researchers dealing with the subject is not whether this relation exists but what underpins it and how it extends our knowledge of both working memory and higher cognitive processes. The chapter deals mainly with one but an extensive area of research namely reasoning, both deductive and inductive. The data in this area come not just from papers dealing strictly with reasoning but also from research focused on fluid intelligence or fluid abilities, which are usually tested with the use of induction reasoning tasks.

Measurement of Working Memory Capacity

Group of memory span tasks are used to determine individual WM capacity by establishing its maximal load (see Conway et al., 2006). This kind of tasks was initially designed to determine the capacity of short-term memory (*simple span task*) or the general efficiency of information processing (*complex span task*). In studies dealing with working memory, these procedures were adapted and the subjects were required not only to store information but also to perform operations on the stored material. The most popular varieties of this task include reading span (Daneman & Carpenter, 1980), operation span (Turner & Engle, 1989), counting span (Case, Kurland, & Goldberg, 1982), verbal/math span task (Oberauer et al., 2003), and so on. For example, in the reading span task, subjects read aloud displayed sentences and at the same time they are asked to remember the last word from each sentence, and researchers can manipulate the number of displayed sentences and so the number of words to remember. A memory test is carried out after displaying several (usually 2–6) sentences. Sometimes, the subjects are additionally asked to verify the truth of each sentence after it has been presented (Turner & Engle, 1989) or to complete displayed sentences (e.g., George is clapping his …) and to remember the answers (Towse, Hitch, & Hutton, 2000). This forces them to simultaneously execute two tasks: processing the content of the sentence and remembering words. Other span tasks preserve the idea of a dual task but use another type of stimulus material. Subjects verify correctness of mathematical equations and simultaneously are trying to remember displayed words (operation span); they count a certain kind of stimuli, e.g., red circles displayed among other geometrical figures, and are asked to remember their sum total (counting span); or they are asked to remember words or numbers displayed between tests, which require making simple decisions (verbal/math span). The number and variety of such tasks, however, is much greater.

Apart from dual tasks, in the studies of WM functions, one uses also certain measures of working memory efficiency, which do not require subjects to store and process information simultaneously. As examples of this kind of tasks, one can distinguish n-back task (Gray, Chabris, & Braver, 2003) and running memory task (Mayes, 1988). The former requires subjects to detect a repetition in a series of stimuli (usually digits or letters) on exactly n-th (e.g., the third) position from the end of the series. The n-back task not only requires subjects to maintain in memory a set of presented stimuli but also requires them to update this set constantly. On the other hand, running memory task consists in presenting subjects with random-length strings of stimuli. The subjects are asked to recall the last several stimuli or state if a target appeared among the last several stimuli. Because the subjects cannot predict when the series will end, the task requires them to update actively their working memory, removing from it stimuli presented several steps back (and so no longer needed).

What is interesting is that recent studies show that the relation between WM and STM tasks is stronger and more complex than it was initially thought to be (see Colom, Abad, Rebollo, & Shih, 2005a). For instance, storing information in tasks requiring subjects to remember spatial information (e.g., layout of dots) or to recall nonspatial information according to some spatial rule (e.g., digits placed in particular way in a certain matrix) significantly engages control processes of working memory. Therefore, such tasks turn out to be good tests of working memory and highly correlate with other, more standard measures of WM, even if they do not include a secondary task (Oberauer, 2005). Even some verbal tasks, provided that silent repetition is limited and chunking pieces of information is obstructed or controlled, appear to be an accurate test of WM (Cowan et al., 2005).

Higher-Level Cognition

Higher-level cognitive processes can be understood as "*information processing phenomena in which the meta-cognitive factors of monitoring and control play a fundamental role*" (Nęcka & Orzechowski, 2005, p. 122). This term seems to be synonymous with complex cognition. It appears, however, that referring to meta-cognitive factors is not sufficiently distinctive, when we want to differentiate between low- and high-level cognition. The factors that could (individually or collectively) help to distinguish between them are: (1) number and/or complexity of mental models that represent a task, (2) number of factors influencing cognitive performance, (3) number of variables used to manipulate with the task's structure, and (4) time needed to complete a certain task (Nęcka & Orzechowski, 2005). Certainly, this list is not complete, and even if it was, the boundary between low and high level cognition would still be unclear, unless it was established arbitrarily. However, in psychology, it has become customary to classify phenomenon like reasoning, problem solving, and decision making as examples of higher-level cognition.

The most numerous and – it seems – most advanced studies are those focusing on the relation between WMC and individual differences in reasoning. Researchers were interested in these relations because they wanted to understand mechanisms of reasoning or intelligence. In Western culture, intelligence is sometimes defined (e.g., Terman) and operationalized as an ability to cope with problems that require abstract thinking. The most popular test of fluid intelligence: the Raven Progressive Matrices (Raven, Court, & Raven, 1983) comes down to the use of tasks requiring inductive reasoning on abstract material. Studies of reasoning by analogy (especially on nonverbal material) are also a source of interesting findings on the relations between WMC and individual differences as far as the effectiveness of inductive reasoning is concerned.

A separate and relatively new source of knowledge on the relation between WMC and higher-level cognition is provided by teams of researchers focusing on reasoning. Their work is valuable, because it supplements our understanding relations between working memory and those kinds of reasoning, which are rarely or never used in intelligence tests, e.g., syllogistic or conditional reasoning. Slightly smaller, but still substantial number of studies deals with the relations between WMC and problem solving as well as decision making. It is not surprising that results of such studies usually show positive correlations. That is why WM researchers are currently not so much interested if there is any relation between WMC and higher-level cognition, as in the mechanism of this relation. They also want to know how learning about this mechanism can enrich our knowledge about working memory and about the analyzed aspects of human complex cognition.

On the other hand, it does not mean that the relation between WMC and higher-level cognition is obvious and completely predictable. Kareev (1995) showed, for instance, that individual differences in working memory capacity are related to the ability to detect correlations. It turned out that subjects with smaller working memory capacity had advantage in the task that required them to detect correlations between two variables. Probably, smaller WM capacity favors simplification and seeing regularities, and that allows for more accurate assessment of the strength of correlation. From this and several similar studies, one can draw a conclusion that bigger working memory capacity does not always lead to greater effectiveness in performing complex cognitive tasks (Hertwig & Todd, 2003). But it is rather an exception than a rule.

Working Memory Capacity and Deductive Reasoning

Reasoning is the process of drawing conclusions from premises. Deductive reasoning consists in drawing conclusions from premises using formal rules of logic. Psychologists are interested in deductive reasoning because – at least at the beginning – research results clearly showed that thinking of formal logic, uneducated people differ from predictions of a normative theory, which most often encompasses basic laws of logic and principles of probability theory (see Evans, 2002). It turned out that, on the one hand, we make systematic logical errors, specific for various inference schemata; but on the other hand, the number of these errors is smaller if the content of deductive tasks is closer to everyday experience or individual competences (see Cosmides & Tooby, 1994; Griggs & Cox, 1982; Tooby & Cosmides, 1990). In all significant theories of deductive reasoning, i.e., the abstract-rule theory (1994b; Braine, Reiser, & Rumain, 1984, Rips, 1994a) and the mental models theory (Johnson-Laird, 1983, 1994; Johnson-Laird & Byrne, 1991), reasoning requires essential involvement of working memory, and the more difficult the task is, the higher this involvement must be. At this level of abstraction, predictions of both theories concerning working memory load do not differ substantially. The rule theory assumes however that reasoning consists in constructing "mental proofs," which connect premises and conclusions. Thus, the more mental steps must be made, the bigger is the working memory load, and consequently – the bigger probability of making errors. On the other hand, in the mental models theory, reasoning consists in creating mental simulations (models) in accordance with the data contained in the premises. The more complex representation of a problem situation is, the larger number of mental models must be created and/or the more complex are these models; consequently – the bigger are requirements for working memory and the greater is risk of error. These general predictions have been confirmed many times, and the researchers found positive correlations between WMC and the performance of the tasks requiring syllogistic reasoning (Kyllonen & Christal, 1990) as well as of the tasks requiring conditional reasoning (Barrouillet & Lecas, 1999; Toms, Morris, & Ward, 1993).

Research on the relation between WM and reasoning, conducted in recent years, has gone in various directions. Generally speaking, studies of the relation between reasoning and WM take into account various forms of reasoning and content of logical tasks as well as various WM functions. Thus, these studies deal with syllogistic and conditional reasoning as two basic kinds of reasoning (but also with e.g., conjunction, alternative) and the content of tasks understood in two ways: abstract vs. concrete, and verbal vs. spatial. Often, more and more WM researchers refer to particular functions of WM, using predictions about their relations with reasoning, especially those that differentiate the rule-theory and the mental models theory. Most often one can see references to Baddeley's multicomponential working memory model, but – mainly due to the research by Oberauer team – one can also find in the literature some attempts to combine particular executive functions with the effectiveness of reasoning.

Klauer, Stegmaier, and Meiser (1997) attempted to combine the effectiveness of particular WM structures, as understood by Baddeley, with certain tasks that required reasoning on nonimaginary content (propositions) and imagery content (spatial relations). The researchers used the dual task paradigm, selectively loading WM subsystems: phonological loop or visuospatial sketch-pad. They assumed that solving tasks that require spatial reasoning as well as simultaneous monitoring of the movement of figures on a computer screen will decrease the accuracy of conclusions. This follows from the involvement of the sketch-pad in both concurrent tasks. Similarly, if subjects are asked to perform a task on propositional content, and simultaneously they must repeat certain figures, the phonological loop will be involved in both tasks, and this will decrease accuracy of conclusions. The results only partly confirmed the above predictions: a decrease of conclusion accuracy was significantly higher in spatial tasks no matter what the kind of the secondary task was. A similar logic was used to verify executive functions involvement in reasoning. Again, the researchers used tasks that required reasoning on spatial material and in the form of propositions. But this time, the secondary task consisted in the procedure of random number generation. It turned out that the load of central executive has an influence on the correctness of conclusions drawn in both kinds of tasks requiring reasoning. Thus, the spatial tasks require bigger involvement of both WM subsystems than verbal tasks, but both kinds of tasks equally load the central executive.

There were many attempts to use the differences in predictions concerning WM involvement which follow from the abstract rule theory and the mental models theory, in order to resolve the dispute between supporters of both these theories. One such attempt was made by Garcia-Madruga and his collaborators (García-Madruga, Moreno, Carriedo, Gutiérrez, & Johnson-Laird, 2001). In their research, they used tasks containing conjunctions and alternatives.

It follows from the rule theory that both situations are comparable with respect to the number of rules that should be applied as well as to the number of mental steps that should be taken in order to solve the task correctly. Thus, there should be no differences in WM load in both conditions. Different predictions follow from the mental models theory. A conjunction is represented with the use of one mental model, while an alternative needs two or even three mental models. Thus, the working memory load will be different in these two conditions: it will be higher for an alternative than it is for a conjunction. Garcia-Madruga (García-Madruga et al., 2001) obtained results, which confirmed predictions coming from the mental models theory, but only when subjects were asked to draw conclusions themselves (in contrast to the condition in which they were asked to judge if a given conclusion is correct). On the other hand, Rips (2004a, 2004b) obtained results, which confirmed the predictions of the rule theory, when subjects were asked to judge the correctness of conclusions presented to them.

Markovits, Doyon, and Simoneau (2002) verified predictions of the mental models theory, based on a detailed analysis of relations between reasoning and individual differences in visual and verbal working memory. In the abstract rules theory, there is practically no need to refer to visual working memory (i.e., to involve visuospatial sketch-pad), even if a task's content is imaginary-spatial. Premises of the task are first of all translated into the abstract language of propositions. Further processing of these premises, requiring application of logical rules takes place only with the participation of verbal working memory (i.e., it involves phonological loop). Thus, the researchers assumed that it follows from the rule theory that the performance of the tasks requiring reasoning should correlate positively with the capacity of verbal working memory. Such correlation is not predicted in the case of visual working memory. The kind of material – abstract or concrete – does not matter for the load of various kinds of working memory, because in both cases the researchers used unified, prescriptive representations. On the other hand, the mental models theory assumes that there is a close relation between spatial abilities and reasoning (Johnson-Laird, 1983), as long as a quasi-analogue representation of a problem situation concerns a concrete material. Thus, in sentences with concrete content, there should be a positive relation between the effectiveness of reasoning and the capacity of visuospatial working memory. A similar relation would not take place in the case of tasks with abstract content. On the other hand, the capacity of verbal working memory would be important in the case of both concrete and abstract tasks, due to the semantic nature of inference processes. Markovits et al. (2002) used an approach quite common in the psychology of individual differences (and rare in the research on reasoning). First, they studied visual and verbal memory systems, testing individual efficiency of these systems, and then, they carried out a series of tasks requiring conditional reasoning based on concrete and abstract material. The results showed that in concrete tasks, the effectiveness depends on the capacity of both the phonological loop and the visuospatial sketch-pad, whereas in abstract tasks – it depends only on the capacity of phonological loop. Moreover, the researchers quote "hard" data from studies conducted with the use of a neuroimagining technique (fMRI), indicating that various brain structures are involved during reasoning on abstract and concrete material (e.g., Goel, Buchel, Frith, & Dolan, 2000), which seems to falsify the abstract rule theory, if one accepts the assumptions explained by the researchers.

Another interesting problem is the question what is domain-general and what is domain-specific in the involvement of working memory in various forms of reasoning. For instance, Capon, Handley, and Dennis (2003) analyzed the relation between particular components of working memory and the spatial and syllogistic reasoning. They tried to examine to what extent the performance of various tasks measuring WMC is related to the correctness of these two types of reasoning. They used simple and complex verbal and spatial WM measures (all in the form of WM span tasks). The obtained results indicate that both the effectiveness of reasoning in spatial tasks and in syllogisms is related to the capacity of visual working memory and the capacity of verbal working memory. The researchers manipulated the way the syllogisms and spatial tasks were presented. In both cases, the presentation was both verbal and visual. In the case of spatial tasks, a visual presentation of the task reduced the load of both WM subsystems, whereas the verbal presentation caused the involvement of both these subsystems. In the case of syllogisms, the form of presentation did not differentiate the level of involvement of both these subsystems, which was high in both the conditions of verbal and visual presentation. Thus, it seems that a visual presentation of a spatial task reduces the general WM load of the task rather than the load within a specific modality. In the case of syllogisms – the form of presentation does not seem to change the involvement of the general mechanism of WM. The researchers carried out a factor analysis and it confirmed the participation of central executive (general factor) in both types of reasoning.

The presented results seem to indicate – although it may be a somewhat premature conclusion – that the participation of WM subsystems differs depending on the type of reasoning and the material used. Thus, it seems that it is rather a domain-specific factor. However, in each of these cases, one can regularly detect the central executive involvement in reasoning, and it is a domain-general factor. This is, at least, the case in adults. On the other hand, studies of development of conditional reasoning conducted on children subjects by Barrouillet and Lecas (1998, 1999) seem to indicate a greater influence of WM capacity on the correctness of inference. It turned out that the differences between age groups of 8-year-olds, 11-year-olds, and 14-year-olds consists in the number of mental models constructed during conditional reasoning. In the youngest group, children used only one model of a given situation – the one which was directly described in the task (e.g., in the implication: "If you put on a white shirt, then you must put on green trousers" they did not consider other variants, i.e., what will be with the trousers, if they do not put on the white shirt, or what will be with the white shirt, if they do not put on green trousers). The researchers noticed that 11-year-olds used two models of the situation, and that 14-year-olds used three such models. The partial correlation between WMC and the correctness of inference (with the children's age controlled) was $r=0.65$. And when the children were divided into three groups according to the WM capacity, it turned out that in the group with the smallest WMC no one took into account all three models, while in the group with a middle WMC – 24% of the children used three models, and in the group with the greatest WMC as many as 67% did so.

The research on the relation between executive functions of WM and reasoning was undertaken by Oberauer and his collaborators (Oberauer et al., 2003). Oberauer attributes also a key role in reasoning to WMC, understood as the "*ability to provide direct access to several independent information elements (chunks) at the same time*" (Oberauer et al., 2007, p. 52). In reasoning, this ability is necessary for creating new relations between many elements representing a logical task, in order to integrate them into a new structural representation. The researchers assume that all kinds of tasks that require reasoning have a common property – construction of a new structural representation is needed in order to solve them. This kind of task involves all three functions distinguished by Oberauer, but it seems that the biggest role is played by derivation and coordination (Oberauer et al., 2003). However, the complexity of this new structural representation is limited by WM capacity. According to Oberauer, the so-called direct access area is of particular importance, because its capacity limits the number of elements, which can be simultaneously placed in the common cognitive coordination system. Thus, it limits the number of elements that can be taken into account in the process of integration and construction of a new structural representation. Oberauer et al. (2007) analyzed many different tasks that require deductive reasoning (syllogism, implications), inductive reasoning (series completion, matrices, analogies), as well as problem-solving tasks that require relational integration. They also presented evidence supporting the claim that there is a relation between the performance of these kinds of tasks and WMC. For instance, meta-analysis of own results (Süß et al., 2002) showed that the aggregated WMC factor (the means of *z*-transformed scores of all working memory measures) correlates with deductive reasoning (a reasoning factor from the Berlin Intelligence Structure Model) at the level of $r = 0.76–0.77$, and with inductive reasoning (general intelligence factor) at the level of $r = 0.69–0.82$. This means, according to Oberauer, that both constructs, i.e., working memory and reasoning are strongly related, but not the same. Oberauer concludes: "*Reasoning is, after all, a little bit more than working memory*" (Oberauer et al., 2007, p. 69). What makes the difference between them? A natural candidate would be the process of abstraction, present in vast majority of complex cognitive tasks, and this seems to be supported by research, including research using the techniques of neuroimagining (e.g., Green, Fugelsang, Kraemer, Shamosh, & Dunbar, 2006).

Independent experimental data that can partly support Oberauer's notion were presented by Buchner, Krumm, and Pick (2005). It turned out that two out of three control functions distinguished by Oberauer correlate with the accuracy of reasoning, namely: the storage and processing of information and the coordination. As an indicator of the accuracy of reasoning, the researchers used the score of an intelligence test; thus, one can assume that these data concern the effectiveness of inductive reasoning (analogy, similarity). Other results supporting Oberauer's notion were obtained by De Neys, Schaeken, and d'Ydewalle (2005), with regard to the process of constructing counter-examples, and by Vandierendonck, Dierckx, and De Vooghta (2004), with regard to a linear and relational syllogisms.

Working Memory Capacity and Inductive Reasoning

Inductive reasoning consists in deriving new claims or hypotheses from a finite number of cases, e.g., from observations. An analysis of particular premises leads – through induction – to detection and formulation of general regularities, expressed in a general statement. So the essence of inductive reasoning is making not fully justified generalizations, because they are derived from a limited number of observations. There is always a probability that the conclusion drawn on the basis of induction is wrong. On the other hand, induction is a way of inference which, as Holyoak and Nisbett (1988) put it, extends our knowledge in the face of uncertainty. Because most problems in real life are of inductive rather than deductive nature, tests of fluid intelligence (but not necessarily tests of crystallized intelligence) use inductive tasks, and in nonverbal form. For instance, in the Raven Progressive Matrices Test, subjects are required to find a relational rule, which governs the arrangement of simple graphic elements, and then to complete a missing element in each matrix. In this sense, it is a task requiring the subjects to perform analogical mapping. Other tests of fluid intelligence (e.g., Berlin Intelligence Structure Model) also use inductive tasks and require subjects to make mental transformations, which are an aspect of relational integration (see Oberauer et al., 2007). Because there are not many studies concerning the relation between WMC and other forms of inductive thinking, this section of the chapter will refer to data obtained in the research on fluid intelligence.

Like the research on the relations between WM and deductive reasoning, this research has also gone in various directions. It seems that the least interesting are studies aiming to find out the percentage of common variance between WMC and fluid intelligence (inductive reasoning, Gf – general fluid). The results of these studies, conducted with the use of a battery of WM and Gf tests, are inconclusive, although they unambiguously indicate that there is a relation between these two constructs. For example, Ackerman, Beier, and Boyle (2005) found in their meta-analysis of 86 studies conducted with the use of short-term or working memory tests as well as aptitude tests that the average strength of correlation between working memory and the *g* factor is relatively weak ($r=0.364$; $r=0.479$ after corrections adjusting to low reliability of methods). The authors questioned the thesis about vital influence of working memory on intellectual abilities, and suggested that the correlation of both measures results indirectly from the statistical nature of the *g* factor. Since it is assumed that the *g* factor fills to a certain extent all cognitive functions, then it manifests itself also in the effectiveness of executing tests of working memory. Meanwhile, Oberauer, Schulze, Wilhelm, and Süß (2005), when they assessed the strength of correlation between indices of WM efficiency and the level of IQ, found the correlation to be $r=0.85$ and presumed that WM efficiency is the most crucial predictor of intelligence, explaining 75% of its variance. The authors questioned some assumptions on which Ackerman et al. (2005) had based their meta-analysis. They suggested that this meta-analysis showed too low a correlation, because it had included some studies with inaccurate methods of measuring working memory and had not taken into account results acquired with Structural Equations Models.

Much more interesting are the attempts to establish a relation between working memory and fluid intelligence level. These studies also have their own special character. On the one hand, the researchers are, by and large, not interested in the variety of inductive reasoning forms (probably due to the fact that Gf test have very good psychometric parameters, which are practically in itself latent measures of fluid intelligence), unlike the researchers of deductive reasoning. On the other hand, various aspects of WM are examined far more thoroughly and operationalized in all possible varieties of STM and WM span tasks.

Currently, in studies of intelligence, the prevailing research methodology is Structural Equations Modelling. It consists in using at least two measurements (in practice there may be far more) of a given latent variable. This allows to reduce the variance of error and to extract from the measurement relatively pure measures of the examined constructs. However, this tool must be used carefully because in case of excessive aggregation of measured variables, one can obtain correlations close to one between the latent variables (e.g., Colom, Rebollo, Palacios, Juan-Espinosa, & Kyllonen, 2004; Kyllonen & Christal, 1990). The problem is that in some measures of intelligence, there are tasks that, to some extent, are loaded with the working memory factor, just like in some measures of WM, e.g., in complex span tasks, one can identify a load of fluid intelligence (inductive reasoning). Thus, it is not surprising to find such strong correlations between the latent measures of both constructs.

The basic problem concerning the relations between fluid abilities and WMC is participation of particular subsystems (verbal vs. spatial abilities) or executive functions in – as it is hypothetically assumed – determining individual differences with regard to inductive reasoning. One of the first such attempts was made by Shah and Miyake (1996) who wanted to find out whether the relation between WMC and Gf comes from general efficiency of working memory, or – on the contrary – whether the capacity of specific subsystems (verbal and visuospatial) is related to inductive reasoning on verbal and visuospatial material. The researchers used verbal and spatial memory tasks as well as verbal and spatial measures of intelligence. The result in a verbal span task was correlated

($r = 0.45$) with the score in a verbal aptitude test, but it did not correlate significantly with the score in a spatial ability test. On the other hand, the result of a spatial span task was correlated with spatial abilities ($r = 0.66$), but the researchers did not find a significant correlations with verbal abilities. Thus, it turned out that the relations between WMC and intellectual abilities are domain specific. Shah and Miyake checked also whether this specific relation between WMC and intellectual abilities is due to the memory aspect (type of material that was to remember) or the processing aspect (dual task) of working memory. It turned out that the result of a spatial task strongly correlated with spatial abilities, no matter if it was performed with a verbal or spatial secondary task. The result of a verbal span task strongly correlated with verbal abilities and also with both versions of the secondary task. Hence, it seems that it was the type of material used in a given task, and not the kind of operation, that was the cause of the observed relation.

Other logic was used by Engle et al. (1999). The researchers used two batteries of tasks, which tested separately functions of working memory and short-term memory. In the case of tasks that tested WM functions, they simultaneously measured storage of information and executive functions, whereas in the tasks for STM – they measured only the storage of information. Interestingly, it turned out that the latent measures of STM and WM are quite strongly correlated ($r = 0.7$). However, after removing the common variance of both memory measures, it turned out that WMC significantly influenced the level of fluid intelligence, whereas the capacity of STM was not significantly related to Gf. Thus, the researchers assumed that the relation between working memory and Gf is due to the executive functions and not to the processes of information storage. Moreover, this relation was not modality-specific (verbal or spatial), because it appeared between a verbal measure of WM and a score in a reasoning test on figurative material. Similarly results obtained Conway, Cowan, Bunting, Therriault, and Minkoff (2002). They found a statistically significant correlation between verbal working memory and Gf measured by nonverbal tests ($r = 0.60$), but correlations between Gf and indicators of STM capacity and processing speed turned out to be statistically insignificant.

The research quoted above does not answer the question what is the cause and what is the effect in the relation between working memory and fluid abilities. Even if we assume that the efficiency of working memory determines the ability to reason and solve problems, one should ask why this is the case. What properties of working memory decide that people perform the above mentioned mental activities more or less efficiently? If the relation between WM and general intelligence is due to a certain specific property of working memory, then what is this property? It seems that a natural candidate would be WMC that determines how many separate items a person is able to process simultaneously (Kane, Hambrick, & Conway, 2005; Süß et al., 2002). However, Cowan (2005b) in his adjustable-attention hypothesis assumes that it is the capacity of the focus of attention that is of key importance for the relation with intelligence. The focus of attention can include only one item – e.g., a goal representation under conditions of strong distraction and interference – but it can also actively encompass more, from 3 to 5 items. The researcher argues that the tasks requiring subjects to store and process information simultaneously are good predictors of intelligence (reasoning), because the secondary task prevents the subjects from chunking remembered pieces of information together or from repeating the pieces of information in the phonological loop. That is why these tasks measure accurately the capacity or scope of the focus of attention, without additional influence coming from automatic and more passive memory stores (i.e., the phonological loop). According to Cowan, the more items are included in the focus of attention, the more complex relations a person can discover among them, and the higher is his or her ability to perform abstract reasoning. In this respect, Cowan's view coincides with above described Oberauer's position, and, additionally, it confirms Oberauer's thesis about homogeneity of various forms of reasoning.

The nature of determination mentioned above is very interestingly explained by a model of relational reasoning (Halford, Wilson, & Phillips, 1998), which assumes that the greater the capacity of focus of attention, the more the dimensions of a relation (i.e., variables for a given predicate) that can be processed simultaneously. After all, finding hidden and – in most cases – multidimensional relations is a fundamental task in tests of reasoning and fluid intelligence.

Engle and his collaborators (e.g., Heitz, Unsworth, & Engle, 2005) suggest another explanation of the strong relation between working memory and Gf. Engle believes that the efficient control of attention determines how well a person is performing both memory tasks and aptitude tests. The key thing is to manage the content of the focus of attention in a way that activates pieces of information relevant for the current mental activity, especially under conditions of strong interference and conflict between competitive stimuli and processes, and which inhibits currently irrelevant pieces of information.

Unsworth and Engle (2005) carried out the analysis of the Raven Progressive Matrices Test focusing on the load imposed on working memory by each test item. The load was estimated on the basis of three independent indicators: a level of difficulty of each item, a number of rules needed to take into account to give a correct answer, and the kind of these rules. The results showed that the strength of relation between the efficiency of WM (measured by an operation span task) and the number of correctly solved test items in each of quartiles divided according to memory-consuming of particular items was similar. If the memory capacity was responsible for the correlation between the efficiency of WM and Gf, this correlation should increase in those parts of the test that have higher working memory demands, because mainly in these cases, persons with large memory capacity could reveal their advantage. Absence of this effect suggests, according to the researchers, that perhaps not the WMC but the control of attention is responsible for the relation between working memory and Gf, which is understood in terms of individual differences in efficiency of inductive reasoning.

Conclusions

Studies of relations between working memory and different kinds of reasoning are now at various points and stages. This is due to various research traditions, which imperfectly communicate with one another. It is visible even in the above review, which focused on deductive and inductive reasoning. Recently, however, there have been some attempts to identify a common mechanism of these kinds of reasoning. For instance, Oberauer suggests a relational integration mechanism, which is a "*parameter of cognitive system that affects a large number of different tasks, thereby explaining the common variance of many experimental working memory tasks, reasoning tasks from intelligence tests, and potentially complex cognitive achievements in everyday life*" (Oberauer et al. 2007, p. 52). Such attempts are not made for the first time (see Sternberg, 1985). However, Oberauer's thesis is supported by empirical data that show the absence of a separate factor for deductive and inductive reasoning (e.g., Wilhelm, 2005).

It seems, however, that each kind of reasoning has its own specific questions and research hypotheses. For instance, Stanovich and West (2000), in their studies of human rationality, proposed a hypothesis that there are two separate systems of reasoning. System 1 is primeval, evolutionary older, and is first initiated. Its activity is autonomous, does not require consciousness, and it is sufficient in many everyday situations. System 2 is complex, rational, conscious, and based on rules of logic. It is initiated mainly during formal education and during experiments on reasoning. The important thing is that effective operation of both systems requires working memory, but only in the case of System 1, a passive representation of data is sufficient for drawing conclusions, whereas initiating System 2 requires also initiating the mechanisms of information processing as well as executive functions in working memory. Thus, it seems that WM executive functions, rather than its capacity, will soon be in the focus of attention of researchers interested in reasoning. Hard neuropsychological data indicate that this is a promising line of research. For example, Prabhakaran and his colleagues (Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997), using fMRI technique, analyzed execution of the Raven Progressive Matrices and other tasks requiring analytical and figural reasoning as well as – in control conditions – simple perceptualmotoric tasks. It turned out that analytic reasoning is correlated with activation of brain areas connected with verbal working memory as well as domain-independent associative and executive processes. Activity of frontal areas, connected with purposeful behavior, changes of strategy, and planning or executive control processes in working memory, also was found to be of vital importance. Figural reasoning turned out to be related to the activation of brain areas connected with spatial/object working memory. What is interesting, in the case of fluid reasoning during completing the Raven test, is that almost all cortexes were strongly activated, including areas identified with cognitive control.

In any event, if the hypothesis proposed by Stanovich and West was confirmed, the research on working memory would significantly contribute to the development of knowledge about basic mechanisms of reasoning. In studies of fluid intelligence, researchers have been for some time searching for the essence of relations between cognitive control and intelligence. However, we know very little about the nature of relations between these two constructs, especially that the mechanism of cognitive control still seems to be unclear and heterogeneous.

Thus, it seems that the concept of WM capacity is no longer the first choice when researchers look for a memory correlate of relational reasoning. Currently, they prefer the concept of cognitive control, which is rather of attentional nature. Hence, after clarifying relations between attention and working memory, the concept of WMC possibly will return to favor.

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