Implicit cognition in problem solving

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Abstract

Psychological theories of problem solving have largely focused on explicit processes that gradually bring the solver closer to the solution step-by-step in a mostly explicit and deliberative way. This approach to problem solving is often inefficient or ineffective when the problem is too complex, poorly understood, or ambiguous. In such a case, a more intuitive or implicit approach to problem solving might be more appropriate. The role of implicit processes in producing creative solutions is called 'incubation'. In this chapter, we review the Explicit-Implicit Interaction (EII) theory of creative problem solving, an integrative framework focusing on the role of implicit processes in problem solving. The EII theory has been implemented using a computational model based on the CLARION cognitive architecture. Results from some of the computational simulations are also reviewed. We conclude by discussing how the EII theory can contribute to cognitive neuroscience research on creative problem solving.

Introduction

Many psychological theories have highlighted a role for implicit cognitive processes (e.g., Ashby, Alfonso-Reese, Turken, & Waldron, 1998; Evans, 2006; Reber, 1989). For instance, similarity has been shown to affect reasoning through processes that are mostly implicit (Sun, 1994; Sun & Zhang, 2006). In problem solving, implicit processes are often thought to generate hypotheses that are later explicitly tested (Evans, 2006; Helie, Proulx, & Lefebvre, 2011). Yet, most theories of problem solving have focused on explicit processes that gradually bring the problem solver closer to the solution in a deliberative way (Dorfman, Shames, & Kihlstrom, 1996). However, when an ill-defined or overly complex problem has to be solved (e.g., when the initial state or the goal state can lead to many different interpretations, or when the solution paths are highly complex), the solution is often found by sudden 'insight' (Pols, 2002; Reber, 1989; Schooler & Melcher, 1995; Schooler, Ohlsson, & Brooks, 1993), and regular problem solving theories are for the most part unable to account for this apparent absence of deliberative strategy (Bowden, Beeman, Fleck, & Kounios, 2005).

A complementary line of research on creative problem solving has tried to tackle complex problem solving for many years. However, theories of creative problem solving tend to be fragmentary and usually focus only on a subset of phenomena, such as incubation (i.e., a period away from deliberative work on the problem; for a review, see Smith & Dodds, 1999) or insight (i.e., the sudden appearance of a solution; for a review, see Pols, 2002). The lack of detailed computational models has resulted in their limited impact on the field of problem solving (Duch, 2006). In this chapter, we review some of the evidence supporting a role for implicit processing in problem solving and an integrative framework that was recently proposed, namely the Explicit-Implicit Interaction (EII) theory (Helie & Sun, 2010). One of the strengths of the EII theory is that it provides a process-based account of creative problem solving that is amenable to computational implementation. To illustrate this point, we then present some example simulation results from a CLARION-based implementation of the EII theory. We conclude with a discussion of how this work on integrative theories can facilitate new developments in the cognitive neuroscience of creative problem solving.

Creative problem solving: Four stages

The role of creativity in problem solving has been acknowledged at least since Wallas' (1926) seminal work. According to Wallas, humans go through four different stages when trying to solve a problem: preparation, incubation, illumination (i.e., insight), and verification. The first stage, preparation, refers to an initial period of search in many directions using (essentially) logic and reasoning. If a solution is found at this stage, the remaining stages are not needed. However, if the problem is ill-defined and/or too complex to be fully grasped, the preparation stage is unlikely to generate a satisfactory solution. When an impasse is reached, the problem solver stops attempting to solve the problem, which marks the beginning of the incubation phase. Incubation can last from a few minutes to many years, during which the attention of the problem solver is not devoted to the problem. The incubation period has been shown to increase the probability of eventually finding the correct solution (e.g., Dodds, Ward, & Smith, 2003; Smith & Dodds, 1999). The following stage, insight, is the "spontaneous" manifestation of the problem and its solution in conscious thought (i.e., the "Eureka!" moment). The fourth stage, verification, is used to ascertain the correctness of the insight solution. Verification is similar to preparation, because it also involves the use of deliberative thinking processes (with logic and reasoning). If the verification stage invalidates the solution, the problem solver usually goes back to the first or second stage and this process is repeated.

Even though the stage decomposition theory is difficult to test empirically, it has been used to guide much of Gestalt psychologists' early research program on problem solving (e.g., Duncker, 1945; Kohler, 1925; Maier, 1931). According to Gestalt psychology, ill-defined problems are akin to perceptual illusions: they are problems that can be understood (perceived) in a number of different ways, some of which allow for an easier resolution (Pols, 2002). Hence, the preparation stage would be made up of unsuccessful efforts on an inadequate problem representation, incubation would be the search for a better problem representation, and insight would mark the discovery of a problem representation useful for solving the problem. The verification phase would verify that the new problem representation is equivalent to the initial problem representation (Dunker, 1945). This Gestalt theory of problem solving provides a sketchy high-level description of creative problem solving but no detailed psychological mechanism was proposed.

More recent research has focused on finding evidence supporting the existence of the individual stages of creative problem solving. Because the preparation and verification stages are thought to involve mostly regular reasoning processes (Wallas, 1926), not much effort has been devoted to these two stages (relevant results can be borrowed from the existing literature; see, e.g., Johnson-Laird, 1999; Sun, 1994). In contrast, incubation and insight have received more attention.

Incubation

A recent review of experimental research on incubation shows that most experiments have found a significant effect of incubation (Dodds et al., 2003; see also Sio & Ormerod, 2009). Those experiments found an effect of incubation length, preparatory activity, clue, and distracting activities on participants' performance. The review suggests that performance is positively related to incubation length and that preparatory activities can increase the effect of incubation. Presenting a clue during the incubation period also has a strong effect. If the clue is useful, the performance is improved; if the clue is misleading, the performance is decreased. Moreover, the effect of clues is stronger when the participants are explicitly instructed to look for clues (Dodds, Smith, & Ward, 2002). The effect of distracting activities is not as clear. Helie, Sun, and Xiong (2008) showed that distracting activities can have different effects on incubation depending on whether the distracting activities share cognitive resources/processing with the task used to assess the presence of incubation. Finally, incubation has also been linked to well-known cognitive effects such as reminiscence (i.e., the number of new words recalled in a second consecutive free recall test; Smith & Vela, 1991) and priming (Yaniv & Meyer, 1987).

Insight

In a recent review of the different definitions used in psychology to characterize 'insight', Pols (2002) found three main elements. First, insight does not constitute just another step forward in solving a problem: it is a *transition* that has a major impact on the problem solver's conception of the problem. Second, insight is *sudden*: It usually constitutes a quick transition from a state of 'not knowing' to a state of 'knowing'. Third, the new understanding is *more appropriate*: Even when insight does not directly point to the solution, it leads to grasping essential features of the problem that were not considered previously.

In experimental psychology, insight is often elicited using ‘insight problems’ (e.g., Bowden et al., 2005; Dorfmann et al., 1996; Isaak & Just, 1996; Mayer, 1995; Pols, 2002). Such problems are diverse and characterized by the absence of direct, incremental algorithms allowing for their solutions. In many cases, they are selected because they have been shown to produce insight solutions in previous studies (Bowden et al., 2005). Empirically, insight is identified by a strong discontinuity in the subjective ‘feeling of knowing’ or the progress made in a verbal report (Pols, 2002). Some research has even shown a sudden increase of heart rate just before insight is reached (whereas regular problem solving is accompanied by a steady increase in heart rate; see, e.g., Jausovec & Bakracevic, 1995).

The Explicit-Implicit Interaction (EII) theory

The Explicit–Implicit Interaction (EII) theory (Helie & Sun, 2010) attempts to integrate and thus unify existing theories of creative problem solving in two different senses. First, most theories of creative problem solving have focused on either a high-level stage decomposition (e.g., Wallas, 1926) or on a process explanation of only one of the stages (Lubart, 2001). Second, the process theories of incubation (e.g., Smith & Dodds, 1999) and insight (e.g., Mayer, 1995; Ohlsson, 1992; Pols, 2002) are often incomplete and sometimes mutually incompatible. EII attempts to integrate the existing theories to makes them more complete in order to provide a detailed description of the processes involved in key stages of creative problem solving. EII starts from Wallas' (1926) stage decomposition of creative problem solving and provides a detailed process-based explanation sufficient for a coherent computational implementation. In this section, we present the core assumptions underlying the EII theory. Details on how EII captures existing theories of incubation and insight can be found in Helie & Sun (2010).

Principle #1: The co-existence of and the difference between explicit and implicit knowledge

The EII theory assumes the existence of two different types of knowledge, namely explicit and implicit, residing in two separate modules (Sun, 2002). Explicit knowledge is easier to access and verbalize and often said to be composed of symbols following hard constraints (Sun, Merrill, & Peterson, 2001; Sun, Slusarz, & Terry, 2005). However, using explicit knowledge requires extensive attentional resources (Curran & Keele, 1993; Sun et al., 2005). In contrast, implicit knowledge is relatively inaccessible, harder to verbalize, often "subsymbolic", and follows soft constraints (Sun, 1994, 2002). However, using implicit knowledge does not require much attentional resources. As such, explicit and implicit knowledge is processed differently. According to the EII theory, explicit processes perform some form of rule-based reasoning (in a very generalized sense; Smith, Langston, & Nisbett, 1992; Sun 1994) and represents relatively crisp and exact processing (often involving hard constraints; Sun et al., 2001), whereas implicit processing is 'associative' and represents soft-constraint satisfaction (Evans, 2008; Sloman, 1996; Sun, 1994).

Principle #2: The simultaneous involvement of implicit and explicit processes in most tasks

Explicit and implicit processes are involved simultaneously in most tasks under most circumstances (Smith & DeCoster, 2000; Sun, 2002). This can be useful because different representations and processing are used to describe the two types of knowledge (as described above in *Principle #1*). As such, each type of processes can end up with similar or conflicting conclusions that contribute to the overall output (Evans, 2007).

Principle #3: The redundant representation of explicit and implicit knowledge

According to the EII theory, explicit knowledge and implicit knowledge are often "redundant": they can amount to re-descriptions of one another in different representational forms. For example, knowledge that is initially implicit is often later re-coded to form explicit knowledge (through "bottom-up learning"; Helie et al., 2011; Sun et al., 2001, 2005). Likewise, knowledge that is initially learned explicitly (e.g., through verbal instructions) is often later assimilated and re-coded into an implicit form, usually after extensive practice (top-down assimilation: Ramamoorthy & Verguts, 2012; Sun & Zhang, 2004). There may also be other ways redundancy is created, e.g., through simultaneous learning of implicit and explicit knowledge. Redundancy often leads to interaction.

Principle #4: The integration of the results of explicit and implicit processing

Although explicit and implicit knowledge are often re-descriptions of one another, they involve different forms of representation and processing, which may produce similar or different conclusions (Sun & Peterson, 1998). The integration of these conclusions can lead to synergy, that is, overall better performance and faster learning (Sun et al., 2001). EII assumes that this synergy is an important component of creative problem solving.

Principle #5: The iterative (and possibly bidirectional) processing

Processing is often iterative and potentially bidirectional according to the EII theory. If the integrated outcome of explicit and implicit processing does not yield a definitive result (i.e., a result in which one is highly confident) and if there is no time constraint, another round of processing may occur, which uses the integrated outcome as part of the new input. Reversing the direction of reasoning may sometimes carry out this process (e.g., abductive reasoning; Johnson & Krem, 2001). Alternating between forward and backward processing has been argued to happen also in everyday human reasoning (Rips, 1994).

Accounting for creative problem solving using EII

The preceding assumptions allow for a conceptual model that captures the four stages of Wallas' (1926) analysis of creative problem solving (see Figure 1). First, Wallas described the preparation stage as involving "the whole traditional art of logic" (p. 84). Hence, the preparation stage is mainly captured by explicit processing in the EII theory. This is justified because explicit knowledge is usually rule-based (*Principle #1*), which includes logic-based reasoning as a special case. Also, the preparation stage has to be explicit in EII because peoples are responding to (explicit) verbal instructions, forming representations of the problem, and setting goals.

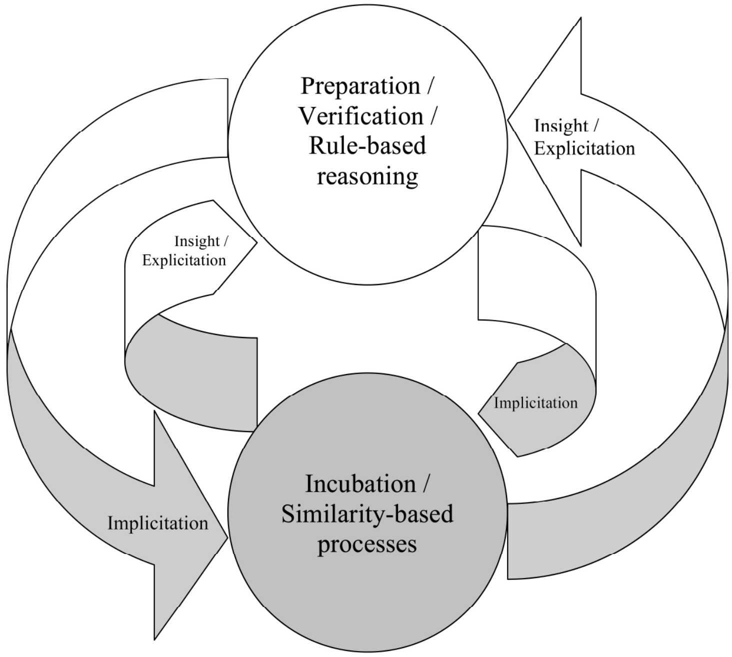

Figure 1. Information flow in the EII theory. The grey sections are implicit while the white sections are explicit.

In contrast, incubation relies more heavily on implicit processes in EII. According to Wallas, incubation is the stage during which "we do not voluntarily or consciously think on a particular problem" (p. 86). This is consistent with EII's account of the difference of conscious accessibility between explicit and implicit knowledge (*Principle #1*). Moreover, incubation can persist implicitly for an extended period of time in Wallas' theory. This characteristic of incubation corresponds well with the above-mentioned hypothesis concerning the relative lack of attentional resource requirement in implicit processing.

The third stage, insight, is "the appearance of the 'happy idea' together with the psychological events which immediately preceded and accompanied that appearance" (Wallas, 1926, p. 80). In EII, insight is obtained by the process of explicitation, which makes the output available for verbal report. It is worth noting that the intensity of insight is continuous (Bowden et al, 2005; Bowers et al., 1990; Pols, 2002). Correspondingly, explicitation is continuous in the EII theory (using an 'internal confidence level' or ICL; Helie & Sun, 2010). In particular, when the ICL of an output barely crosses the explicitation threshold, the output is produced but does not lead to an intense "Aha!" experience. In contrast, when the ICL of an output suddenly becomes very high and crosses the explicitation threshold, a very intense experience can result. According to the EII theory, intense insight experiences most likely follow the integration of implicit and explicit knowledge, as it can lead to a sudden large increase of the ICL and synergy (*Principle #4*).

Finally, the verification phase "closely resembles the first stage of preparation" (Wallas, 1926, pp. 85-86): it should thus involve mainly explicit processing according to the EII theory. In addition, environmental feedback can be used in place of rule-based verification (when available). Regardless of how verification is accomplished, if it suggests that the insight solution might be incorrect, the whole process is repeated by going back to the preparation stage (*Principle #5*; see also Finke et al., 1992; Wallas, 1926). In that case, EII predicts that the preparation stage can produce new information, because the knowledge state has been modified by the previous iteration of processing (e.g., some hypotheses may have been discarded as 'inadequate' or abductive reasoning might bring a new interpretation of the data).

A CLARION-based implementation of the EII theory for simulating empirical data

This section summarizes EII explanations and reviews the corresponding CLARION-based simulation results for some well-established psychological paradigms (e.g., free recall, lexical decision, and problem solving). Detailed explanations and simulations can be found in Helie and Sun (2010).

Incubation in a Lexical Decision Task

Yaniv and Meyer (1987) showed participants word definitions that were weakly associated with their definiendums. The participants had a limited time to find each definition's definiendum (i.e., the rare-word association task). If the participant found the definiendum, they were transferred to a lexical decision task where they had to classify briefly presented strings of letters as 'word' or 'non-word'. If the participant did not produce a definiendum, they were asked to rate their feeling of knowing (FOK) and then continued with the lexical decision task. The elapsed time between the rare-word association task and the lexical decisions task was interpreted as incubation (Yaniv & Meyer, 1987). The results show that definitions that allowed for the retrieval of the correct definiendums or generated high FOKs produced priming (i.e., faster reaction times) for the target word in the lexical decision task.

According to the EII theory, a rare-word association trial produces a simultaneous search in explicit and the implicit memories (*Principle #2*). Because the target association is rare, explicit memory search is not likely to yield a satisfactory solution within the allotted time (i.e., the existing set of hard constraints do not necessarily lead to solutions). In contrast, implicit memory search is more likely to retrieve the desired association if given enough time, because soft constraint satisfaction can allow for a partial match that can be iteratively improved. However, implicit memory search is often cut short by the experimenter who then asks the participant to take part in lexical decision trials. At the beginning of the lexical decision trials, implicit knowledge is still in the same state as it was at the end of the corresponding rare-word association trial. Hence, if the association was retrieved or nearly retrieved during the rare-word association trial (i.e., with high FOK), the memory search is not wasted and the target word is primed for the lexical decision trials. In contrast, the correct recognition of unrelated words (distractors) is not affected by the previous state of implicit knowledge in the lexical decision trials, because the cognitive work during the corresponding rare-word association trial was irrelevant. This conceptual explanation by EII led to a detailed computational model that produced simulations in line with Yaniv and Meyer's (1987) results. The results of 3,000 simulations with a CLARION-based model are shown in Figure 2.

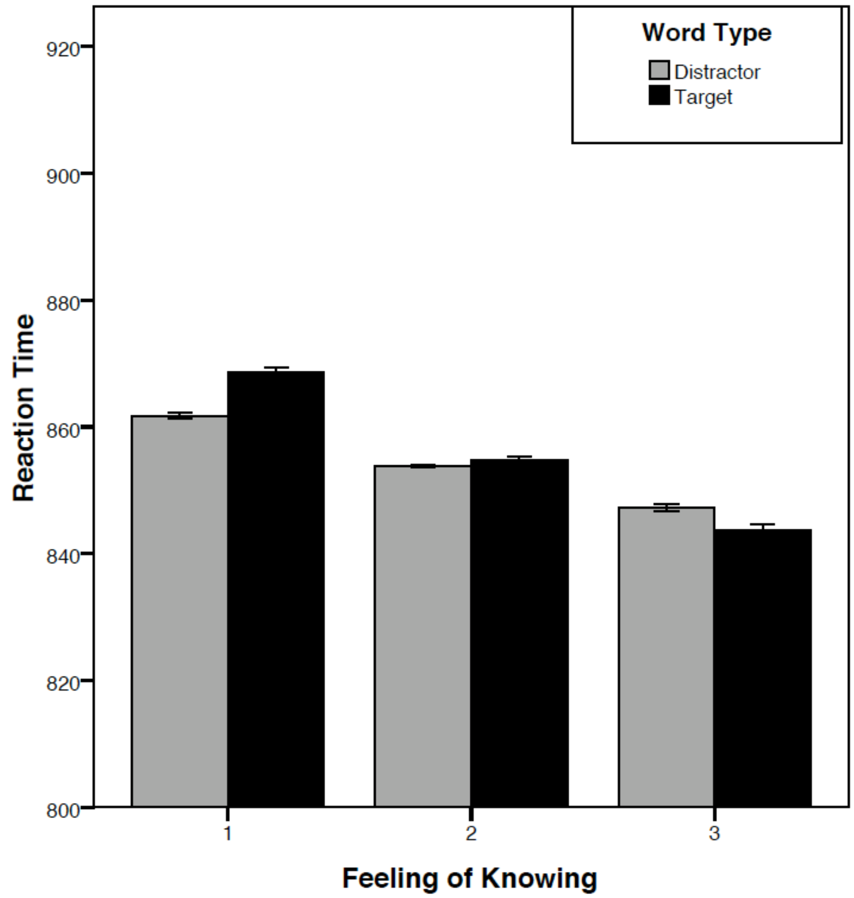

Figure 2. Simulated response times in the lexical decision task for participants who did not produce a definiendum in the rare-word association task. Details can be found in Helie & Sun (2010).

<u>Incubation in a Free Recall Task</u>

Smith and Vela (1991) asked participants to recall as many words as possible from a study list in two separate free recall tests. The independent variables were the test durations and the elapsed time between the free recall tests (incubation). The dependent variable was reminiscence (i.e., the number of new words recalled in the second test that were not recalled during the first). The results show that incubation length increases reminiscence, but not test duration.

According to the EII theory, parallel memory searches are conducted in explicit and implicit memories during the free recall tests. However, the incubation period is different: *Principle #1* of the EII theory stipulates that explicit memory search requires more attentional resources whereas implicit memory search is mostly automatic (i.e., it requires very little attentional resources). Thus, mostly implicit processes are deployed during the incubation phase, and words are retrieved from implicit memory (but not much from the explicit memory) during that period. These additional words are output at the beginning of the second test, increasing the number of words recalled in the second test (but not the first test). This conceptual explanation led a detailed model that produced simulations in line with Smith and Vela's (1991) results. The results of 12,000 CLARION-based simulations are shown in Figure 3.

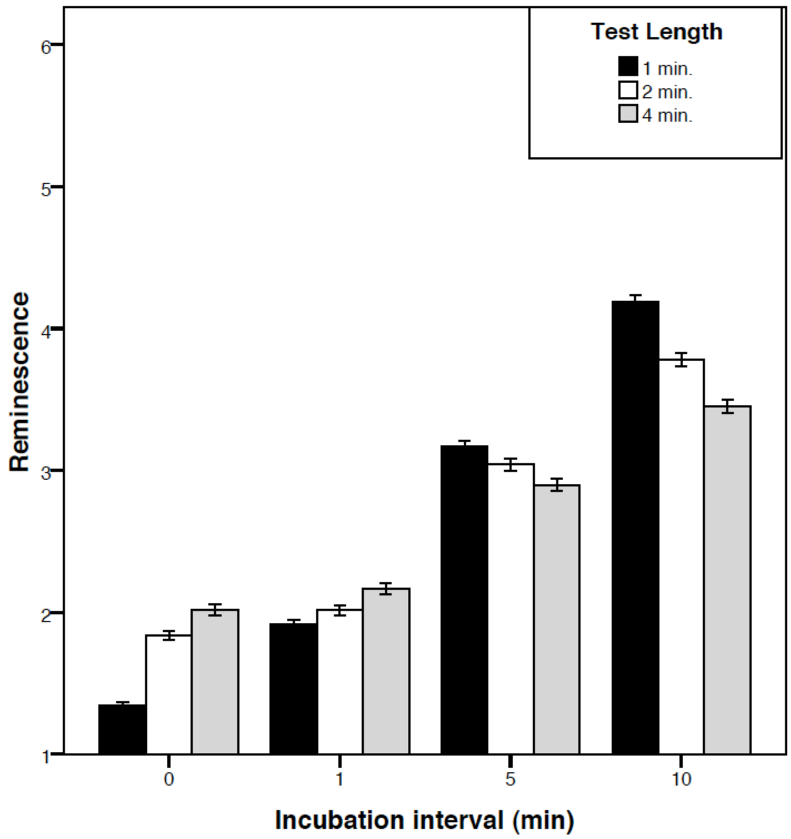

Figure 3. Simulated reminiscence effect. Details can be found in Helie & Sun (2010).

Insight in Problem Solving

Durso, Rea, and Dayton (1994) asked participants to explain the following story:

A man walks into a bar and asks for a glass of water. The bartender points a shotgun at the man. The man says 'thank you', and walks out.

The participants' task was to explain why the sight of the shotgun replaced the man's need for a glass of water (i.e., because he had the hiccup). To explain this story, the participants had two hours to ask the experimenter yes/no questions. When the time elapsed, each participant was classified as a 'solver' or as a 'non-solver' and its knowledge graph was drawn. Solvers and non-solvers knowledge graphs were shown to have different connectivity.

According to EII, reading the story results in both explicit memory retrieval and implicit memory search (incubation). However, explicit processing mostly brings up stereotypical semantic associations from the words included in the story (*Principle #1*). In contrast, the gradient of associations is flatter in implicit memory (Mednick, 1962). The search is more diffused, and more remote ("creative") associations can be retrieved using soft constraint satisfaction. According to the EII theory, implicit processing allows for the retrieval of more approximate, more hypothetical associations that differ from those retrieved explicitly. These implicit associations are then integrated with the result of explicit processing (*Principle #4*). If the chosen integrated association is deemed plausible (i.e., if the ICL is high enough), a question concerning the validity of this association is put to the experimenter. If the experimenter confirms the association, it is added into explicit knowledge; otherwise, it is removed (the participants' knowledge graph was likely explicit; see Durso et al., 1994). This process is iterated, with explicit and implicit processing reinitiated with the new state of the knowledge. This iterative process ends when the participant finds the correct solution or the allowed time elapses. The results of 8,000 CLARION-based simulations show that, consistent with this EII explanation, the probability of solving the problem increases with the amount of noise in (or flatness of) the implicit association retrieval (as measured by the number of edges differing between the knowledge graph and the solution graph; see Figure 4 below).

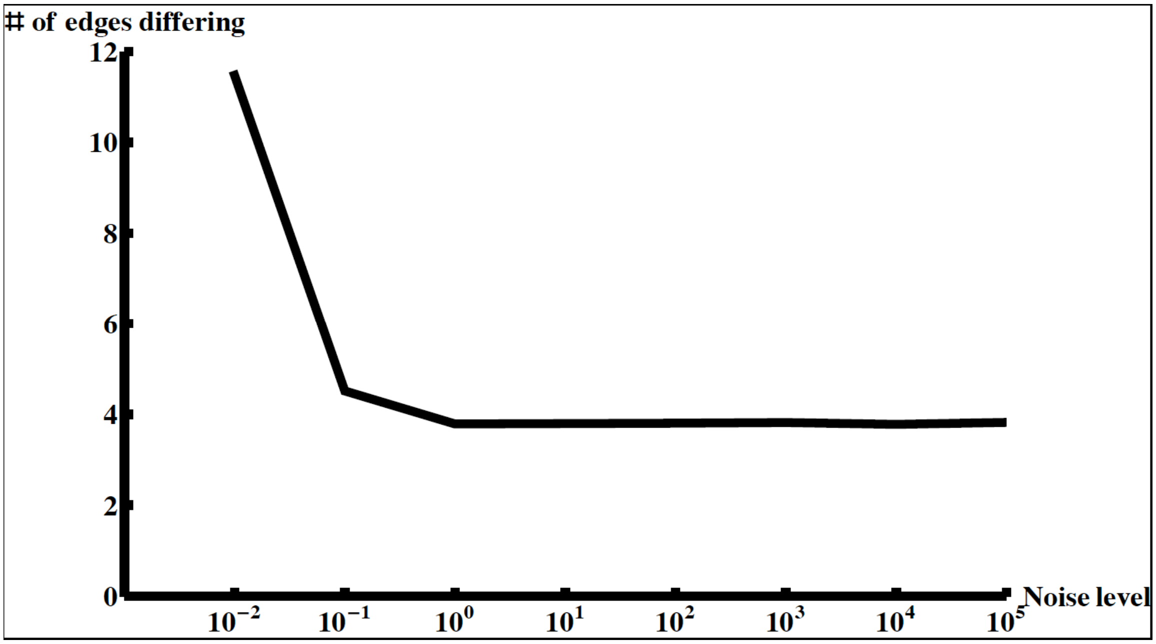

Figure 4. Mean number of edges differing between the knowledge graph output by the CLARION simulations and the solution graph. More details can be found in Helie & Sun, (2010).

<u>Overshadowing in Problem Solving</u>

Schooler, Ohlsson, and Brooks (1993) asked participants to solve the following problem:

> *A dealer of antique coins got an offer to buy a beautiful bronze coin. The coin had an emperor's head on one side and the date 544 B.C. stamped on the other. The dealer examined the coin, but instead of buying it, he called the police. Why?*

Each participant had two minutes to solve this problem. Following this initial problem-solving period, half of the participants were assigned to an unrelated task while the remaining half were asked to verbalize their problem solving strategies. In both cases, the interruption period lasted 90 seconds and was followed by another four-minute attempt to solve the initial problem. The dependent variable was the proportion of insight problems solved by the participants. The results show that an overly explicit mode of problem solving (verbalization) reduces the probability of solving insight problems.

According to the EII theory, both explicit and implicit processing is initiated by the problem (*Principle #2*). However, insight problems are more likely to be solved by the implicit processes, because rule-based processes are ineffective in solving such problems (Bowden et al., 2005). In line with the earlier explanation of Durso et al.'s (1994) experiment, hypotheses are generated using implicit knowledge and then verified using explicit knowledge. When the participants were interrupted to take part in an unrelated activity, hypotheses were still being generated implicitly [similar to the explanation of Smith and Vela's (1991) reminiscence data]. In contrast, participants who had to verbalize their problem solving strategies could not generate implicit hypotheses easily (because they were forced into an explicit processing mode). When the participants went back to working on the problem, the verbalization group had fallen behind, so the overall probability of solving the problem by the verbalization group was lower than that of the control group. The results of 10,000 CLARION-based simulations are shown in Figure 5.

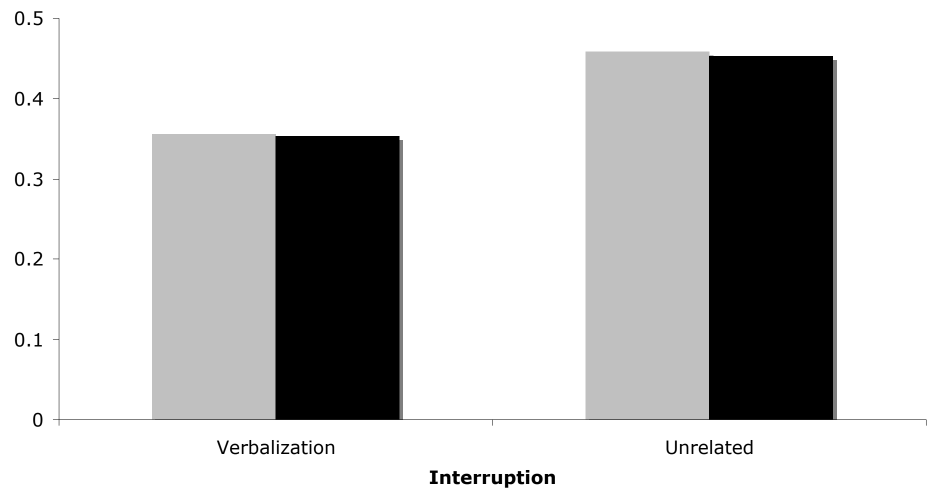

Figure 5. Proportion of correct explanations selected by the participants in Schooler et al.'s (1993) Experiment 1 (gray bars) and by the CLARION simulations (black bars). More details can be found in Helie & Sun (2010).

Implications for cognitive neuroscience research on creative problem solving

The search for a neuroscientific account of creative problem solving has been particularly elusive (Dietrich & Kanso, 2010). While many authors have argued for a theory of right-hemisphere dominance (e.g., Bowden et al., 2005), an extensive review of the literature conducted by Dietrich and Kanso found that many studies did not support the right-hemisphere dominance hypothesis. The only brain area that consistently shows task-related activation is the prefrontal cortex and, even in this case, it is unclear what kind of change or which specific structure is activated. For instance, many electroencephalography (EEG) studies reported task-related changes in the lower portion of the alpha band (8-12 Hz) in the prefrontal cortex (e.g., Fink et al., 2006; Razumnikova, Volf, & Tarasova, 2009). However, many other studies did not find task-related changes in the alpha band measured in the prefrontal cortex (for a review, see

Dietrich & Kanso, 2010). A similarly confusing picture emerges in temporal and parietal cortices (e.g., Fink et al., 2009). As such, Dietrich and Kanso (2010) concluded that "not a single currently circulating notion on the possible neural mechanisms underlying creative thinking survives close scrutiny." (p. 845). One possible reason for this confusion may be that searching for the locus of creative thinking or creative problem solving is ill-defined and too big an endeavor, and that one should instead focus on sub-processes involved in creative problem solving (as argued in, e.g., Dietrich & Kanso, 2010; Fink et al., 2009). For instance, insight research has focused on conflict resolution, and the results are more consistent: The anterior cingulate cortex plays an important role in insight, and the superior temporal gyrus plays a role at least in verbal problems (Dietrich & Kanso, 2010).

It is interesting to note that these results are in line with the process account of insight in the EII theory. Anterior cingulate cortex is often associated with uncertainty and conflict resolution (Botvinick, Cohen, & Carter, 2004), which corresponds to the internal confidence level and explicitation threshold in EII. The superior temporal gyrus is an interface between the ventral and dorsal visual pathways that allows for the exploration of both object-based and spatial information (Karnath, 2001). Hence, it is an ideal locus for synergistic integration, which is an important component of insight in EII. Integrative process theories like EII can be useful in decomposing the task into sub-processes that are responsible for creative problem solving and make predictions about their neural underpinning. For instance, EII predicts that rules are used, albeit often unsuccessfully, during creative problem solving. This predicts the presence of lateral prefrontal cortex activation, which has been observed in many creative thinking experiments (Dietrich & Kanso, 2010). In addition, EII predicts an important role for memory and associative retrieval in creative problem solving. The hippocampus, which along with the medial temporal lobes is associated with declarative memory (Eichenbaum. 1997, 2004), has shown task-related activation in a series of creative thinking tasks (Fink et al., 2009). Hence, although EII was not motivated by neuroscience, it can contribute to cognitive neuroscience research by guiding the search for neural processes and networks of activation.

Conclusion

Clearly, much work is still needed in order to make sense of the various areas of research included under the umbrella term 'creative problem solving'. In this chapter, we reviewed work on the EII theory (Helie & Sun, 2010), an integrative framework for re-interpreting and integrating some important (but fragmentary) theories of incubation, insight, and creativity. In addition to contributing to the theoretical coherence and integration of these research areas, EII has been used to develop a unified computational model (based on CLARION), and some simulation results have been reviewed. The simulation of these tasks suggests the psychological plausibility of both the EII theory and the CLARION-based model. In addition, the possible implication of EII for cognitive neuroscience research on creative problem solving has been discussed. Although the EII theory may not account for all instances of creative problem solving, nevertheless it is an important first step in the development of integrative frameworks in order to develop a coherent picture of creative problem solving.

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References

Ashby, F. G., Alfonso-Reese, L. A., Turken, A. U., & Waldron, E. M. (1998). A neuropsychological theory of multiple systems in category learning. *Psychological Review*, *105*, 442-481.

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: An update. *Trends in Cognitive Sciences*, *8*, 539-546.

Bowden, E.M., Beeman, M. J., Fleck, J., & Kounios, J. (2005). New approaches to demystifying insight. *Trends in Cognitive Science*, *9*, 322-328.

Bowers, K.S., Regehr, G., Balthazard, C., & Parker, K. (1990). Intuition in the context of discovery. *Cognitive Psychology*, *22*, 72-110.

Curran, T., & Keele, S.W. (1993). Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19*, 189-202.

Dietrich, A., & Kanso, R. (2010). A review of EEG, ERP, and neuroimaging studies of creativity and insight. *Psychological Bulletin*, *136*, 822-848.

Dodds, R.A., Smith, S.M., & Ward, T.B. (2002). The use of environmental clues during incubation. *Creativity Research Journal, 14*, 287-304.

Dodds, R.A., Ward, T.B., & Smith, S.M. (2003). A review of experimental literature on incubation in problem solving and creativity. In M.A. Runco (Ed.), *Creativity Research Handbook. Vol. 3.* Cresskill, NJ: Hampton Press.

Dorfman, J., Shames, V.A., & Kihlstrom, J.F. (1996). Intuition, incubation, and insight: Implicit cognition in problem solving. In G. Underwood (Ed.), *Implicit Cognition* (pp. 257-296). New York: Oxford University Press.

Duch, W. (2006). Computational creativity. *Proceedings of the International Joint Conference on Neural Networks* (pp. 435-442). Vancouver, BC: IEEE Press.

Duncker, K. (1945). On problem solving. *Psychological Monographs*, *58*, 1-113.

Durso, F.T., Rea, C.B., & Dayton, T. (1994). Graph-theoretic confirmation of restructuring during insight. *Psychological Science*, *5*, 94-98.

Eichenbaum, H. (1997). Declarative memory: Insights from cognitive neurobiology. *Annual Review of Neuroscience*, *48*, 547-572.

Eichenbaum, H. (2004). Hippocampus: Cognitive processes and neural representations that underlie declarative memory. *Neuron*, *44*, 109-120.

Evans, J.B.T. (2006). The heuristic-analytic theory of reasoning: Extension and evaluation. *Psychonomic Bulletin & Review*, *13*, 378-395.

Evans, J.B.T. (2007). On the resolution of conflict in dual process theories of reasoning. *Thinking & Reasoning*, *13*, 321-339.

Evans, J.B.T. (2008). Dual-processing accounts of reasoning, judgment, and social cognition. *Annual Review of Psychology*, *59,* 255-278.

Fink, A., Grabner, R., Benedek, M., & Neubauer, A. (2006). Divergent thinking training is related to frontal electroencephalogram alpha synchronization. *European Journal of Neuroscience*, *23*, 2241–2246.

Fink, A., Grabner, R. H., Benedek, M., Reishofer, G., Hauswirth, V., Fally, M., Neuper, C., Ebner, F., & Neubauer, A. C. (2009). The creative brain: investigation of brain activity during creative problem solving by means of EEG and FMRI. *Human brain mapping*, *30*, 734-748.

Finke, R.A., Ward, T.B., & Smith, S.M. (1992). *Creative Cognition: Theory, Research, and Applications*. Cambridge, MA: MIT Press.

Hélie, S., Proulx, R., & Lefebvre, B. (2011). Bottom-up learning of explicit knowledge using a Bayesian algorithm and a new Hebbian learning rule. *Neural Networks, 24*, 219-232.

Hélie, S. & Sun, R. (2010). Incubation, insight, and creative problem solving: A unified theory and a connectionist model. *Psychological Review*, *117*, 994-1024.

Hélie, S., Sun, R., & Xiong, L. (2008). Mixed effects of distractor tasks on incubation. In B.C. Love, K. McRae, & V.M. Sloutsky (Eds.) *Proceedings of the 30th Annual Meeting of the Cognitive Science Society* (pp. 1251-1256). Austin, TX: Cognitive Science Society.

Isaak, M.I. & Just, M.A. (1996). Constraints on thinking in insight and invention. In R.J. Sternberg & J.E. Davidson (Eds.) *The Nature of Insight* (pp. 281-325). Cambridge, MA: MIT Press.

Jausovec, N. & Bakracevic, K. (1995). What can heart rate tell us about the creative process? *Creativity Research Journal*, *8*, 11-24.

Johnson, T.R. & Krems, J.F. (2001). Use of current explanations in multicausal abductive reasoning. *Cognitive Science*, *25*, 903-939.

Johnson-Laird, P.N. (1999). Deductive reasoning. *Annual Review of Psychology*, *50*, 109-135.

Karnath, H. –O. (2001). New insights into the functions of the superior temporal cortex. *Nature Reviews: Neuroscience*, *2*, 568-576.

Kohler, W. (1925). *The Mentality of Apes*. New York: Liveright.

Lubart, T.I. (2001). Models of the creative process: Past, present and future. *Creativity Research Journal*, *13*, 295-308.

Maier, N.R.F. (1931). Reasoning in humans: II. The solution of a problem and its appearance in consciousness. *Journal of Comparative Psychology*, *12*, 181-194.

Mayer, R.E. (1995). The search for insight: Grappling with Gestalt psychology's unanswered questions. In R.J. Sternberg & J.E. Davidson (Eds.) *The Nature of Insight* (pp. 3-32). Cambridge, MA: MIT Press.

Mednick, S. A. (1962). The associative basis of the creative process. *Psychological Review*, *69*, 220-232.

Ohlsson, S. (1992). Information-processing explanations of insight and related phenomena. In M.T. Keane & K.J. Gilhooly (Eds.) *Advances in the Psychology of Thinking. Volume 1* (pp. 1-44). London, UK: Havester Wheatsheaf.

Pols, A.J.K. (2002). *Insight Problem Solving*. Doctoral Dissertation, Department of Psychology, University of Utrecht, Netherlands.

Ramamoorthy, A., & Verguts, T. (2012). Word and deed: A computational model of instruction following. *Brain Research*, *1439*, 54-65.

Razumnikova, O. M., Volf, N.,&Tarasova, I. V. (2009). Strategy and results: Sex differences in electrographic correlates of verbal and figural creativity. *Human Physiology*, *35*, 285–294.

Reber, A.S. (1989). Implicit learning and tacit knowledge. *Journal of Experimental Psychology: General*, *118*, 219-235.

Rips, L.J. (1994). *The Psychology of Proof: Deductive Reasoning in Human Thinking*. Cambridge, MA: MIT Press.

Schooler, J.W. & Melcher, J. (1995). The ineffability of insight. In S.M. Smith, T.B. Ward, & R.A. Finke (Eds.) *The Creative Cognition Approach* (pp. 97-133). Cambridge, MA: MIT Press.

Schooler, J.W., Ohlsson, S., & Brooks, K. (1993). Thoughts beyond words: When language overshadows insight. *Journal of Experimental Psychology: General*, *122*, 166-183.

Sio, U. N., & Ormerod, T. C. (2009). Does incubation enhance problem solving? A meta-analytic review. *Psychological Bulletin*, *135*, 94-120.

Sloman, S.A. (1996). The empirical case for two systems of reasoning. *Psychological Bulletin*, *119*, 3-22.

Smith, E.E., Langston, C., & Nisbett, R.E. (1992). The case for rules in reasoning. *Cognitive Science*, *16*, 1-40.

Smith, E.R. & DeCoster, J. (2000). Dual-process models in social and cognitive psychology: Conceptual integration and links to underlying memory systems. *Personality and Social Psychology Review*, *4*, 108-131.

Smith, S.M. & Dodds, R.A. (1999). Incubation. In M.A. Runco & S.R. Pritzker (Eds.) *Encyclopedia of Creativity* (pp. 39-43). San Diego, CA: Academic.

Smith, S.M. & Vela, E. (1991). Incubated reminiscence effects. *Memory & Cognition*, *19*, 168-176.

Sun, R. (1994). *Integrating Rules and Connectionism for Robust Commonsense Reasoning*. New York: John Wiley and Sons.

Sun, R. (2002). *Duality of the Mind: A Bottom-up Approach Toward Cognition*. Mahwah, NJ: Lawrence Erlbaum Associates.

Sun, R., Merrill, E., & Peterson, T. (2001). From implicit skills to explicit knowledge: A bottom-up model of skill learning. *Cognitive Science, 25*, 203-244.

Sun, R. & Peterson, T. (1998). Autonomous learning of sequential tasks: Experiments and analyses. *IEEE Transactions on Neural Networks*, *9*, 1217-1234.

Sun, R., Slusarz, P., & Terry, C. (2005). The interaction of the explicit and the implicit in skill learning: A dual-process approach. *Psychological Review, 112*, 159-192.

Sun, R. & Zhang, X. (2004). Top-down versus bottom-up learning in cognitive skill acquisition. *Cognitive Systems Research*, *5*, 63-89.

Sun, R. & Zhang, X. (2006). Accounting for a variety of reasoning data within a cognitive architecture. *Journal of Experimental and Theoretical Artificial Intelligence*, *18*, 169-191.

Wallas, G. (1926). *The Art of Thought*. New York: Franklin Watts.

Yaniv, I. & Meyer, D.E. (1987). Activation and metacognition of inaccessible stored information: Potential bases for incubation effects in problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *13*, 187-205.