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EMBODIED PROBLEM SOLVING: A REVIEW OF EXPERIMENTAL PARADIGMS

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Основные экспериментальные парадигмы в исследованиях воплощенного познания в области решения мыслительных задач

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Abstract

Recent studies of thinking increasingly often rely on Embodied cognition, a popular cognitive psychology approach. This approach provides ample opportunity to test new hypotheses and ask new questions about the mechanisms of problem solving. This article aims to systematize the existing experimental paradigms for testing hypotheses of this kind, especially those that describe the functional effects of motor activity on problem solving. The review analyzes the main experimental paradigms in this area, namely, the influence of previous motor and/or oculomotor activity on problem solving (when, before solving the main problem, the solver performs certain movements that represent a fragment of a future solution or are semantically related to it), the influence of concurrent motor activity on the process and result of the solution (when performed in parallel with the solution movement tasks have a significant impact on the process and/or result

Резюме

Современные исследования мыслительных процессов все чаще обращаются к одному из популярных в когнитивной психологии направлений — «воплощенному познанию». Благодаря эвристической ценности этого подхода появляются возможности для проверки новых гипотез и формулирования новых исследовательских вопросов о психологических механизмах решения задач. Целью данной статьи является систематизация предложенных экспериментальных парадигм, позволяющих проверять гипотезы такого рода, в частности, посвященные функциональному вкладу моторной активности в процесс решения мыслительных задач. В обзоре анализируются основные экспериментальные парадигмы в этой области: влияние предшествующей моторной и/или окуломоторной активности на решение задач (когда до начала решения основной задачи решатель выполняет определенные движения, представляющие собой фрагмент будущего решения или семантически связанные с ним), влияние сопутствующей моторной активности на процесс и результат решения (когда выполняемые of the thought process), the influence of interactivity effects on the solution of the problem (when, due to the direct interaction with the problem material, subjects reduce the load on working memory and/or increase the success of the solution), the influence of the number of gestures on the solution (when the number of gestures of a certain type during the description of the found solution is positively correlated with successful solutions), as well as the influence of different modes of motor planning on the process of problem solving (when only one of its types – on-line planning (planning movement in the course of its execution) – positively affects the success of the solution).

Keywords: experimental paradigm, problem solving, embodied cognition, interaction, motor activity, cognition, movement.

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параллельно с решением задачи движения оказывают значимое влияние на процесс и/или результат мыслительного процесса), влияние эффектов интерактивности на решение задачи (когда за счет непосредственного взаимодействия с материалом задачи испытуемые снижают нагрузку на рабочую память и/или повышают успешность решения), влияние жестов на решение задачи (когда количество жестов определенного типа в ходе описания найденного ответа положительно связано с успешностью решения), а также влияние разных режимов моторного планирования на процесс решения мыслительных задач (когда только один из его вариантов — планирование движения по ходу его выполнения — положительно влияет на успешность решения).

Ключевые слова: экспериментальная парадигма, решение задачи, воплощенное познание, интерактивность, моторная активность, мышление, движение.

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Embodied cognition is a modern approach within cognitive research. It postulates that cognitive processes are strongly linked to the sensorimotor interaction of the human body with the environment (Loginov & Spiridonov, 2017a, 2017b; Madni & Spiridonov, 2018). The heuristic value of this approach has already been demonstrated by experiments concerning perception (Tipper et al., 2006), memory

(Glenberg, 1997), emotions (Niedenthal et al., 2009), etc. However, in their studies of thinking processes, especially the process of problem solving, researchers did not immediately embrace the theory of embodied cognition. It took them some time to enrich their own explanatory models and to borrow experimental paradigms for testing new hypotheses. Most such hypotheses explore the possible effects of motor activity on thinking processes. Standard approaches in psychology of thinking suggest, explicitly or implicitly, that human motor activity is limited to its instrumental function, in other words, that it implements the principle of solution already discovered by the mind (Newell & Simon, 1972; Ohlsson, 1984). Embodied cognition, on the other hand, makes it possible to formulate and test hypotheses about the functional role of movement in problem solving. The functional role of movement is defined as a potential effect of motor activity on psychological mechanisms of problem solving.

This article aims to systematize existing experimental paradigms for testing such functional hypotheses. At this stage, this area of research will greatly benefit from a comparative analysis of existing methods, accompanied by an assessment of their potential and limitations.

Effects of Movement Priming on Problem Solving

The use of hints is the most widely used method in problem solving. Within its framework, a problem is perceived as a structured set of sources of difficulty that hinder the achievement of the goal. By using various hints, researchers test hypotheses regarding different sources of difficulty in a particular problem. They can influence the solving rate for a problem by adding (or, more often, removing) existing sources of difficulty.

Of all hints, movement priming yields the most surprising results in prompting a solution. First, it occasionally proves to be more effective than verbal hints. Existing theories in problem solving (the problem space theory, the representation change theory, and the satisfactory progress theory) do not explain how such motor hints work. This section focuses specifically on the motor activities that precede the solution of the main problem.

Most studies compare the success rate and/or solution time achieved for the same problem while employing different types of movement priming (or using none). Within this methodology, a fragment of the solution movement can be trained in some cases, while in others, the movement-prime might be semantically related to the solution and “hint at” its principle. For example, movement priming has been extensively used to increase the solving rate of the classic nine-dot problem, which requires the solver to connect nine dots with four straight lines without lifting the pencil from the paper (Weisberg & Alba, 1981; Lung & Dominowski, 1985; Kershaw & Ohlsson, 2004; Spiridonov & Lifanova, 2013; Spiridonov et al., 2019). In most cases motor training matched the alleged sources of difficulty in this problem: crossing the lines of the perceptual square, turning on a non-dot point (the “non-dot turn”), and reducing the count of possible lines after going outside of the square. In the training phase, participants were asked to connect other sets of dots (different from the main problem) with straight lines. This required going outside of the square and turning on a non-dot point.

A study based on the classical two-string problem also demonstrated the effects of motor priming. Two strings hang from a ceiling, far enough apart that the solver cannot grasp them at the same time. To tie them together and solve the problem, the subject should pick up a pair of pliers (lying among other objects in the room), attach them to one of the strings as a weight, then swing the string like a pendulum, grasp it and tie the two strings together. Motor training of the pendulum principle was used before the main problem. One group had to swing their arms like a pendulum, the other group, stretch their arms left and right (Thomas & Lleras, 2009). In another study, some participants were asked to swing their arms like a pendulum, others, to step onto a chair (this movement hints at a second solution: strings can be tied together if they are accessed from a chair or a table), while the third group did nothing (Werner & Raab, 2013). The problem-solving process consisted of several attempts, with motor training preceding each attempt. This was necessary because the effects of movement priming on cognitive functions seem to be short-term. This experimental paradigm was also tested on water jar problems (Werner & Raab, 2013; Werner et al., 2019) and insight symmetry tasks (Kuritsyn & Chistopolskaya, 2020).

This experimental paradigm, called movement priming or motor priming, is useful for testing hypotheses regarding the effects of motor activity on the sources of difficulty for a given problem. Its significant limitation is the lack of direct correlation of experimental effects with specific psychological mechanisms. It should be also noted that while many studies highlight the positive effects of motion priming, practically no publications state the opposite. This phenomenon might stem from the extent of said effects, or from a publication bias (negative or null findings do not get published).

Effects of Oculomotor Priming on Problem Solving

A similar method involves the manipulation of the subject's eye movements. In their experiment, Grant and Spivey used the "radiation problem", sometimes referred to as the X-ray problem, which requires the subject to find a way of destroying an inoperable tumor with special lasers, while doing no harm to the healthy tissue around it (Grant & Spivey, 2003). A conventional solution is to arrange several low-intensity lasers around the patient's body so that the beams meet at the tumor. In this case, the combined intensity of the lasers will be sufficient to destroy the tumor. At the first stage of the experiment, participants were given a schematic representation of the main conditions (the tumor, the healthy tissue, the skin and the area around it). An eye tracker recorded their eye movements.

The researchers discovered that in the last stage of their solving process, successful solvers viewed the skin area longer. Grant and Spivey linked this kind of eye movement to the solution that required several lasers to be placed around the skin. In the second experiment, the researchers presented new subjects with schematic images on which either the skin region or the tumor region was blinking. In the blinking skin group, the solution rate was twice as high as in the blinking tumor group and the control group.

This study gave rise to a whole new area of exploration. Researchers proposed and tested new ways of controlling the subjects' eye movement to increase the solving rate of the "radiation problem":

a) asking the subject to follow the eye movement pattern of a successful solver or of a person who looked at the diagram while following specific instructions (Litchfield & Ball, 2011);

b) tracking the eye movement pattern of a person who deliberately moved their eyes across the skin area several times, but was not asked to solve the problem (Ibid.);

c) asking the subject to identify digits from 1 to 8 presented in different locations within the diagram. The arrangement and order of appearance of these digits could hint at some part of the solution (Thomas & Lleras, 2007).

These studies emphasize the potential usefulness of these nascent methods for learning. Presumably, it might be possible to speed up the learning process by controlling the learner's eye movements, just as by controlling the solver's eye movements it might be possible to increase the solution rate. The limitations of this paradigm include reliance on just one problem, as well as the chance that the results of this experiment might be explained by mechanisms of distribution of visual attention, not by oculomotor activity patterns semantically related to the solution principle.

Effects of Concurrent Motor Activity on Problem Solving

Apart from motor priming, concurrent motor activity can also affect problem solving. Studies of this kind use motor activities as interventions. Typical examples of the main problem include addition, subtraction, and multiplication of two-digit numbers in the subject's head (Michaux et al., 2013). Participants in the experimental group were given a small ball and instructed to place their dominant hand on top of it and move their fingers one after another while solving mathematical problems. These participants did sums and subtractions significantly slower than the control group, but multiplication speed was not affected. Among other possible explanations, interference of finger movement with the automatically actualized motor programs associated with mathematical operations ("finger counting") might account for this effect.

A study of mental rotation yielded similar results. If two tasks were concurrent (mental rotation of three-dimensional figures and physical rotation of objects by hand), concordant rotation directions sped up mental rotation, while discordant directions slowed it (Wohlschläger & Wohlschläger, 1998).

This experimental paradigm is useful for testing hypotheses that describe motor interference at various stages of the solution process. It can further the understanding of the sequentially changing role of motor activity in overcoming the sources of difficulty. The main limitation of this method is the fact that it is not suited for problems with a motor component (for example, the nine-dot problem), since motor interference/facilitation reveals nothing about the functional role of movement in the problem-solving process.

Effects of Interactivity on Problem Solving

Effects of interactivity comprise another notable area in the study of motor activity in problem solving. Researchers explore how actively the solver manipulates the elements of a problem situation and how this affects the solution rate. Some good examples come from matchstick arithmetic problems (Weller et al., 2011). An erroneous mathematical inequality is laid out in matchsticks. One match must be moved to correct it. In one study, actively interacting with the matchsticks was permitted for one test group, but forbidden for the other. The solving rates were found to be different, with the active manipulation group having a clear advantage. Additionally, the authors of this study measured a whole range of spatial and mathematical skills and used these values as predictors of successful problem solving in different conditions. The hypothesis was that mathematical skills would predict problem solving performance without interaction, while spatial skills would predict active interaction with the elements of the problem.

Studies of these effects possess heuristic value; however, it has been reported that some of these effects could not be replicated (Spiridonov et al., 2021). It appears that interactivity only manifests in certain conditions: given the opportunity to manipulate the stimuli, not all participants used it. One possible explanation is the phenomenon of cognitive offloading, which involves movement and surrounding physical objects to simplify information processing. Existing models (Dunn & Risko, 2016) presume that people do not always resort to cognitive offloading. To predict whether a person will offload and interact with the stimuli, one should consider the metacognitive evaluation of the problem complexity. Such hypotheses have yet to be tested, since most cognitive offloading studies explored perceptual and mnemonic processes rather than thinking processes.

The experimental paradigm associated with the effects of interactivity was also applied to distinguish several types of actions which the problem solver carries out while interacting with the world. Kirsch distinguished between pragmatic actions (carried out to solve the problem proper and get closer to the goal) and epistemic actions (carried out to find additional information about the problem and simplify the solution process) (Kirsh & Maglio, 1994). This gives researchers ample opportunity to test new hypotheses regarding the “epistemic” motor activity of the solver and its potential effects on the solving rate.

Effects of Gestures on Problem Solving

What usually comes to the forefront in the discussion of gestures is their functional role in communication. However, gestures can also play their part in problem solving. An experiment that studied the role of gestures in solving the Tower of Hanoi problem (Beilock & Goldin-Meadow, 2010) was carried out in several stages. First, the participants faced the classic variant of this problem, with three rods and three disks of different diameters. The goal was to move all three disks from the first rod to the third, obeying a set of rules. After they solved the puzzle, the participants were asked to explain how they did it in front of a camera. While explaining their reasoning, the subjects gesticulated actively. Subsequently the experimenters counted gestures of a certain type – those that showed exactly how the subjects grasped the disks. Some indicated the transfer of the disk with one hand, some with both. At the second stage of the experiment, the same participants had to solve the same puzzle, but the disk weights were modified: the largest was in fact the lightest, and the smallest one was the heaviest.

The experimenters discovered a positive correlation between the number of one-hand gestures used to explain the original solution and the increase in solution time of the modified problem. In other words, the more gestures of this type the subject used, the more difficult they found the modified problem. One possible explanation is that the representation of the problem contains a motor component; gestures manifest its content and prime the corresponding motor programs for moving disks. These gestures become a hindrance if they are at variance with motor programs relevant for the modified problem.

This experimental paradigm can be used to test hypotheses regarding the peculiarities of representation for the solver of problems with communicative components (for example, the twenty questions game) and problems with motor aspects that can be illustrated by gestures (for example, the Tower of Hanoi problem). In other cases, gestures are unlikely to provide enough data for cognitive scientists.

Effects of Motor Planning Modes on Problem Solving

The solution of several problems entails certain movements. The sixth experimental paradigm measures several parameters of these movements in the course of problem solving (for example, the number and duration of pauses between movements, the number and speed of their execution, the range of motion, etc.) and uses these parameters not as new dependent variables, but as correlates and predictors of a successful solution.

Participants of a study (Spiridonov et al., 2019) were asked to solve the nine-dot problem by drawing lines on the tablet with their finger. A special program recorded the various parameters of finger movement. The authors hypothesized that the subjects relied on two different motor planning modes, online and offline. Offline planning conceptualizes the lines first, and drawing happens after. Online planning occurs as the line is drawn. The first planning mode is characterized by longer pauses in the process of drawing lines, and the second planning mode, by slower drawing and more submovements (several movements to draw one line). The study showed that at the third (last) stage of the solution process successful solvers drew lines significantly slower than unsuccessful ones. This suggests that online planning is required to arrive at the solution of this problem.

A similar approach was implemented in a study based on engineering problems (Stahovich et al., 2019). Participants wrote out equations and drew a schematic representation of the physical system described in the problem they tried to solve. While they were doing it, experimenters recorded and measured several parameters of their writing (the frequency of short, medium, and long pauses, the total time spent on drawing diagrams, the total time spent on constructing equations, etc.). The study showed that these values account roughly for 40% of the variance in the subjects' ability to arrive at the correct answer. Although the authors of this study do not distinguish between different motor planning modes, they rely on similar methodology, which could be retrospectively reconceptualized from the point of view of motor planning. A specific finding of this study is the positive correlation between short pauses and a successful solution, and the negative correlation between medium and long pauses and a successful solution. It can be conjectured that a tendency for offline motor planning (manifested in longer pauses) is linked to a lower solution rate.

This experimental paradigm needs theoretical development, potentially focusing on different types of a mental lookahead. For example, offline planning (for the nine-dot problem) can be described in terms of a narrow but long mental lookahead, which allows for a detailed visualization of the line sequence. Online planning in this paradigm would be perceived as a wide, but short mental lookahead that extends an already started line towards various dots.

Conclusion

To sum up, researchers of problem solving have access to a fairly large number of experimental paradigms that rely on the ideas of embodied cognition. However, the present overview reveals insufficient theoretical exploration of the psychological mechanisms that might underlie the effects discovered in different studies. The paradigms described here are based on different problems, they are isolated and not correlated. This circumstance seems to be the "Achilles' heel" of this entire line of research. It also clearly lacks meta-analyses and replications (first attempts were made by Kuritsyn et al., 2020 and Spiridonov et al., 2021). Despite all the shortcomings, this is a rapidly developing area of study that already has the researchers' attention. It might overcome its growing pains in the foreseeable future.

Theoretical development of the existing models in the field of problem solving could take two distinct directions:

a) studies of the motor component of the mental representation of the problem, which can manifest in gestures, interfere with the current motor activity or be affected by motor or oculomotor priming.

b) studies of various implementations of mental operators (or mental operations), with and without interaction with the environment and in connection to different motor planning modes.

In this area of study there is still a long way to go to improve experimental procedures and to verify alternative explanations for the discovered effects.

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