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Incubation and Activation of the Semantic Network

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The issue of incubation is a central and paradoxical topic in the psychology of thinking and creativity. The paradox arises from the observation that problem-solving can advance during periods when the solver is not consciously focused on the problem but is instead engaged in unrelated activities. Despite extensive research on incubation, a unified explanation for this phenomenon remains elusive. This article introduces a new theoretical approach characterized by two distinctive features. First, it advocates for the examination of the general problem of incubation through tasks that facilitate a precise analysis of the underlying processes—specifically, Mednick's triads. Second, to enable a comprehensive analysis of problem-solving processes, this approach incorporates methods from general network theory. Consequently, the theoretical model developed to elucidate incubation encompasses two levels of processes: the propagation of activation across the semantic network and the control processes driven by goal-setting when the individual accepts the problem.

Keywords: Incubation, network models, Remote Associates Test.

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Феномен инкубации и активация семантической сети

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Проблема инкубации является одной из центральных и парадоксальных в психологии мышления и творчества. Парадоксальность проблемы связана с тем, что решение задачи продвигается в то время, когда решающий не думает о задаче, а отвлечен на совсем другие дела. Хотя инкубация довольно интенсивно исследуется в разных странах мира, до сих пор не существует единого объяснения этого явления. В статье изложен новый теоретический подход, который отличается двумя особенностями. Во-первых, предлагается исследовать общую проблему инкубации на материале задач, допускающих максимально точный анализ задействованных в их решении процессов — триад Медника. Во-вторых, для реализации точного анализа процессов решения задач используется подход из общей теории сетей. В итоге теоретическая модель, разрабатываемая для объяснения инкубации, включает два уровня процессов: распространение активации по семантической сети и управляющие процессы, исходящие из целеполагания при принятии задачи субъектом.

Ключевые слова: инкубация, сетевые модели, Тест отдаленных ассоциаций.

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In contemporary psychology, combining the study of significant theoretical problems with detailed analyses of underlying processes remains a rare achievement [8]. This limitation is particularly evident in the psychology of thinking. On one side, the field investigates general phenomena such as incubation, insight, and Eureka moments. On the other, it develops precise — often computational — models to understand specific problem-solving tasks. However, these two approaches frequently operate in isolation. The study of general phenomena tends to abstract away from the specific processes involved in problem-solving, while computational models often focus narrowly on the details of task-specific processes, neglecting broader theoretical questions.

This article aims to delve into the relationship between these approaches and propose a framework to reconcile their differences. To achieve this, we will focus on a well-documented phenomenon and a corresponding task type where this phenomenon is prominently observed. The phenomenon should be sufficiently studied and crucial for understanding creative thinking processes. The phenomenon of incubation meets these criteria and will be the primary focus of this discussion.

The task — or rather, the category of tasks — used to investigate thinking should allow for precise descriptions of problem-solving processes, including computational modeling. In recent years, advances have enabled the precise modeling of processes involved in solving tasks from Mednick's Remote Associates Test (RAT), which will serve as the primary example in this analysis. These tasks consist of word triads where participants must identify a fourth word that forms a meaningful association with each word in the triad. For example, given the words “red,” “sword,” and “meat,” the correct answer is “fish” (yielding the combinations “red fish,” “swordfish,” and “neither fish nor fowl”).

The development of detailed models of linguistic associative networks over the past decade has made it possible to describe how participants solve “Mednick-type” tasks by navigating the semantic network's connections. These tasks are also widely employed in studies on the phenomenon of incubation.

It is worth noting, however, that Mednick's triads are not the only type of task relevant in this context. Anagrams, for instance, are also extensively used in incubation research, and contemporary methods have been developed to describe and manage the processes involved in solving them.

This article will include a focused review of studies on incubation and the network mechanisms underlying the resolution of Mednick's triads. The review will reveal a gap in existing research: even when Mednick's triads are used to study incubation, detailed analyses of the problem-solving processes involved are often absent, leaving critical questions about how these processes relate to incubation unanswered. Conversely, studies that focus on the detailed processes of solving Mednick's triads rarely consider the role of incubation or related phenomena in solving other types of problems.

Following the review, we will propose a constructive program aimed at studying incubation while incorporating a detailed understanding of the processes involved in solving Mednick's triads. In conclusion, hypotheses will be presented on how a unified cognitive system architecture might emerge from integrating general and detailed approaches to problem-solving.

The Phenomenon of Incubation

The phenomenon of incubation was first mentioned in the introspective works of notable 19th-century thinkers. For instance, German mathematician Carl Gauss, after a groundbreaking discovery in number theory, reflected: “Finally, two days ago, I succeeded — not through my greatest efforts, but by God's grace. Like a flash of lightning, the problem was suddenly resolved. I cannot say what guiding thread connected what I already knew with the insight that brought success” [1, p. 71].

Henri Poincaré further explored and provided an explanation for the incubation phenomenon [6]. He theorized that during periods when individuals are not consciously working on a problem, their unconscious mind remains active. This activity resembles the chaotic motion of “concept molecules,” colliding like molecules in an ideal gas. Occasionally, these collisions produce new, harmonious combinations that surface as ideas, accompanied by a profound sense of illumination [7].

The term “incubation” gained wider recognition after Graham Wallas's seminal work [62], which outlined four stages of the creative process: preparation, incubation, illumination, and verification. In the preparation stage, individuals consciously attempt to solve a problem. During the incubation stage, they abandon these efforts and divert their attention to other activities. This shift enables unconscious processing, leading to the illumination stage, characterized by the sudden realization of a creative solution — what modern psychology refers to as insight [54]. Finally, in the verification stage, the validity of the idea is tested, and the solution is formalized [41].

While some researchers have questioned the validity of Wallas's four-stage model [20], it continues to serve as a widely adopted framework for conceptualizing and analyzing the creative thinking process.

Experimental Methods of Studying and Explaining Incubation

Modern research on incubation relies on two experimental paradigms. The first is referred to as “delayed incubation.” In experiments following this paradigm, participants are divided into two groups: experimental and control. Participants in the experimental group first attempt to solve a set of problems, then take an incubation break, and afterward try again to solve the unsolved problems. In the control group, participants also first attempt to solve the tasks but immediately make a second attempt without any break. The incubation effect is calculated as the difference in problem-solving success between the groups during the second attempt [3].

The second paradigm, “immediate incubation,” involves participants taking an incubation break immediately after receiving the task instructions

[16]. Meta-analyses have shown that both delayed and immediate incubation can improve task-solving success [46, 55].

The cognitive mechanisms underlying the incubation phenomenon are a topic of significant debate among researchers. Numerous theories and hypotheses have been proposed, some of which have undergone experimental testing. These explanations can be broadly divided into two approaches: specific and non-specific. The specific approach suggests that active processes aimed at finding a solution occur during the incubation period. In contrast, the non-specific approach posits that incubation merely creates more favorable cognitive conditions for finding a solution.

One of the simplest explanations within the specific approach is the "conscious work hypothesis," which suggests that problem-solvers intermittently return to the task during the incubation period, even though they later fail to recall doing so [64]. However, experimental studies have not found evidence supporting this view [23, 24, 10].

Some experimental studies have demonstrated that distracting participants from solving a task leads to an incubation effect [16, 17, 24]. A meta-analysis by M. Strick confirmed the existence of this effect [55]. These findings have led to the development of the "unconscious work theory," which posits that unconscious processes aimed at solving the problem occur during incubation. However, the precise nature of these processes remains unclear. One hypothesis is that during the incubation period, activation spreads through elements of the associative memory network, potentially bringing key elements into working memory [25, 30]. However, experimental results have been mixed [47, 66]. Thus, while this hypothesis is promising, the mechanisms of unconscious problem-solving remain poorly understood.

Proponents of the non-specific approach argue that no problem-solving occurs during incubation; rather, the break merely creates better conditions for finding a solution. For instance, the "fatigue dissipation hypothesis" suggests that incubation allows individuals to recover from unsuccessful solution attempts [45]. However, this idea is called into question by findings that solving unrelated complex tasks during incubation often positively affects solving the main task [44].

One of the most influential theories of incubation is the "selective forgetting hypothesis," which proposes that incubation facilitates finding the correct solution by enabling the forgetting of fixations [49]. Many experiments have shown that the incubation effect occurs only when participants were initially provided with stimuli that misdirected them from the correct answer [29, 38, 50, 51, 61]. However, some studies challenge the claim that fixation forgetting is the mechanism at play. For instance, it has been shown that the duration of incubation does not affect the magnitude of the effect [46], incubation often succeeds without prior fixation procedures [16], and it does not reduce the number of fixation-related answers in the second attempt [58].

Another explanation for the incubation phenomenon is the "attention withdrawal hypothesis" [44]. Gestalt psychologists of the mid-20th century linked insight to a sudden shift in how a problem is perceived, involving the restructuring of the existing gestalt [65]. When tackling a problem, individuals often form an initial organizing assumption that integrates elements of the problem into a coherent structure. However, this assumption can be incorrect, leading to a dead end [43]. In such cases, incubation may help withdraw attention from the erroneous organizing assumption, allowing for the formation of a new, correct structure. In experiments with an insight puzzle, Segal (2004) found that the incubation effect was not dependent on the duration of the break. Segal concluded that false assumptions were not forgotten (as suggested by the selective forgetting theory) but were overcome instantaneously through attention shifts. Furthermore, Segal found that solving complex incubation tasks produced a stronger incubation effect, likely because they require greater concentration, which better withdraws attention from the false assumption [44].

According to the "opportunistic assimilation theory," incubation is seen as a process of waiting for external cues [45]. These cues are assimilated by the cognitive system by matching them to "failure markers" — elements of long-term memory formed when the solution reaches an impasse. These markers encode features of the task as characteristics of environmental stimuli. When new information relevant to the solution is encountered, the problem representation is restructured, increasing the likelihood of insight. This theory was tested in several experiments [19, 31], which demonstrated that cues could aid problem-solving but did not produce an incubation effect. Thus, no evidence has conclusively supported the validity of the opportunistic assimilation hypothesis.

While most incubation research has been conducted in Western psychology, important theoretical developments have also emerged in Russian science. For example, in the work of the prominent Russian researcher Ya. A. Ponomarev, ideas central to understanding the mechanisms of incubation are discussed. According to his structural-level model of the creative process, the emergence and articulation of creative ideas result from the sequential collaboration of the logical and intuitive poles of thinking. In terms of his theory, the incubation period represents a shift to an intuitive mode of thinking, granting access to a vast repository of knowledge and connections formed during past activities without conscious involvement. Ponomarev referred to these as "by-products of action" [5]. These ideas have been further developed in recent works, such as a series of experiments by E.A. Valueva and N.M. Lapteva, which tested a model suggesting that incubation serves to eliminate barriers preventing the conscious realization of pre-activated implicit solutions [2, 4].

Incubation in Problem Solving Across Various Tasks

To synthesize and organize the findings of numerous studies, several meta-analyses [46, 55] and review papers [18, 22] have been conducted. These works not only confirm the existence of the incubation effect but also offer a detailed examination of the factors influencing its magnitude.

Sio and Ormerod's meta-analysis assessed the strength of the incubation effect across different types of creative tasks. Their findings highlighted that the duration of the preparatory phase is crucial for many tasks, while the length of the incubation period is significant only for divergent tasks. The authors suggest this supports the unconscious work theory, as the process of activation spreading through a semantic network — which takes time — may be especially important for divergent problem-solving. For linguistic tasks, such as the Remote Associates Test (RAT), the most substantial incubation effect was observed when the break was filled with simple activities. The authors attribute this to the selective forgetting hypothesis, proposing that fixations often hinder the problem-solving process in such tasks, while simple tasks help redirect attention, reducing fixation effects [46].

In summary, the incubation phenomenon is well-supported by experimental evidence. It likely plays a significant role in real-world creative processes, making its clarification essential for a theoretical understanding of thinking.

Despite its broad application across various tasks, incubation is often studied without a detailed investigation of the specific processes underlying task solutions. General explanatory constructs — such as conscious and unconscious work or fixation — are applied as if universally valid. However, deeper analyses of task-solving processes for divergent and convergent thinking, decision-making, and other cognitive tasks reveal that these constructs are often unnecessary or unused. For instance, does fixation occur in solving anagrams or Mednick's triads? This question is far from trivial and demands rigorous study. What exactly constitutes the "work" of solving these tasks? Providing a definitive answer is unlikely to be simple. At a minimum, as will be shown later, precise studies of these problem-solving processes often employ a different, more detailed terminology.

Network Models for Solving RAT problems

n exciting avenue for advancing research in this field is the adoption of methodologies grounded in cognitive network models [12, 30]. As verbal tasks, Mednick's triads are believed to be solved through the spread of activation within a semantic network, linking words with sufficient associative proximity, as suggested by contemporary cognitive psychology.

This network-based interpretation of cognitive activity in solving triads stems from Mednick's foundational work. He theorized that individuals with many weak associations in their semantic networks are better at forming new connections through distantly related elements — a hallmark of creativity [32]. Conversely, those with networks dominated by fewer, stronger associations — typically more conventional — are less adept at generating creative ideas. This hypothesis has spurred the rise of network-based approaches, now widely used to model mechanisms in RAT tasks and assess creative potential [27, 37].

This perspective allows for more precise reformulation of hypotheses about incubation, effectively translating them into a new scientific framework. Conscious and unconscious work during incubation can be reconceptualized as the continuation of activation spreading processes while attention shifts to a different task. The boundary between these two types of work becomes less distinct in this context: cognitive models like J. Anderson's ACT-R suggest that activation processes bring elements into consciousness once a specific activation threshold is reached. Opportunistic cue assimilation aligns with this view, as cues activate specific network elements, enhancing their effectiveness as intermediaries in problem-solving.

Mechanisms like fixation forgetting and attention withdrawal can also be reframed within this framework. From a semantic network perspective, these processes may reflect activation getting stuck on irrelevant elements, hindering progress toward target nodes.

Nevertheless, activation spreading alone cannot fully explain goal-directed problem-solving. While relevant to free association and daydreaming, such processes must operate within boundaries set by task-related goals. Understanding problem-solving requires integrating the role of executive control structures, which may contribute to incubation.

For creative, non-algorithmic tasks — where solution paths are unclear — executive control structures might function more by disinhibition than activation. This contrasts with algorithmic tasks, where control structures focus cognitive resources on predefined steps. In non-algorithmic tasks like Mednick's triads, control mechanisms prevent the system from lapsing into free association while guiding focus toward goal-relevant content. Effective focus requires supporting relevant activation while inhibiting interference, a balance that becomes increasingly challenging in creative tasks where predefined algorithms are absent.

When paired with network models, executive control structures offer a means of disinhibiting irrelevant nodes in the semantic network, preventing excessive activation spreading and preserving goal-directed behavior.

This approach also provides a fresh cognitive interpretation of fixation. Fixation may arise not from activation getting stuck in the semantic network but from persistent constraints imposed by executive control structures. Incubation, in this case, may work by gradually relaxing these constraints over time, enabling new solutions to emerge.

Refining Approaches to Incubation: Insights from Mednick's Triad-Solving Processes

The considerations outlined above mark a substantial advancement in experimentally validating theoretical models. A successful experimental approach to addressing these challenges should enable precise intervention in the processes underlying the resolution of Mednick's triads. This can be achieved effectively using the psychological method of priming, both positive and negative, as outlined by Falikman and Koifman [9]. Priming provides a means to control the activation levels of specific elements within a semantic network.

In the framework of incubation studies for RAT problems, priming serves two primary purposes. First, it can be used to assess the state of the semantic network during the problem-solving process. In this case, the problem-solving activity itself acts as a form of priming, while the experimenter's role is to detect the activation patterns within the semantic network that arise during the process. Lexical decision-making emerges as a straightforward experimental technique for this purpose.

The second purpose is to manipulate the activation of the semantic network and executive control structures experimentally, observing how these changes affect task-solving speed and accuracy under incubation and non-incubation conditions. Positive priming is understood as enhancing the activation of specific nodes in the semantic network, whereas negative priming introduces inhibitory control mechanisms.

This experimental framework generates distinct hypotheses depending on the incubation models under consideration. Conscious or unconscious work is expected to increase the activation of nodes relevant to the solution. Spontaneous cue assimilation should produce a similar effect but only in response to appropriate external signals. Attention withdrawal should result in decreased activation of irrelevant nodes. Finally, the awareness model predicts poorer performance under negative priming of solution-relevant nodes.

However, a critical question arises: how can we identify, for each triad, which nodes are relevant to the solution, which are irrelevant and misleading, and which are neutral and unrelated? Research into the structure of semantic networks offers a pathway to answering this question.

Semantic Networks and Complex Network Analysis

In recent years, network science and its associated approaches to analyzing complex systems have become an active interdisciplinary research field. Prominent examples include semantic networks, where concepts are linked through shared meanings [40]; social networks, where people are connected through relationships [33]; and neural networks, where neurons are connected via axons and dendrites [39].

Once nodes and connections are defined and the network is constructed, its topology can be studied using descriptive tools from network science [34]. For example, researchers can describe the global topology of a network, such as whether it resembles a small-world network or a random graph [63], or assess the position and significance of individual elements, such as node and edge centrality. Such analyses are often performed to link structural features of the network to the system's dynamics [35].

Network science serves as a productive theoretical and methodological foundation for understanding cognitive processes. Cognitive science and network science share complementary goals: cognitive science seeks to understand mental representations and processes [57], while network science provides tools to analyze the structure of complex systems and how this structure influences their dynamics [56].

Networks, particularly in the context of cognitive research, are valuable not only for accounting for the multidimensional architecture of complex systems [21] but also for offering tools to develop formal theories of dynamic processes that shape and sustain these systems [13, 14]. One notable example of this approach is the dynamical model of general intelligence [59], which explains positive correlations between intelligence test scores based on network concepts. This model quantitatively demonstrates how the structure of cognitive networks influences their dynamic processes. It has also been expanded to explain various empirical phenomena reported in intelligence research [42, 60].

An important and rapidly growing area within linguistic networks involves "word embedding." Word embedding is a set of language modeling techniques that map words to numerical vectors in multidimensional Euclidean space. Semantic similarity between two words is determined, in the simplest case, as the scalar product of their vectors, and more recently, using neural network algorithms. Recently, attempts have been made to treat semantic networks as multiplexes (i.e., multilayer networks). Such approaches appear to offer deeper insights into the formation of the mental lexicon [53] and early word acquisition [52].

Closely related to semantic networks are free association networks [15]. These are constructed through experiments in which participants are given words and asked to write the first word (or words) that come to mind in response. Aggregating these responses builds directed, weighted networks of connections between words (stimuli and responses), reflecting the frequency of associations.

The emergence of precise semantic network descriptions has allowed researchers to tackle the problem of verbal creativity as measured by Mednick's triads. Studies have demonstrated significant differences in the lexical-semantic and associative networks of more and less creative individuals. The networks of creative individuals are more interconnected, flexible, and reliable, supporting Mednick's hypothesis about creativity [27]. In another study [48], researchers analyzed sequences of guesses generated by participants during the RAT. Using latent semantic analysis (LSA), they measured the similarity between guesses, stimuli, and answers, concluding that there are two systematic strategies for solving linguistic tasks with multiple constraints, including the RAT. In the first strategy, guess generation is primarily based on one of the three stimuli, while the second strategy involves generating new guesses partially based on prior attempts.

Another study used a Metropolis-Hastings graph search model, where transition probabilities were based on geodesic (shortest) distances in the network from stimulus words to the solution [11]. The authors emphasized the critical influence of associative strength between key words on the outcomes of RAT performance.

A computational model was also developed, implemented, and analyzed to solve RAT tasks [36]. This model relied on a unified structure for organizing and processing knowledge ("knowledge graphs"), incorporating associative links between concepts and their frequency. Results showed that both the strength of associations and the number of potential pathways (graph paths) significantly influenced RAT success [37]. Finally, a spiking neural network model was proposed, simulating RAT solutions as a superposition of two cognitive processes: one generating potential answers and the other filtering them [26].

Today, there is a substantial body of work providing detailed insights into solving triads through semantic network analysis. These networks are often derived from associative experiments. However, it is important to note that reliable and complete network models currently exist predominantly for English and some other languages, but not for Russian. This limitation can be viewed as a temporary technical shortcoming that requires resolution.

Empirical validation is carried out by comparing the time and accuracy data of solving triads with model predictions. These predictions are based on the semantic network structure obtained through associative experiments and navigation algorithms simulating activation spreading from task conditions to solutions.

Studies have demonstrated a high level of prediction accuracy for Mednick's triads based on these models, justifying assumptions about activation pathways during problem-solving. This allows researchers to reliably identify target points for priming interventions and to test the activation patterns that form during task resolution.

How can we evaluate the precision of the description of Mednick's triad-solving processes obtained through this approach? The ultimate criterion of precision appears to be the ability to reproduce the process as a computer-implementable algorithm. The described modeling methods, with certain limitations, allow this for processes occurring within semantic networks. However, these models currently do not account for individual differences and can only predict average behavior within a sample. For executive control structures, the precision is significantly lower and applies mainly to their interaction with the semantic network, specifically in areas where they allow certain network nodes to participate in the solution.

Conclusion

The analysis presented here highlights that modern cognitive psychology possesses the tools necessary to conduct precise studies of even highly complex phenomena, such as problem-solving and incubation. However, an enduring question remains: what is the relationship between general phenomena, such as incubation or insight, and the mechanisms underlying the resolution of specific tasks? This study has shown that it is possible to investigate complex phenomena (in this case, incubation) through detailed descriptions of processes (e.g., the solving RAT problems). Nevertheless, a crucial question arises: to what extent are the cognitive processes driving incubation consistent across different types of tasks? Addressing this question will require further, targeted research. Even so, it is possible to outline some initial avenues for variation.

It seems plausible that the interplay between dual processes — network activation and focused executive control — may explain incubation phenomena across a range of contexts and tasks. However, the relative importance of factors such as long-term activation spreading within the network, the resolution of activation stalling, or the relaxation of executive constraints is likely to vary depending on the nature of the task. Consequently, the mechanisms and degree of incubation may differ across tasks, reflecting the structural and procedural demands unique to each problem type.

Importantly, this does not preclude the existence of entirely different sources of incubation for other classes of tasks, sources that might not be identifiable through the analysis of Mednick's triads.

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