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THE ROLE OF WORKING MEMORY AT DIFFERENT STAGES OF INSIGHT PROBLEM SOLVING: A CRITICAL REVIEW

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Роль рабочей памяти на разных этапах решения инсайтных задач: критический обзор

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Abstract

This paper offers a critical review of studies published over the past few years that explore the role of working memory at different stages of insight problem solving. The overall contribution of working memory (WM) to insight problem solving remains a matter of controversy, since there is supporting evidence for both the positive and the negative roles of executive control and WM in insight problem solving. A promising way to approach this contradiction is to trace WM loading dynamics in the course of a solution. Data analysis revealed that insight problem solving is generally WM-demanding, although to a lesser extent than analytic problem solving. The WM load peaks at the beginning and at the end of insight problem solving. The initial WM load may be linked to the interpretation of a problem

Резюме

В этой работе критически обозреваются данные, опубликованные за последние несколько лет по вопросу о роли рабочей памяти на различных этапах решения инсайтных задач. Обсуждение вопроса об общем вкладе рабочей памяти в успешность решения инсайтных задач создает противоречивое впечатление: есть данные как в поддержку идеи ключевой роли рабочей памяти в успешности решения инсайтных задач, так и данные о негативной роли рабочей памяти и контроля. Способом разрешения этого противоречия является рассмотрение роли рабочей памяти в динамике. В представленном обзоре предлагается анализ имеющихся данных о роли рабочей памяти и контроля на разных этапах решения инсайтных задач. Анализ показал, что, в целом, решение инсайтных задач требовательно к рабочей памяти, хотя и в меньшей степени, чем решение аналитических задач. Наибольшая степень загрузки рабочей памяти наблюдается в начале и конце решения инсайтных задач. Начальная

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description, creating the initial representation, and analytic reasoning within the initial problem space. Subsequently, in the case of insight problems, the WM load decreases noticeably, which can be linked to a search for a new representation or to an impasse. At the last stage of problem solving, a short peak in the WM load precedes the solution detection, which can be linked to the restructuring of representation and the beginning of a new solution process in a new problem space.

Keywords: working memory, executive control, insight, insight problem, reasoning, psychology of problem solving.

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загрузка может быть связана с пониманием условий, построением первоначальной репрезентации и аналитическим поиском в первоначальном пространстве решений. В дальнейшем загрузка рабочей памяти в решении инсайтных задач заметно снижается, что можно связать с режимом поиска новой репрезентации или состоянием тупика. На последнем этапе решения инсайтных задач был обнаружен короткий подъем загрузки рабочей памяти перед обнаружением решения, что может быть связано с построением новой репрезентации и запуском поиска решения в новом пространстве решений.

Ключевые слова: рабочая память, контроль, инсайт, инсайтная задача, мышление, психология мышления.

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The role of WM in finding solutions, especially to insight problems, has been the focus of extensive research in psychology of problem solving. Two competing approaches to the role of WM have emerged: the “specific”, or “special-process” approach, which postulates that insight requires specific low-level processes of representation change (Ohlsson, 1992, 2011; Öllinger et al., 2013), and the “nothing-special”, or “business-as-usual” approach, which assumes that all problem solving processes are fundamentally similar (Chein et al., 2010; Chuderski, 2014). WM plays a key role in problem solving in general, and the positive correlation between working memory capacity (WMC) and insight solutions is usually interpreted as supporting evidence for the non-specific approach (Chuderski & Jastrzębski, 2018a). Several reviews on the role of WM in problem solving have been published to date (Gilhooly & Webb, 2018; Hambrick & Engle, 2003; Vladimirov & Korovkin, 2014). These papers found a diverging understanding of the overall contribution of WMC to insight solutions, with a tendency to interpret the evidence in favor of the important role of WM. The present review attempts to move away from the discussion of the overall contribution of WM to successful solutions and to examine existing evidence on the dynamics of WM loading in insight problem solving.

WM is conceptualized as a resource in which current information is retained and actively processed (Baddeley, 2002; Cowan, 1999; Oberauer, 2019; Velichkovskii, 2015). Its two commonly separated aspects are the executive system (central executive, control of attention) and the passive system of information storage (modal-specific storages with a multimodal episodic buffer or an activated part of long-term memory). Either of these two aspects can be of interest in insight problem research. The passive storage system is responsible for problem representation and intermediate solution states, while the executive control system processes this representation. However, most of the studies do not treat WM as a process, but instead use it as an individual's measure of capacity within a differential approach. Therefore, in most cases we can draw conclusions about the general role of WM, but we cannot precisely pinpoint the processes involved in solving insight problems.

The General Role of WM in Insight Problem Solving

Studies convincingly demonstrate that WM, especially the central executive of WM, plays an important role in solving insight problems and other creative tasks (Chuderski, 2014; Chuderski & Jastrzębski, 2018a; Cinan & Doğan, 2013; De Dreu et al., 2012; DeYoung et al., 2008; Murray & Byrne, 2005; Nęcka et al., 2016; Smirnitskaya & Vladimirov, 2017). A number of studies have also shown that modal-specific WM storages are primarily important for solving insight problems, in particular the visuo-spatial sketchpad for visual insight problems and the phonological loop for verbal insight problems (Chein et al., 2010; Chein & Weisberg, 2014; Gilhooly & Fioratou, 2009). This evidence is most often cited in support of the non-specific approach, which postulates that insight does not entail any special processes that would distinguish it from the solution process of non-insight problems. In other words, the solution of insight and non-insight problems relies on the same analytic processes of heuristic search.

At the same time, executive control and WM have been shown to be either less important (Fleck, 2008; Lavric et al., 2000; Luneva & Korovkin, 2019; Xing et al., 2019), or even detrimental for insight problem solving (Baird et al., 2012; Beilock & DeCaro, 2007; DeCaro et al., 2016; DeCaro & Van Stockum, 2017; Jarosz et al., 2012; Reverberi et al., 2005; Ricks et al., 2007; Vladimirov et al., 2018). This idea relies on the concept of insight as overcoming an impasse through representational change. In this case, executive control and overconcentration might inhibit representational change. Therefore, loading WM or redirecting attention or control may facilitate the solution of an insight problem. Recent studies revealed the low reproducibility of experiment results which had supported a positive correlation between WM loading or executive control distraction and insight solutions (Chuderski & Jastrzębski, 2017; Drążyk et al., 2020).

Modern research in psychology of thinking tends to move away from analyzing the process of insight problem solving towards analyzing insight itself (Moroshkina et al., 2020). Recent studies demonstrated that the cognitive load on WM does hinder insight solutions (measured as Aha! Experiences) to some, but a much lesser extent, than analytic solutions of a single set of Compound Remote Associates tasks (Stuyck et al., 2022). The authors of this study argue that insight solutions require fewer WM resources compared to analytic solutions. However, research that explores the relationship between WM and insight experiences is still in its infancy.

Existing evidence paints a conflicting picture of the correlation between WMC and insight problem solving. This conflict mainly emerged as a result of multiple attempts to establish a general linear connection between WM and successful solutions, which didn't account for the diversity of processes involved. In general, it has been demonstrated that the solution of both insight and analytic problems is strongly related to WM. However, solution of insight problems relies on WMC to a lesser extent, and in some cases an inverse relationship can be observed.

Stages of Problem Solving

Diverging evidence could arise from the variation in problem solving processes (DeCaro et al., 2017). The solving process of insight problems normally goes through several stages: (1) understanding the problem (constructing a representation, the initial search for a solution), (2) encountering an impasse, and (3) going through a representational change, or restructuring, in which WM might be involved to varying degrees (Korovkin et al., 2018). It is generally assumed that at the first stage the solver reads and understands the problem description, forms the initial representation, constructs the problem space and initiates the search for a solution. Analytic problem solving should entail the same processes, therefore, their demand on WM resources should be the same. The stage of impasse is usually characterized either by the absence of any actions aimed at solving the problem or by the repetition of ineffective actions. The WM load at this stage is either unchanged or drastically decreased. One would expect both passive forced inactivity, which can lead to selective forgetting of incorrect solution paths (Simon, 1977), and active, mostly ineffective, actions, which lead to the accumulation of negative feedback (Ohlsson, 2011). The third stage, the representation change, involves at least two main processes, the rejection of the old representation and the forming of a new representation, which enables a new search. This solution stage is key to understanding insight. The idea of variation in solution stages has been advanced in eye-movement studies (Ellis et al., 2011; Knoblich et al., 2001; Yeh et al., 2014), which demonstrated that search strategies can change between solution stages. Thus, a promising strategy of conceptualizing WM in relation to insight is to study it at different stages of the solution process.

Approaches to Studying WM at Different Stages of Insight Problem Solving

Several approaches to analyzing problem solution stages have been proposed. The first aims to reduce the proportion of analytic processes in insight problem solving. Ash and Wiley (2006) suggested that the demand for WM is greater during the first stages of insight problem solving, when the solver is dealing with the initial incorrect representation using analytic solution methods, whereas the final restructuring stage that involves representational change is not as WM-heavy. The authors developed a set of insight problems, each of which exists in two variants: actions within the initially incorrect representation are either available (many moves available, MMA) or limited (few moves available, FMA). Experiments with these problems demonstrated that the overall WM performance predicts a successful solution of MMA problems, which involve both the search and the restructuring stages. At the same time, WMC is not a predictor of success for FMA problems, in which representation change is the key stage. Based on these findings, the authors conclude that the restructuring or representation change does not require executive control and relies on automatic processes such as redistribution of activation. However, a recent study by Chuderski & Jastrzębski (2018b) showed that the number of available actions within the initial representation does not affect either objective or subjective indices of insightful solutions. After a large number of participants had solved problems with either a little or a large number of available actions within the initial representation, Chuderski and Jastrzębski found no consistent variation in success rates, self-reported experiences, or fatigue between these two problem types. The resulting correlations points at WM contribution to the solution of both types of problems. Therefore, evidence from this study disproves the idea that WM is linked only to the solver's development of an initially incorrect representation. It follows that insight problems with a different number of available moves within the initial representation are not, at this point, very useful for analyzing the role of WM at different solution stages.

The second approach aims to identify and influence local events that might be linked to insight. One such event is the state of impasse. Markina and Vladimirov (Markina & Vladimirov, 2019; Markina, 2020) tested the negative effect of executive control on insightful solutions by distracting solvers with additional tasks during an impasse. The authors hypothesized that an intervention at the stage of impasse would weaken executive control, thus facilitating re-representation and shortening solution time. The resulting evidence from a small sample supports this claim only indirectly, partially due to complications in detecting impasse subjectively and objectively.

The third approach to exploring the different role of WM at different solution stages divides the solution time into several time periods and analyzes the data collected from them. Yeh and colleagues (Yeh et al., 2014) analyzed the link between individual WM values and the developments in attention in the process of problem solving. Participants solved creative problems with graphically represented objective situations. To measure the participants' WM, researchers asked them to remember graphically represented objects. After analyzing protocols and eye movement patterns, the authors loosely identified the following three stages of problem solving: the initial stage (the first 5 seconds), the final stage (the last 4 seconds), and the intermediate stage (time between the other two stages). This study revealed that at the intermediate stage participants with a greater WMC directed their gazes to the target objects (a part of the solution) more often and for longer periods of time than participants with a smaller WMC. Moreover, participants with a greater WMC demonstrated more frequent saccades toward the target object at the final stage. Lv (2015) studied the involvement of WM and inhibitory control functions at different stages of insight problem solving. Based on verbal protocols, problem solving was divided into two stages: initial solution search and restructuring. The author analyzed correlations between WM tests and inhibitory control functions and demonstrated that a greater WMC shortens the initial solution search stage, while active inhibition helps to concentrate on the task, just like in analytic solutions. The restructuring stage is more closely linked to spontaneous inhibition. Depending on the problem, spontaneous inhibition can have two effects and either suppress the initially constructed wrong representation and facilitate restructuring or suppress alternative interpretations and prevent insight.

Monitoring the WM Load with a Probe Task

Of the three approaches mentioned above, the latter is the most developed. One practical application of this approach in insight problem solving is the method of monitoring WM dynamics with a probe task (Korovkin et al., 2014). This method entails performing a simple task (a probe task) that loads WM while solving a cognitive problem. To assess the WM load, the reaction time of the probe task, rather than the less informative number of errors, was used (Vladimirov et al., 2016). In a series of studies, the authors of this method modified the difficulty (Korovkin et al., 2016), content (Korovkin & Savinova, 2016; Savinova & Korovkin, 2019a), modality (Korovkin et al., 2018; Savinova & Korovkin, 2019b; Chistopolskaya, 2017), and rule awareness (Lebed & Korovkin, 2017) of the probe task and compared the results for insight and analytic problems. These experiments revealed noticeable variation in the WM load in insight and analytic problems, the overall WM load being significantly lower for insight problems than for non-insight problems. Additionally, these studies showed that the variance in WM loading becomes salient for different problem types only in the second half of the solution, which the authors attribute to the increased number of intermediate computations in analytic problems. Most studies (Korovkin et al., 2016) have also demonstrated that in the case of insight problems that involve choosing from several alternatives, the solver's WM load peaks just before the answer is found. This increase in the WM usage that precedes a solution may indicate that WM, in particular executive control, contributes to insight. Savinova (Savinova, 2020) explored the causes of this increase in the WM load at the last stage of insight problem solving. Consistently ruling out possible explanations (fatigue, verbalization, and analytic reasoning), the author concluded that this WM load increase is related to representational change.

Chistopolskaya and colleagues (Korovkin et al., 2018; Chistopolskaya, 2017) implemented the dual-task method to demonstrate the importance of modal-specific processing in visual and verbal insight problem solving. Visual insight problems and visual probe tasks most noticeably competed for WM resources. Visual and verbal problems loaded WM to a similar extent, which generally confirms the evidence from earlier studies of modal-specific WM storages. At the same time, the loading of modal-specific storages did not reveal any noticeable dynamics.

Attempts to select a probe task content that would resemble insight problems closely enough to reflect the natural dynamics of their solution and maximize competition for WM resources have yielded negative results: probe tasks with different content revealed similar WM dynamics in insight problem solving (Korovkin & Savinova, 2016; Savinova & Korovkin, 2019a). Regardless of the content of a probe task, the extent to which it loaded WM depended primarily on the task difficulty (Korovkin et al., 2018; Savinova & Korovkin, 2019b). Probe task difficulty affected the reaction time for both insight and analytic problem solving, i.e., it increased WM load equally for both types of problems. Upping the difficulty of the probe task increased reaction time, but it did so in accordance with the previously identified pattern of WM loading dynamics, i. e. the central executive contributes to insight problem solving at the very beginning of the process and just before a solution is found. In a recent study, Savinova and colleagues (Savinova et al., 2023) looked at the three control functions of the central executive: updating, shifting, and inhibition. They hypothesized that different control functions come into play at different stages of the solution: updating contributes to building the problem representation, inhibition to overcoming an impasse, and shifting, to representational change. These hypotheses were not confirmed; conversely, what matters is not the type of control function, but the overall complexity of the tasks loading the central executive. The more any of the control functions is loaded, the more it affects insight problem solving.

Therefore, evidence yielded by this approach indicates that the processes involved in insight problem solving require access to various WM systems throughout the solution. One finding shows that WM storages of the appropriate modality are required to retain a representation throughout the solution process. Other findings point to the importance of modal-nonspecific functions in increasing the WM load prior to solution detection.

This review demonstrates the rather conflicting nature of accumulated evidence on the relationship between WM and insight problem solving. Although the data shows that insight problems generally engage WM resources, they do so to a lesser extent than analytic problems. The emerging controversy regarding the nature of differences in insight and analytic problem solving might be explained by considering the dynamics of WM loading in the process of solution. Three approaches to analyzing WM dynamics have been identified: (a) creating problems that would include or exclude certain stages that make these problems insightful; (b) attempting to target WM at critical solution stages, (c) employing probe task monitoring of WM loading throughout the solution. The third approach is currently the most developed.

Analysis of WM loading at different stages of problem solving seems to be a very promising research area. It demonstrates the heterogeneity of the solution process with regards to the WM contribution. On the one hand, insight problem solutions nonspecifically rely on the central executive and modal-specific information storages at the first stages of the solution (in understanding the problem, forming a representation, and searching for a solution within the existing representation). On the other hand, while analytic problem solution is characterized by a gradual WM load increase, insight problems demonstrate a gradual WM load decrease up to the very last episodes which show growth. The effects we observed require replication in independent laboratories, as well as verification by more subtle and valid methods. In addition, current scholarship calls for more data concerning the differences in insight and analytic solutions. The processes that take place in WM just before detecting an insightful solution might be the same non-specific processes related to the construction and exploration of representation and problem space that are observed at the first stage of a problem solution. They can also be significantly different, since they can involve processes aimed at representational change. In any case, it seems that the analysis of WM loading at different stages of the solution reveals new, previously inaccessible evidence.

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