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Studying insight problem solving with neuroscientific methods ☆

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Abstract

Insights are sporadic, unpredictable, short-lived moments of exceptional thinking where unwarranted assumptions need to be discarded before solutions to problems can be obtained. Insight requires a restructuring of the problem situation that is relatively rare and hard to elicit in the laboratory. One way of dealing with this problem is to catalyze such restructuring processes using solution hints. This allows one to obtain multiple insight events and their accurate onset times, which are required for event-related designs in functional magnetic resonance imaging (fMRI) and Electroencephalogram (EEG), and to reliably record the activity associated with the restructuring component of insight. In this article, we discuss in detail the methodological challenges that brain research on insight poses and describe how we dealt with these challenges in our recent studies on insight problem solving.

Keywords: Insight problem solving; Problem solving; Aha! experience; Creative thinking; fMRI; ERP; Neuroimaging

1. Introduction

Insight is a classical topic in the psychology of thinking [1–4] and refers to solution ideas ("Aha!" experiences) that suddenly pop into a problem solver's mind after systematic solution attempts have repeatedly failed. Insight in problem solving has been studied for almost a hundred years with behavioral methods, generating a variety of functional models of insight [5–8]. However, we know surprisingly little about the brain processes that generate sudden insights in problem solving. In addition to neuropsychological studies [9], neuroimaging methods such as fMRI and EEG could provide powerful means to determine the neural correlates of insight.

However, brain researchers using these methods [10–14] encounter two major obstacles when trying to identify the neural underpinnings of insight. The first obstacle is that it is hard to find appropriate tasks for the systematic study of insight. Classical insight problems, such as the "nine-dot problem" [15], the "two string problem" [3], and the "candle problem" [1], greatly vary with regard to different sources of difficulty they pose for the solver [16] and only few are available [5]. The second obstacle is created by the particular nature of insight: by definition, insight opens up a new solution path for solving problems on which the solver got stuck [8]. Thus, once insight has been attained on a problem, subsequent exposure to closely related problems is no longer regarded as insightful. This is in contrast to neuroimaging method's requirement of precise timing of repeatable behavior on well-controlled tasks. Furthermore, for difficult problems the time to solution is well beyond the constraints of the data acquisition method (it can take hours, days, or even weeks to solve a difficult insight problem).

In the research we have conducted so far we have dealt with these issues in the following way: first, we collected different classes of puzzles and riddles that can reliably produce insight-like experiences within a relatively short time

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window. Second, after a pre-specified time we provided the solution or hints to the solution to participants who had failed to solve the problem on their own. This allowed us to produce insight like experiences at particular points in time and to record neural activity correlated with these experiences in particular time windows [11–14,17,18]. In the following, we will discuss in detail the methodological challenges that brain research on insight poses and we will describe how we tried to deal with these challenges in our recent fMRI and EEG researches on insight problem solving.

2. Defining requirements for neuroimaging studies of insight

An ideal experimental paradigm for studying the neural correlates of insight with fMRI or EEG should have at least the following features:

(1) *Elicit restructuring*. The mental events that occur while a person tries to solve problems should capture some essential features of insight. Although there is still debate about how the cognitive and neuronal processes that make insight special are best characterized, most modern researchers agree with the early Gestalt psychologists that insight involves a restructuring of the problem situation [1,2,4,19]. More specifically, in order to solve insight problems one needs to detach oneself from one's prior experience with similar problems and to see the problem in a new way, or one needs to establish a new relation between the problem elements [20,21,8,22]. Recent research suggests that different types of restructuring can occur. Restructuring can involve a perceptual re-interpretation of the problem [8], directing attention to the critical problem elements [23–25], a re-combination of elements that gives the problem a new meaning [5,26], or a change in the goal of problem solving [8]. Regardless of the specific processes involved, the material used in any study of insight problem solving needs to reliably produce insight events in the laboratory.

(2) *Multiple insight events and accurate onset time*. The neuroscientific study of insight requires that multiple insight events can be elicited within a limited time period. Routine event-related fMRI or ERP studies require 10–50 trials in each condition to guarantee reliable analysis. Although it is possible that efficient single trial analysis methods can be reliably established in the future, for now, multiple insight events are a must. A related requirement is that one needs to be able to precisely time lock the insight events. In event-related fMRI or EEG studies, one must exactly know the temporal onset of the critical mental events in order to accurately model the target events for statistical analysis. It might seem that block designs provide a more flexible alternative to study insight with fMRI. In this type of analysis knowledge of the exact time of the critical events is not necessarily required. However, we believe that block designs are not well suitable for the study of insight. The reason is that restructurings are sporadic, short-lived moments of exceptional thinking that would only make up a tiny fraction of all mental processes occurring within a block. Thus it is likely that brain activations reflecting insight will get lost in myriads of other activations when using block designs.

(3) *Hypothesis testing*. The ideal experimental paradigm to study insight should allow one to perform flexible manipulations to test various kinds of research hypotheses. This includes general hypotheses derived from functional theories as well as hypotheses about the precise function of particular brain areas. For example, during the moment of insight, an old inefficient way of thinking is replaced by a new and more efficient way of thinking. This replacement implies cognitive conflict. Thus one could predict that brain areas that mediate the processing of cognitive conflict (e.g., the anterior cingulate cortex, ACC [27–29]) should participate in the restructuring occurring during insight. This hypothesis is based on cognitive models of insight and should hold across different studies of insight, regardless of the particular problem used. However, in addition to testing this general hypothesis, it is also important to know the exact function of a given region in restructuring. To determine this function is not as simple as it might seem, because insight is a holistic process in which people achieve multiple breakthroughs in one single step [16]. The ideal experimental paradigm for the study of insight would be flexible enough to enable a number of manipulations to test more specific hypotheses. In our example, ACC activation could be related to different functions, such as conflict monitoring (realizing the contradictions between different ways of thinking), error detection (realizing that one's initial thinking was inappropriate), problem success (realizing the crucial step towards the solution), or general attentive control. The ideal experimental paradigm for the study of insight would be flexible enough to enable precise tests of these alternative hypotheses.

(4) *Reference states*. An ideal insight paradigm should enable researchers to define suitable reference states. Brain imaging analysis relies heavily on the contrast between a target state and a reference state (i.e., the baseline). An ideal reference state should be comparable with the target state in every aspect except the one to be examined. Compared to other domains of brain imaging research, it is relatively difficult to come up with good reference states in studies of insight problem solving, because insight includes a set of highly integrated processes that are released in one moment. This makes insight somewhat incomparable with other analytical modes of thinking.

(5) *Internally vs. externally triggered insights*. Finally, the ideal insight paradigm should allow one to study internally and externally triggered insights. This refers to the fact that problem solvers can achieve restructurings on their own or that, alternatively, restructuring can be triggered by solution hints. Although many behavioral and neuroimaging experiments addressing insight problem solving are based on the assumption that solution hints trigger similar processes as internally generated solution attempts [16,30,31,11], one cannot be sure whether this assumption really

holds. Without doubt, the phenomenon of interest is internally generated insight. Triggering insights externally is just a way of creating paradigms that make scientific research on insight tractable. Clearly, there is a conflict between the requirement of ecological validity that dictates to investigate internally generated insights and the methodological requirement of accurate onset times for target events in fMRI and EEG studies (see point 2). Accurate onset times are much more easily obtained for externally triggered insights, because it is difficult to determine the exact onset time of an internally generated insight. Although we can ask participants to indicate the time of their insight (e.g., with a button press), participants' reports will be delayed. Thus one has to go back several hundreds milliseconds to anchor the onset time of the internally generated insight and one can never be sure whether the event timing is correct.

In the following, we will apply the criteria defined above to our recent attempts to identify the brain processes that underlie restructuring during insight problem solving. Generally speaking, the methods we have developed so far are relatively well with respect to criteria (1) to (4) and not so well with regard to (5).

3. Rationale of insight paradigm

3.1. Restructuring

The process of restructuring is regarded as the essential feature of insight problem solving. Weisberg provided a framework to determine whether restructuring has occurred while a person solved a particular problem [22]. According to this framework, one should diagnose the solver's initial attempts to solve a problem and compare them to later problem solving steps that led to the correct solution. If one can observe an obvious discontinuity between the initial way of thinking and the final correct solution, and if the final solution is structurally different from the initial way of thinking, then one may infer restructuring has occurred in the course of the problem solving process.

One way to elicit restructuring is the use of riddles and ambiguous sentences where solvers need to overcome the initially suggested meaning of the single words to answer a question or to make sense of an ambiguous sentence. For instance, in one neuroimaging study [11], we used riddles such as *"The thing that can move heavy logs, but cannot move a small nail"* and asked participants to guess what the answer is. In order to come up with the correct answer "river" one has to ignore object weight that is the focus of the problem description, and restructure the question in a way that allows one to reformulate the problem in terms of object density. In another study participants were given ambiguous sentence such as *"The haystack was important because the cloth ripped"*. They were required to figure out what situation the sentence referred to [12,13]. Finding the correct situation "parachute jumping" requires a similar restructuring as the riddles mentioned above. Participants were given sufficient time to ponder over the problem and to thoroughly try plausible approaches until they felt they could not solve the problem by themselves. Then the solution was uncovered. Most participants achieved an insightful understanding of the problem within 2 s after presentation of the solution.

Why is this procedure sufficient to elicit restructuring? First, there was a clear discontinuity in participant's thinking about the problem: their initial attempts to solve the problems failed whereas the presentation of the correct solution led to a sudden understanding. Second, this discontinuity was brought about through restructuring processes. The riddles or puzzles we used in the study always contained misleading components in the initial statement of the problem. For example, in the above-mentioned "river" riddle, the words "move" and "heavy logs" usually mislead the participants to think about something like a crane; in the "parachute" riddle, the words "cloth" and "ripped" usually mislead the participants to think about clothes one wears on one's body. These unwarranted assumptions were so dominating that it was virtually impossible for many participants to interpret the words in any other way. Restructuring processes as triggered by the solutions cue "river" or "parachute" led to the alternative interpretation that logs can float on water but nails cannot, and the interpretation that cloth can refer to canopy and that therefore the role of the haystack is to cushion a fall.

Third, to examine whether the process of restructuring was evoked in each individual for each puzzle, participants were asked to retrospectively recall how they solved each puzzle. It turned out that for the majority of problems (72.9%), participants attributed their failure to having thought about the problem in the wrong way. Furthermore, they reported that upon seeing the solution cue they discarded their previous assumptions and changed their mental perspective in a way that led to the solution [13]. Thus the participant's reports provide a further piece of evidence indicating that restructuring did occur in our experiments.

A further requirement for restructuring is that it should involve a change in the deep structure of the problem representation rather than superficial changes [22]. In a recent study, we compared the neural network for different kinds of changes in the problem representation (Luo et al., unpublished experimental observations). The participants worked on brainteasers like the following one before brain scanning started: *"Unfortunately, Smith and his son met a traffic accident; Smith died on the spot and the boy was badly hurt. They brought the boy to the hospital for he needed an immediate operation. However, the surgeon saw the son and said: 'sorry, I cannot perform an operation to my own son.' How could this occur?"* (The answer is "The surgeon is boy's mother").

For each participant a list of brainteasers was selected so that he/she understood the puzzles very well but could not solve them. Then, during fMRI scanning, we showed each participant the selected puzzles, followed by three kinds of hints: restructuring hints (RESH) that should result in a deep structural change of problem representation (e.g., *the surgeon has long hair*); unrelated hints (UH) that should induce superficial changes in the problem representation but should not lead to restructuring (e.g, *the surgeon has blue eyes*); and repetition hints (REPH) that restated the original problem description (e.g., *the surgeon was unable to do the operation*). The results showed that different types of hints led to activation of different neural networks. Most importantly, in the RESH condition we observed activation in bilateral superior frontal gyrus (BA 8/6), medial frontal gyrus (BA 8) extending to cingulate cortex, and bilateral posterior middle temporal gyrus, suggesting that this network is involved in restructuring. In contrast, the more superficial change in the problem representation induced in the UH condition was associated with activation in anterior parts of bilateral superior and middle temporal gyrus (BA 22/21), together with frontal activation in superior/medial superior frontal gyrus (BA 8) and in left middle frontal gyrus (BA 9).

However, these results are open to an alternative explanation. The frontal activation evoked in RESH relative to UH could reflect differences in the attentive control of task-related information rather than specific processes required for restructuring. In other words, participants might have used a quick filtering process to differentiate between task-related hints and task-unrelated ones. This would have allowed them to quickly decide whether or not a hint is critically related to the present problem. Once they felt a hint was unrelated, they might have stopped focused processing of the hint.

To control for the effects of attentive control, we compared the processing of crucial hints to the solution of the brainteasers described above and the processing of answers to unknown knowledge questions. The knowledge questions required the completion of traditional sayings which participants had some familiarity with, but for which they could not recall the exact answer. For example: *"There is an old saying that 'after boys and girls reach the age of seven, they cannot …', What can they not do?"* The answer is that they cannot sit and eat together at the same table (this old saying is about the tradition of male–female separation and such sayings appear frequently in the old famous Japanese and Chinese novels). Like the brainteasers puzzles, the answers to unknown quiz questions also evoke an attentive processing of task-related information and a transition from not knowing to knowing, but the additional information does not lead to a restructuring of the earlier processed information. The contrast between the processing of the solution hints to the brainteasers and the processing of answers to knowledge questions exhibited positive activities in bilateral posterior middle temporal/occipital gyrus and left middle frontal gyrus and negative activation in left middle temporal gyrus, right superior temporal gyrus, and right lingual gyrus. However, the activation in superior and medial frontal gyrus that occurred in the contrast of restructuring hints (RESH) versus unrelated hints (UH), was no longer present in this comparison. This result implies that the superior and medial frontal gyrus were involved equally in the processing of the two kinds of answers. Thus one can infer that the function of these areas in restructuring was the allocation of general attentive control on task-related information.

A final issue related to restructuring is that a change in problem representation should occur during the final stage of problem solving. This implies that the solution should not be part of the initially defined problem space. Take the Wisconsin Card Sorting Task (WCST) as an example for the latter situation [32]. The WCST asks the participant to match test cards to reference cards according to the color, shape, or number of stimuli depicted on the cards. Feedback is provided after each match, enabling the participant to acquire the correct rule of classification. After a certain number of correct matches, the rule is changed without notice, and the participant needs to shift to a new way of classification (discover a new rule). Thus, the WCST measures cognitive flexibility, which is the ability to alter a behavioral response mode in the face of changing contingencies (set-shifting). However, in contrast to solutions that require restructuring, all of the rules in WCST are within the space of possibilities suggested by the original problem representation.

Comparing the results of brain imaging studies on insight with those on performance of the WCST reveals a key difference between finding a new rule in the WCST and restructuring during insight problem solving [11,12]. The anterior cingulate cortex (ACC), an area known to be involved in cognitive conflict monitoring [27], was activated during insight problem solving but not in the key contrast of brain imaging studies on the WCST: activation in trials in which people receive negative feedback minus activation in trials in which people receive positive feedback [32]. Although this contrast reflects the brain activation that goes hand in hand with the need for a mental shift to a new response set, ACC activation was absent. In fact, the area that is sensitive to set-shifting in the WCST is the left lateral prefrontal cortex (PFC) [32]. A likely reason for this difference is that in the WCST, participants always know what to do next when they receive negative feedback. Accordingly, they are able to implement some task-general strategy or top-down control.

However, the situation is different for insight problems. Insight comes unexpected and marks a new breakthrough that even the participants themselves cannot predict: behavioral studies show that participants usually give accurate feeling-of-warmth (FOW) ratings, when they are on the verge of solving analytical problems (such as those found in standardized tests). However, participants are virtually unable to rate their progress on insight problems [33–35]. This implies that insight is beyond the monitoring of metacognition. ACC activation seems to be generated by the occurrence of a sudden unexpected solution idea to a seemingly unsolvable problem. The two studies we describe next show further methods of determining whether the "unexpectedness" of a solution is an important to constituent of insight.

In the first study [13], participants worked on a long list of riddles that was separated into three blocks. We examined how ACC activation changed across the first, second, and third block. The results showed that, relative to the resting state, all three blocks were associated with activities in both the ACC and left lateral PFC. However, greater ACC activity was observed for the first block than for the second and third block, with a comparable ratio of insight events across the three blocks. This observation suggests that ACC becomes functionally less important when solvers start to develop general strategies to deal with a particular type of task, even when most tasks require a restructuring of particular problem elements.

In another study, we compared the neural correlates of solving two kinds of puzzles [17]. In Condition A, the participants solved a list of puzzles that were constructed according to different principles, whereas in Condition B, all of the puzzles were constructed according to the same principle. Thus, it was easier for the solvers to develop a task-general strategy in Condition B than in Condition A where the development of such a general strategy was more difficult to achieve due to the larger heterogeneity of the problems. In both conditions, the list of puzzles for each participant was selected through a pre-scan test. In addition to making sure that the participants understood the idea behind the puzzles, only those puzzles were selected for which the participant had dwelled on unsuitable approaches and had not found the answer yet. During scanning, we provided the solution to catalyze restructuring processes.

The results showed that, relative to the resting baseline, both conditions evoked comparable activities in the left lateral PFC, but that Condition A evoked much more stronger ACC activity than Condition B. One methodological implication of this result is that we need to be cautious in selecting the task material in the study of insight problem solving. Insightful solutions might loose much of their "unexpectedness" once the basic principle to construct the problem was grasped by the problem solver. Of course, our emphasis on the issue that insightful solutions should be newly discovered and that they should occur unexpectedly does not imply that the solution has to be rare or that it has to have groundbreaking implications for society.

3.2. Multiple insight events and accurate onset time

An example of how our methods satisfy the requirements of multiple insight events and accurate onset time comes from a recent study on chunk decomposition. This process describes the decomposition of familiar patterns into their component elements so that they can be regrouped in another meaningful manner. Such a regrouping is required in some problems because during problem encoding problem elements become automatically grouped into familiar chunks. For instance, we perceive letters as a whole and not as being composed of single strokes. This can prevent the solution of a problem if the single elements that are part of a chunk need to be re-arranged in order to solve the problem.

Although chunk decomposition is an equally important process of changing problem representations as relaxing constraints on possible goal states [36,16,30,25], only few studies have addressed this topic. In one study [21], problem solvers were given a false arithmetic statement, written using roman numerals (e.g., 'I', 'II', and 'IV'), operations ('+' and '–') and an equal sign ('=') and were required to transform the statement into true equation by moving only one stick from one position to another. It was easy for the participants to transform the equation 'VI = VII + I' to 'VII = VI + I', whereas it was difficult for them to transform the equation 'XI = III + III' to 'VI = III + III'. The reason is that "X" is a tight chunk because the parts that form the chunk are not meaningful themselves (slanted sticks have no meaning in these task). In contrast, the chunk "VII" consists of three parts that are meaningful themselves, "V", "I", "I". Although such tasks can produce behavioural evidence that chunk decomposition is a source of difficult in insight problem solving, they are not appropriate for neuroimaging studies, because the task domain does not provide large enough variety of problems.

To overcome this problem, we developed a new chunk decomposition task using Chinese characters as materials [14]. As a logographic language system, Chinese characters are ideal examples of perceptual chunks [37–42]. Chinese characters are composed of radicals, which in turn, are composed of strokes (Fig. 1). Strokes are the most simple and basic components of a Chinese character. Usually, isolated strokes do not carry meaning. In contrast, radicals convey information about the meaning and pronunciation of the character. They usually consist of several strokes and can be thought of as sub-chunks of a character. Thus radicals are meaningful chunks whereas strokes are not meaningful in isolation. According to the chunk decomposition hypothesis it should be much easier to separate a character by its radicals than to separate a character by its strokes, because particular strokes are tightly embedded in a perceptual chunk. In other words, the decomposition of characters into strokes should require a specific process that

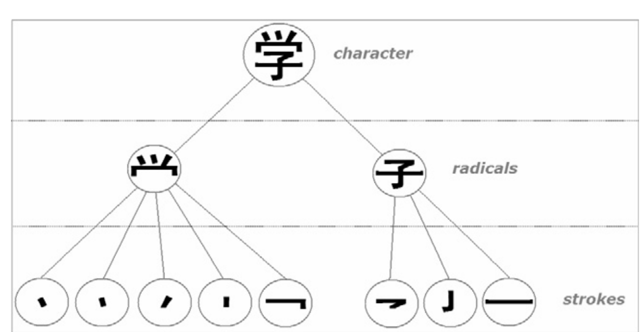

Fig. 1. The construction principle of Chinese characters. The character depicted here means "learn" or "study".

breaks the tight bond among strokes created by the perceptual chunk.

Participants were given tasks that always involved two valid characters, one on the left side of the display and the other one on the right. They were asked to remove a part of the right character and add it to the left character so that two new valid characters resulted after the move (Fig. 2). There were two conditions. In the tight chunk decomposition (TCD) condition, the problem could be solved only if participants decomposed the character into separate strokes and moved some of the resulting strokes from the right to the left character. In the loose chunk decomposition (LCD) condition it was sufficient to decompose the character into separate radicals and to move one of the resulting radicals to the left character. Pilot studies showed that problems requiring the decomposition of a tight chunk were much more difficult than problems requiring the decomposition of a loose chunk. The former were often not solved or took several minutes to solve whereas the latter were usually solved within 2–4 s.

The large differences in problem difficulty make it generally difficult to address the brain processes related to problem solving. Therefore, we provided a hint to catalyze the puzzle solving process, after the problem solvers had failed to solve the puzzle by themselves and got into an impasse state. During the hint stage, the to-be-moved part of the right side character was highlighted in another color (Fig. 2). This methodology enabled us to produce a large enough number of chunk decomposition trials in the TCD condition. Contrasting the processing of the hint between the TCD condition and the LCD condition (where participants had already solved the problem on their own and the presentation of the hint just confirmed their previous solution), we were able to identify the brain areas contributing to chunk decomposition. Our results showed that the early visual cortex was less active in the TCD condition than in the LCD condition whereas the higher visual cortex was more active in the TCD condition. These results suggest the following interpretation: the individual features/components contained in a chunk are processed in the early visual cortex [43]. During normal chunk perception, the processing of these individual features/components will be automatically grouped to form a holistic chunk. However, chunk decomposition requires that these individual chunk features be rearranged into a different perceptual chunk. Thus processing of individual features is suppressed as reflected by the inhibition in early visual cortex while the grouping is rearranged as reflected by the higher activation in higher visual cortex.

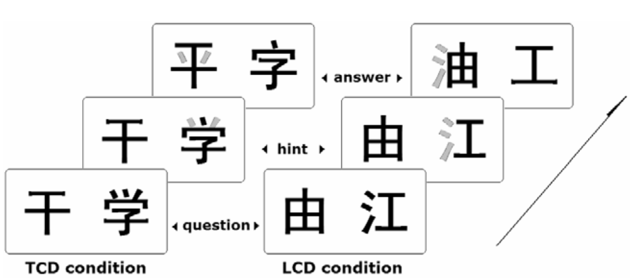

Fig. 2. Illustration of the cognitive task used in the chunk decomposition study.

The methodological implication of this study is that brain imaging studies of insight pose many more constraints than behavioral studies on insight. Thus, it is not possible to just use any behavioral insight paradigm for brain imaging studies of insight. Rather, we had to come up with a new task domain in order to be able to produce multiple insight events, and we had to provide solution cues in order to get accurate onset times for these events. Nevertheless, the fMRI results directly support an important hypothesis that goes back to the Gestalt psychologist and could not have been tested behaviorally: perception can be crucial in problem solving.

3.3. Hypothesis testing

As in other research, the aim of studies of restructuring in insight is to test hypotheses that have different degrees of specificity. For instance, one general hypothesis that follows from theories of insight is that during restructuring, new associations are formed among the existing knowledge nodes [11]. This leads to the prediction that hippocampus may participate in insight in some cases, because its role in forming association is well known. But insight studies should also allow us to test more specific hypotheses that are based on previous experimental observations. For example, if hippocampus activation were observed in insight, the experimental method should be flexible enough so that one can differentiate various kinds of possible roles the hippocampus may play in restructuring. In the following discussion, we will demonstrate how our method allowed us to test general and specific hypotheses on insight. In particular, we will show that the method of triggering restructuring with external hints may provide some advantages for specific hypothesis testing. That is, systematically varying hints (to the solution) of comparable problems and comparing the resulting brain activation can help one to understand the precise function of a given area.

3.3.1. General hypothesis testing

One important debate in insight research is whether processes of restructuring qualitatively differ from processes involved in routine thinking. In spite of some early researchers' arguments that insight problem solving is indeed not different from analytical problem solving [31,44–46], by now most researchers think insight is indeed specific. The distinction between insight and routine problem solving is supported by multiple sources of evidence: (a) retrospective reports of great thinkers; (b) experimental observations on animals (such as chimpanzee and pigeon) and children [e.g., 47,48]; (c) studies that investigated metacognition [35], verbalization [49], and time course of information processing during insight problem solving [50]; and (e) studies on the brain-damaged patients [9,51]. In addition to Reverberi and colleagues recent study that showed patients with deficits in lateral PFC were more capable to relax unwarranted constraints on the goal of problem solving [9], there is also circumstantial evidence that the famous patient H.M. who suffers from a lesion of the hippocampus and adjacent areas, did not have "Aha!" experiences when he was asked to detect ambiguities in sentences (such as 'the captain likes his new position' [position can be a place to sit on or a title]) [51] (but also see [52]).

To address the "nothing special" vs. "restructuring" controversy, one needs to compare insight problem solving and non-insight problem solving. For example, Metcalfe and Wiebe compared the accuracy of metacognition during analytic problem solving and insight problem solving [35]. Knoblich and colleagues compared people's eye-movements while solving routine and insightful matchstick arithmetic tasks [23]. In one of our fMRI studies (unpublished experimental observations), we asked participants to read sentences that had a high likelihood of being meaningful after a first reading (e.g., *"The office was cool because the windows were closed"*) or a high likelihood of not being meaningful after a first reading (e.g., *"The haystack was important because the cloth ripped"*). Shortly later, they received a cue that was likely to fully disambiguate the sentence (e.g., "parachute") or a cue that just confirmed participants' earlier interpretation of the sentence (e.g., "air-conditioned").

In the first step of the analysis of the imaging data, we identified the neural networks involved in the processing of solution-cues that resulted in restructuring (the restructuring cue, R-Cue) or did not result in restructuring (the confirming cue, C-Cue), respectively. In a second step, we identified the brain regions that were common to both types of solution-cue processing by inclusively masking the neural network participating in the processing of the R-Cue with the ones participating in the processing of the C-Cue. Finally, we identified the areas that were unique to the process of restructuring by exclusively masking the neural network that took part in the processing of the R-Cue with the one that was activated during processing of the C-Cue.

This method enabled us to go one step further than previous studies [11–13,10] where the conclusions were simply based on the direct comparison between a task condition and a baseline condition. In particular, we were able to determine whether restructuring occurred in similar brain areas that also support normal understanding, or whether restructuring requires specific neural networks. The result showed that, both R-Cue and C-Cue were associated with increased activation in medial and superior PFC, right superior temporal gyrus, posterior cingulate, and bilateral middle temporal gyrus. In addition, they were associated with decreased activation in right posterior cingulate gyrus and precuneus. However, R-Cues uniquely evoked positive activation in medial prefrontal gyrus and left posterior temporal gyrus (areas known to be involved in the detection of cognitive conflict and the flexible interpretation of problem situations, respectively), together with negative activation in posterior cingulate, bilateral inferior and middle occipital gyrus and orbital frontal gyrus. This result implied that most of the brain areas that were activated during restructuring were located within the neural network that was also active when a previously established meaning was confirmed. It seems that at least in this case the generation of a new meaning during restructuring is achieved by a part of the brain network that is also involved in normal understanding. These observations are, of course, not sufficient to provide a decisive answer for the "nothing special vs. something special" controversy. However, they provide evidence that helps to lead a more qualified discussion.

3.3.2. Specific hypothesis testing

In addition to test general hypotheses, an ideal method to study insight should also allow one to test more specific hypothesis. As mentioned earlier, more specific hypotheses with regard to restructuring can be derived for ACC and medial frontal gyrus. ACC and left lateral prefrontal cortex (PFC) activations were observed in restructuring when the restructuring cue was contrasted with the confirming cue [13]. However, the exact function of these areas in restructuring remained unclear. Further analyses compared restructuring cues that were judged by the problem solver as "understandable, but fairly hard" and those judged as "obvious to understand" [13]. The results showed that the lateral PFC was sensitive to the difficulty of processing the solution cue (i.e., the more difficult it was to understand the cue, the more activation in lateral PFC). In contrast, ACC activation was not affected by the difficulty of processing the solution cue. A likely reason for this observation is that ACC serves as an "early warning system" and signals the need for attentive control, whereas lateral PFC actually implements this top-down control.

This interpretation was supported by an ERP study that indicated that ACC activation was present as early as 380 ms after the onset of the restructuring cue [12]. Given that it takes around 2000 ms for the participants to fully understand the meaning of a solution cue, the problems were still not completely solved when ACC became active. Therefore, activation of ACC might be related more to the detection of cognitive conflict rather than finding the solution to the problem.

A study by Qiu and colleagues further tested this interpretation [18]. They used traditional Chinese logographs as materials and compared three kinds of solutions: hints that confirmed participants' initial, correct thinking; hints that led to a successful restructuring that allowed participants to solve insight problems they could not solve on their own and hints that did not lead to a successful solution of insight problems. The results showed that, relative to the confirming hint, the two other hints elicited more negative ERP deflections between 250 and 400 ms. The dipole analysis localized the generator of the difference waves within ACC. This observation implies that the activation of ACC is unrelated to finding a solution. As long as the hint suggests a new solution path the solvers did not think about so far, ACC activation increases.

In a further recent study (Luo et al., unpublished experimental observations), we compared four types of solution cues: correct solutions to comprehensible questions (Type 1, e.g., *"air-conditioned"* to *"The office was cool because the windows were closed"*); correct solutions to ambiguous questions (Type 2, e.g., *"parachute"* to *"The haystack was important because the cloth ripped"*), fake solutions to comprehensible questions (Type 3, e.g., "*knife*" to "*The dirty clothes were cleaned, because the rotation had been done"* (the solution is washing machine); and fake solutions to fake questions (Type 4, e.g., "*raining*" to "*the teacher changed a classroom, because the surface is round"*). The results of sixteen participants showed that, relative to correct solutions to comprehensible questions (Type 1), not only the true solutions to ambiguous questions (Type 2), but also the fake solutions to comprehensible questions or fake questions (Type 3 or 4) evoked lateral and medial PFC activation (the territory of activation extended into ACC).

This result implied that these PFC areas participated in the processing of the unexpected solution, regardless of whether the solution finally turned out to be reasonable or not. However, further contrasts between the correct solutions (Type 2) and the fake ones (Type 3 or 4) exhibited left superior and middle PFC activation. This suggests that some dorsolateral and anterior PFC areas, together with an area in left posterior middle temporal gyrus, are crucially involved in restructuring. These examples, together with the previously mentioned one on structural vs. superficial changes of the problem representation, demonstrate that the function of brain areas for insight can be examined through manipulating hints to the solution. In particular, this approach was efficient in exploring the precise role of PFC areas (often associated with the so-called executive functions) in the processing of solution cues.

3.4. Reference states

Brain imaging analysis relies on contrasts between a target state and a reference state. As it was mentioned earlier, an ideal reference state should be comparable with the target state in every aspect except the one to be examined. With regard to insight problem solving, a good reference state should contain similar problem elements and solution procedures as the insight ones in question, but should differ from the latter in the key aspect of restructuring. The occurrence of Aha! experiences is a "marker" that can be used to categorize problem solving as involving restructuring or not. Such subjective experiences are frequently reported when sudden restructurings or breakthroughs occur. However, one also has to keep in mind that subjective reports of Aha! experiences may simply reflect that a solution occurred so quickly that the problem solver is aroused by its suddenness [22]. Therefore, in using the Aha! experience to diagnose the occurrence of restructuring, one needs to keep in mind the problem background and the context in which thinking occurs. Otherwise, one might, for instance, misinterpret an emotional response as a marker for a special kind of thinking process.

In our studies, the key component we aim to explore is a representational change triggered by a solution hint. Thus the ideal reference state should involve hint-related processing that does not catalyze fundamental change in the problem representation. So far, various kinds of baseline have been used. Most studies used a "one question-one hint procedure" in which each question was followed by only one hint. The events that have been used as a baseline for the contrast with the crucial restructuring event include: the passive resting state [11]; initial processing of the problem [11]; processing of hints that confirm already known solutions [12–14]; processing of answers to unknown knowledge questions (Luo et al., unpublished experimental observations); processing of veridical hints to unsolved problems for which the solvers knew the construction principles [17]; processing of veridical hints that were not comprehended by the solver [18]; processing of fake hints to problems that had already been solved; processing of fake hints to the fake problems that have no solution (Luo et al., unpublished experimental observations).

In addition, in one study we used a "one question-multiple hints procedure" (Luo et al., unpublished experimental observations). In this procedure, each question was followed by several hints that did or did not lead to restructuring. The tentative baseline events in this study included fake hints that only led to superficial changes in the problem representation but did not lead to restructuring (i.e., "The surgeon has blue eyes" to the "surgeon mother" problem) and hints that provided only a reformulation of the problem (i.e., "The surgeon was unable to do the operation" to the "surgeon mother" problem).

Although the fake hint appears to be a reasonable reference state for restructuring because it is comparable with a veridical hint in most respects, one needs to use this type of hint with caution. One side effect that might be caused by fake hints is that participants become less willing to take the hint seriously once they become aware that some of the hints are faked. In the study where we use fake hints, participants solved fewer problems with the help of veridical hints than in a situation where all hints were veridical. Moreover, the activation in some key areas (such as in ACC) also appeared to be reduced when fake hints were used.

Another point one needs to consider when setting the baseline restructuring events are compared with, is that some brain areas may show deactivation or inhibition during insight. Reverberi and colleagues found that patients with deficits in lateral PFC were more capable to relax unwarranted constraints on the goal of problem solving than control participants [9]. Similarly, our study found that the early visual cortex was deactivated during chunk decomposition [14]. Therefore, in setting the baseline, one should not only consider the baseline's effects in demonstrating the positive activation in insight, but also its effects in detecting negative activations.

3.5. Internally vs. externally triggered insights

Jung-Beeman and colleagues have developed a large set of simple problems, named compound remote associates or CRA problems, for research on insight [10]. In the CRA task, participants are given three words (e.g., pine, crab, and sauce). They are required to produce a single solution word (apple) that can form a familiar compound word or phrase with each of the three given words (pineapple, crab apple, and applesauce). Because participants were able to solve more than half of the CRA problems in a short time without any external help, they were able to investigate internally triggered insights.

The puzzles and riddles used in our studies were much more difficult. The participants could not solve most of the puzzles without external hints. The reason for adopting these puzzles is that one can be more certain that they require a restructuring process in order to be solved. The cost of this approach is that giving external hints is inevitable. Is there any ecologically valid situation where external hints triggered insights? Well, there are many. For instance, Archimedes found the solution to the golden crown problem when he stepped into his bath and caused the water to overflow. The key difference to our present paradigms, though, is that Archimedes did not know in advance what the hint was and when it would appear. So one challenge, for future studies could be to provide hints in a more incidental way.

3.6. The influence of materials and cognitive task

Insights may occur in many different kinds of problem solving. Therefore, there is no reason to believe that all kinds of insights will recruit exactly the same brain networks. That does not preclude the possibility that some brain areas are generally involved in restructuring. However, given that restructuring is a strong cognitive brain dynamic process that requires extensive re-organization of the problem representation, the function of the task-specific areas may be the core of restructuring. This would imply that understanding the role of particular brain areas in particular tasks might be the key to understanding restructuring. For example, in one of our studies [11], hippocampus activation was observed because the riddles described familiar things (e.g., "river") in unusual ways (e.g., *"The thing that can move heavy logs, but cannot move a small nail"*). Thus solving these riddles required the formation of novel associations among the old concepts.

In contrast, while solving compound remote associates (CRA) problems [10], activation of anterior superior temporal gyrus was observed. This is likely due to the fact that the generation of a word (e.g., "apple") that forms a compound associate with three target words (pine, crab, and sause) requires one to relate distant semantic information. Other than in the above-mentioned semantic tasks that mainly challenged the medial or lateral aspect of the temporal lobe, the chunk decomposition task evoked robust activation in visual areas [14], which is presumably due to the perceptual nature of restructuring required in this type of task.

Although different task-specific areas were observed in different types restructuring, some brain areas seem to be generally involved in different types of restructuring. For example, activations of medial PFC and ACC were not only observed for traditional Japanese riddles and for ambiguous sentence restructuring [11,13], but also when solvers decomposed thigh perceptual chunks [14].

In addition to the type of cognitive task used, the way in which an insight solution is generated may also affect the pattern of brain activations observed during restructuring. For example, in contrast to internally generated insights that mainly evoked activation in the right hemisphere [10], it appears to be that the externally triggered insights tend to mainly activate the left hemisphere [13,14]. Further studies on restructuring should take these factors into consideration in order to achieve a more comprehensive understanding of the neural pathways to cognitive insight.

4. Concluding remarks

Because the paradigms used in traditional insight research do not meet the requirements of neuroimaging methods, recent studies adopted new approaches to reveal the brain mechanisms underlying insight and restructuring. Two experimental approaches seem to be promising at the present stage: The riddle and puzzles paradigm developed by Luo and colleagues [11–14,18] which was the focus of this paper. Another promising approach is the compound remote associates (CRA) used by Jung-Beeman and colleagues [10,5,53]. Regardless of the particular approach there are several experimental requirements that neuroimaging studies of insight should meet. They should elicit restructuring, generate multiple insight events, and provide accurate onset times. In addition, they should also have the capacity for testing general and specific hypotheses, allow one to define meaningful reference states, and they should allow one to compare internally vs. externally triggered insights. It is unlikely that any approach will be perfect in satisfying all of these requirements, but they provide a list of criteria brain research addressing insight in problem solving should strive for. At present, the relationship between different types of approaches should be thought of as supplementary rather than competitive. We have just begun the study of the brain bases underlying restructuring and multiple approaches will be necessary to blaze a trail for a better understanding of the nature of insight.

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