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ScienceDirect
Methods 42 (2007) 87–99
METHODS
www.elsevier.com/locate/ymeth

Methods for investigating the neural components of insight

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Accepted 21 November 2006

Abstract

The authors describe how they have used visual-hemifield and event-related neuroimaging approaches to study their theory specifying some of the neural components of insight. A set of problems developed by the authors, and the use of solvers' self reports of insight, are presented to argue that advances in our understanding of insight are being unnecessarily stifled by over reliance on traditional insight problems and a widespread failure to determine whether insight has occurred on a solution-by-solution basis.

Keywords: Insight; Problem solving; Neural components; Visual hemifield; Neuroimaging; Remote associate problems; Self report; Right hemisphere; fMRI

1. Introduction

Since the beginning of psychology as a science more than a century ago, one of the central areas of interest has been in understanding problem solving (e.g., [1,2]). A distinction has been made between step-by-step analytic problem solving and a distinct "all-at-once" process called insight, in which the solution to a problem appears in consciousness suddenly and without conscious access to the solving process [3,4]. Instances of insight-like phenomena can also be found in perception (e.g., sudden recognition of an object in a blurred or ambiguous picture; [5]) and language comprehension (e.g., sudden comprehension of the meaning of a joke or metaphor, [6]). Thus, insight is not limited to problem solving but appears to be a general phenomenon or mechanism of cognition.

When discussing insight researchers have used terms such as representational change, restructuring, and chunk decomposition to describe the cognitive processes necessary for insight solutions [7–15]. However, until very recently almost no attempts had been made to link these descriptions to the underlying brain structures and neural activity.

Advances in theories of brain function and neuroimaging techniques have made it possible to predict and view the neural activity associated with differences between insight and non-insight problem solving. For example, Functional Magnetic Resonance Imaging (fMRI) allows the entire brain to be imaged repeatedly while a person is engaged in a task, providing a view of all regions involved in the task. Thus, by making it possible to view differences in the neural activity underlying insight and non-insight solutions, the use of fMRI provides a significant addition to the information that can be gained with traditional behavioral techniques. However, many fundamental issues remain unresolved [16], and the cognitive and neural mechanisms by which people solve problems with insight remain underspecified.

It is our goal to move toward demystifying insight by revealing the neural components of problem solving. To this end we have used both behavioral and neuroimaging methods (see [17–21]). Other researchers are also using neuroimaging to investigate the neural components of insight (e.g., [22–24]).

Of course, the methods that researchers use should always be determined by the questions they are attempting to answer. We began with the hypothesis that the cerebral hemispheres process information differently. Specifically, both hemispheres process all types of information but the

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1046-2023/$ - see front matter © 2006 Elsevier Inc. All rights reserved.
doi:10.1016/j.ymeth.2006.11.007

right hemisphere (RH) engages in coarser coding of information while the left hemisphere (LH) engages in finer coding of the same information. This hypothesis predicts differences in the kind of information each hemisphere should have available, therefore we began our research by using a visual-hemifield presentation paradigm, which can reveal hemispheric differences. We also have hypotheses that are more precise in their predictions about where, when, and how the brain produces solutions with insight, therefore we have used fMRI, which can provide precise information regarding the locations of activation, and electro-encephalography (EEG), which can provide precise information regarding the timing of cognitive events.

In practical terms the methods we have used can be placed into two categories: inexpensive, easy, but inexact, and expensive, complicated, but more precise. Visual-hemifield presentation is an inexpensive and relatively easy approach that can provide gross information regarding whether critical solution information is more available in one hemisphere than the other. In contrast, fMRI and EEG are expensive and complex methods that can provide far more detailed information about the location and timing of neural activity.

The aim of this paper is to provide a description of the methods we have used at a level that will be appropriate for researchers just venturing into studies of the neural mechanisms of insight and creativity. We will attempt to provide enough detail so that common and easily made mistakes can be avoided. We also will provide more details for visual-hemifield than for neuroimaging methods because individual researchers with limited resources can carry out visual-hemifield experiments. In contrast, neuroimaging experiments require a team of researchers and extensive resources therefore it is not necessary for any individual to possess all of the required technical knowledge.

We will begin by providing some background so that the rationale behind our use of these methods is clearer.

2. What is insight?

The term "insight" designates the clear or deep perception of a situation, a feeling of understanding, the clear (and often sudden) understanding of a complex situation, or grasping the inner nature of things intuitively. In cognitive psychology insight is used in contrast to step-by-step analytic problem solving. Just as different instances of analytic problem solving can arise from a wide variety of processes, only some of which will always be present, instances of insight can arise from different sets of processes. As we discuss below in Section 3, we believe that insight is not a single process by which some problems are solved rather it is the consequence of several interacting processes.

Insight is thought to arise when a solver breaks free of unwarranted assumptions, or forms novel, task-related connections between existing concepts or skills. There is widespread agreement that insight solutions differ from non-insight solutions in a number of ways: While working on a problem that is eventually solved with insight, solvers often reach an impasse (e.g., the solver feels that she is not making progress toward a solution [25] solvers usually cannot report the processing that enables them to overcome the impasse [26]; and they experience their solutions as coming suddenly and unexpectedly [27,28], yet the solution appears to be obviously correct). In addition, performance on insight problems is correlated with creative thinking and other cognitive abilities that are not correlated with performance on non-insight problems [29].

Though we have restricted our work to the phenomenon of insight in problem solving, we strongly believe that our findings are relevant to understanding creativity and insight-like cognitive phenomena in general. We believe that insight is an act of creativity because it requires that the solver view the problem in a new way. That is, the solver must abandon a "traditional" approach to the problem in favor of a novel (at least to that solver) approach. For the record, we follow Boden [30] in defining as creative any solution that is new to the solver. Boden refers to this as psychological or personal creativity (P-creative) in contrast to historically creative ideas (H-creative). An idea is P-creative if the person in whose mind it arises has not had it before. It does not matter how many times other people have already had the same idea. Thus, a person could solve a problem with insight that is solved by most people without insight. A person can also solve without insight a problem that most people solve with insight. For that solver the solution is not an insight and is not creative. The presence or absence of insight resides in the solver's solution rather than in the problem. Therefore, as we will discuss below, we have chosen to rely on reports from the solvers themselves to determine when an insight has occurred.

2.1. Identifying the occurrence of insight

There have been several efforts to categorize problems as insight or non-insight problems [29,31,32]. We believe these efforts are important because they allow researchers to select problems that are more or less likely to be solved with insight and may reveal which characteristics of problems produce these differences. However, quite often problems are presumed to be insight or non-insight problems with no justification other than that they have been used as such in previous research [31]. Oddly, there are few instances of researchers gathering information regarding solvers' experiences of their solutions (see [26,27,33]). We see this as an unfortunate situation because very few problems can be relied upon to always produce an insight solution in all solvers, thus data from insight and non-insight solutions are unknowingly combined and the power of the data is reduced.

We also believe that this has led to some unnecessary disagreement about whether specific problems, or types of problems, should be considered insight or non-insight problems. Two examples are anagrams and Remote Associate problems. Because both types of problems *can* be solved without insight (trial-and-error rearrangement of the letters of the anagram until a recognized word is formed; repeated search of semantic memory for associated words until one is found that is associated with all three members of the problem), critics of their use often argue that they are not insight problems. However, this argument can be made against almost any "insight" problem. Just because a problem can be solved without insight does not mean that it should not be used to investigate insight. In fact, we argue that these are precisely the problems that should be used in insight research because they eliminate some confounds inherent in using different types of problems as insight and non-insight problems within the same experiment.

We advocate the use of problems based on the presence or absence of characteristic the researcher believes are important to creativity, and then gathering data regarding whether the solver actually solved the problem with or without insight.

How does one identify when a problem has been solved with insight? One way of distinguishing between insight and non-insight solutions is to use different problems, some traditionally classified as "insight", others as "non-insight". These traditional classifications have been achieved by various means (e.g., see [32]), often by noting discontinuities of solving strategy and/or subjective responses associated with solutions. The use of such traditionally classified "insight problems" and "non-insight problems" (or analytic problems) has been supported by differences in the way each problem set elicits feelings of progress toward solution [27], descriptions of solutions (i.e., coming "all at once", [26]), awareness of hints [26,33], and so on. However, we argue that the processes that contribute to insight and non-insight solutions may contribute to a wide variety of problems, varying idiosyncratically for each problem and each problem-solver [34]. The processes themselves are different, and the use of them is only imperfectly correlated with traditional classifications of problem type.

Another way to identify when the different processes are used is to use subjective reports of the solving experience (e.g., [19,26]). The reports are subjective, but they are yoked to each solution, indicating what solving processes were engaged on a trial-by-trial basis. This method has the further advantage of contrasting insight versus non-insight processes (at solution, or the preceding processes that bias toward such solutions) when task, goals, and fundamental processes (decoding stimuli, etc.) remain constant.

When people solve a problem with insight they generally report a pleasant feeling of surprise and that the solution—or an understanding of how to reach the solution—came all at once [3]. In contrast, non-insight solutions are characterized by solvers feeling, from the beginning, that they know the procedure necessary to reach a solution, and that the solution was produced in a series of steps. One approach to identifying insight solutions would be to provide people with a description of these differences then allow them to categorize their solution experiences. Some researchers have dismissed this approach because they believe it is too sensitive to experimenter demands. Other researchers dismiss this approach arguing that insight is merely epiphenomenal—an emotional response to the suddenness of solution—and does not involve distinct cognitive processes, therefore subjective reports are not useful [31,35–37]. However, such a position begs the question of why, if the cognitive processes are the same, some problem solutions produce this distinct experience whereas other solutions do not. We will address these concerns below.

We argue that the insight experience results from the particular pattern of cognitive processing involved, and as such can be a reliable marker of insight processing [34,38]. We believe that researchers often have unnecessarily distanced their models from the subjective experience when the subjective experience is, in fact, an important component of insight [39].

We have used participants' reports of their solution experiences to categorize solutions to Compound Remote Associate (CRA) problems (described below) as having been achieved with insight versus non-insight processing. Instructions to participants regarding these ratings involved participants evaluating several aspects of their solutions, including: whether it was achieved with a conscious strategy; how suddenly they became aware of the solution ("did the solution come to you all at once?"); how confident of their solution they were prior to verifying it; as well as whether they experienced an "Aha!" sensation of surprise. Solutions categorized in this manner are associated with distinct patterns of cognitive processes and behavior [17,19,28], as well as distinct patterns of neural activity [20,21]. This approach allows objective observations to be associated with the subjective experience that is agreed to accompany insight, complementing the traditional approach of researchers forming a consensus about what are likely to be insight or non-insight problems (based in part on the perceived likelihood of each problem producing the "Aha!" experience, as well as the need for restructuring (e.g., [7,8,11])), or the suddenness of solution [27].

Similar judgments have been used to great benefit in psychophysics, memory research, and other domains and we believe they will prove their value in insight research. For example, insight judgments are analogous to judgments in the remember/know memory paradigm [40], in which after making a recognition judgment about an item, participants are asked whether they actually remembered the prior occurrence of the item, or just "knew" that the item occurred before. The subjective experience is used to classify each recognition judgment [41].

3. The distinct cognitive and neural bases of insight

Our research has been guided by a theory that states that multiple processes contribute to both non-insight and insight solutions, and that differences in how the cerebral hemispheres process information play an important role in whether a solution is produced with or without insight. The theory is derived from connectionist models of cognition (e.g., [42]), and is supported by evidence from research on visual processing (e.g., [43–47]) and language comprehension (see [48,49]). Solving a particular problem will emphasize certain of these processes making the solution more or less "insight-like", however, we have also predicted that some processes are unique to insight solutions. Our theory also suggests that there are individual differences and specific brain states that are conducive to insight [21].

According to our framework, insight is not a simple, unitary, process. It is a general cognitive mechanism resulting from a constellation of neural and cognitive events. Insight can occur in a variety of cognitive domains, from perceptual identification of degraded or ambiguous visual stimuli [5], through word puzzles, jokes and metaphors [6], riddles, and up to complex reasoning. Insight can occur spontaneously, or following experimenter-presented hints (e.g., [33,50]). It can occur for trivial problems, artistic creations, personal revelations, and for important scientific or theoretical breakthroughs. All of these domains and degrees of insight obviously require a variety of basic cognitive processes—object recognition, verbal retrieval, and so on—many of which are shared by non-insight problem solving. We propose that insights in various domains share something more than an epiphenomenal emotional experience. They share patterns of neural and cognitive processing that are qualitatively similar and are different from non-insight processing. However, insights in different domains or modalities are likely to rely on some processes unique to the specific domain or modality.

We have developed a cohesive multi-component theory of how solving problems with insight differs from solving with analytic non-insight processes. Generally, when people attempt to solve a problem, they can achieve solution either through straightforward analytic non-insight strategy, or with insight. Insight solutions are most likely to come about (1) when initial solving efforts include solution-related processing, yet the product of that processing exists outside of awareness, so solvers reach impasse prior to solving; (2) when solution is achieved through integration of problem elements via non-obvious or non-prepotent relations; (3) when cognitive control, at a preconscious level, is required to switch processing strategies; and (4) when sensory gating allows a weakly activated solution representation to be retrieved into consciousness. Further, because of basic cognitive processing asymmetries across the hemispheres, the initial strategies or associations that are strongly active, but ultimately unsuccessful, are likely to occur more strongly in the LH. In contrast, the processing that produces weak but mutually reinforcing activation that supports integration of distant problem elements is more likely to occur in the RH. We would like to emphasize that our theory does not preclude the possibility that insights can arise from the formation of new associations rather than becoming aware of existing weak associations, only that insights are more likely to arise as the result of integrating existing weak associates.

We believe that greater knowledge of the neural substrates involved in insight will help constrain theories about how the component cognitive processes of insight and non-insight solutions differ and by limiting the possible mechanisms by which insight arises. For instance, one critical cognitive process distinguishing insight solutions from non-insight solutions is that solving with insight requires solvers to reinterpret the problem according to distant or unusual relations; hence, insight-specific neural activity should reflect that process. The most likely area to contribute to this component of insight problem solving is the anterior superior temporal gyrus (aSTG) of the RH. Language comprehension studies demonstrate that the RH is particularly important for tasks that require the use of distant semantic relations between words [48,49,51,52], and bilateral aSTG is involved in semantic integration. For example, sentences and complex discourse increase neural activity in aSTG bilaterally [53,54], and discourse that places particular demands on recognizing or computing distant semantic relations specifically increases neural activity in RH temporal areas (e.g., understanding figurative language [55,56], extracting themes [57], and connecting weakly related sentence pairs [58]), especially aSTG (e.g., detecting syntactic violations [59], and generating the best ending to a sentence [60]).

We indeed did find greater activation in the RH [17–19] and more specifically the RH aSTG [20] for insight than for non-insight solutions. Thus, the hypothesis that the restructuring necessary for insight might, at least partially, rely on accessing less likely interpretations and integrating distantly associated problem elements is supported by the finding of increased activation in the area thought to carry out this very process. Other cortical areas, such as prefrontal cortex and the anterior cingulate (ACC) may also be differentially involved in producing insight and non-insight solutions [61,62].

4. Compound remote associates

As mentioned above, we had begun to develop hypotheses regarding how hemispheric differences in processing might play an important role in insight. We thought that fundamental differences in the way that the Right-hemisphere and Left-hemisphere process information might be important for understanding differences between insight and non-insight solutions.

We quickly realized that the use of traditional insight problems would pose several difficulties for designing experiments to test our hypotheses. Whereas we needed a large number of problems each of which could be solved quickly (e.g., an average solution time of less than one minute) traditional insight problems are usually complex, allowing participants to attempt only a few such problems (occasionally only one) in an experimental session. The use of only a few problems can greatly reduce the reliability of the data collected and is especially problematic when the central data to be collected is reaction time data. Furthermore, the complexity of traditional insight problems can lead to the confounding of variables, which hinders the clear decomposition of the component processes of problem solving. We also needed problems for which the solutions were physically "compact" enough to be presented laterally (i.e., could be clearly given in a single word), so that initially only one hemisphere received the information (see the description of visual hemifield experiments below). We also wanted problems that might benefit from a single word hint so that we could present hints laterally. Finally, and most importantly, we wanted problems that could be solved with or without insight.

The only types of problems we could find that met our criterion were anagrams—which we had used before [33]—and items from the Remote Associates Test (RAT) [63]. Mednick [64] developed the RAT as a means of measuring creative thought without requiring knowledge specific to any field. He constructed two college-level versions of the test, each consisting of 30 items [63]. Each item consists of three words, each of which might be associated with a solution word in a number of ways; thus, for example, the three words SAME/TENNIS/HEAD are associated with the solution MATCH by means of synonymy (same = match), formation of a compound word (matchhead), and semantic association (tennis match). Reaching a solution requires "creative thought", because the first information retrieved for each word in the problem is usually not the information that leads to the solution, and solvers must think of more distantly related information in order to connect the three words.

Because our Right-hemisphere coarse coding theory specifies that the RH is more sensitive to distant associations than is the LH, RAT items seemed ideal for our purposes. However, we wanted a greater number of problems than were available in the original RAT. We also wanted to present participants with a more consistent task—that is, the solution word would always be related to the problem words in the same way. To this end, we created our own set of problems, so that the solution word was associated with all three words of the triad through formation of a compound word (or two-word phrase) (e.g., AGE/MILE/SAND form the compounds STONE-AGE, MILESTONE, and SANDSTONE with the solution word STONE).

We initially developed a set of 144 Compound Remote Associate (CRA) problems. The complete list, with solution percentages and mean solution times by problem at different solution periods, can be found in Bowden and Jung-Beeman [65]. These normative data can be used in the selection of problems according to difficulty or mean time necessary for reaching a solution.

We believe that CRA problems have several advantages over more typical insight problems: (1) They can be solved in a short time, so that many can be attempted in a single experimental session of 1 hour or less. (2) They are simpler than traditional insight problems, thus allowing better control of possible confounding variables. (3) They have single-word, unambiguous solutions, making collection of response time data more precise, and making it easier to score responses as correct or incorrect.[1] (4) They are physically compact, so that they can be presented in a small physical space or short period of time. These features allow for better control and measurement of timing variables (e.g., measuring the time between presentation of the problem and production of a solution, controlling timing of hint presentation or timing of solution presentation for solution judgment tasks, etc.) and display variables (e.g., position of the problem and/or solution on the display). These features also allow for the use of various paradigms (e.g., priming, solution recognition, and hemispheric differences paradigms).

4.1. Are CRA problems insight problems?

As discussed above (see Section 2.1), we believe that disagreement about what is or is not an insight problem is misguided. We argue that for any type of problem it is not important whether the entire set of problems can be categorized as insight problems, rather it is important to determine whether people ever solve the problems with insight and, if so, are insight solutions frequent enough to produce useful data. Nonetheless, we will briefly justify our use of RAT-like problems for insight research.

RAT and RAT-like problems have a history of use in the study of problem solving and creative thinking prior to our using them (e.g., [29,66–69]). Although RAT items are not as complex as traditional insight problems, they exhibit the three properties of insight problems that distinguish insight solutions from non-insight solutions: (1) They misdirect (or fail to direct) retrieval processes. For example, in the CRA problem PINE/CRAB/SAUCE the word PINE might direct the initial search of memory toward items such as PINE TREE or PINE CONE rather than PINEAPPLE. (2) Solvers often cannot report the processing that has led them to the solution [70]. (3) Upon solving RAT items, solvers often have the Aha! experience [19]. This third property is often considered the central defining feature of insight problems. Thus, solving RAT or RAT-like items appears to involve the same component processes critical for, and the same phenomenological experience of, insight solutions to more complex problems. In addition, problem solvers' success on items from the original RAT reliably correlates with their success on traditional insight problems [29].

The above argues that RAT items, and by extension CRA problems, have characteristics of traditional insight problems and are often solved with insight, therefore can be used in investigating insight.

[1] We discovered that in at least one instance (HOUSE/DISTRICT/HIGH) there were two possible solutions—SCHOOL or COURT.

One possible obstacle to using multiple instances of a problem type, especially a relatively simple problem type, is that the solutions might become less insight-like as the solver gains experience with the specific problem type. We would argue that experience with insight problems in general makes solvers more likely to recognize the underlying "tricks" and thus reduce the feeling of insight associated with the solutions. Furthermore, simple problems, such as CRA problems, anagrams, matchstick algebra problems, and riddles, produce lower intensity feelings of insights than do more complex problems. However, CRA problems require finding different associates each time so that over the course of a single experiment the feeling of insight changes only slightly.

We also believe that the use of CRA problems, or problems with these characteristics, will allow researchers to more clearly determine areas of interest in the brain. Once such areas of interest are better determined, smaller sets of problems with longer solution times, and which produce stronger feelings of insight, can be used (e.g., riddles, traditional problems).

5. Procedure

The basic procedure used in each of our experiments is straightforward: On each trial a tone is played and a central fixation cross is presented for 500 ms. This is done so that participants are alerted that a problem is about to appear and that they should direct their gaze to the center of the display. The fixation cross is then replaced by three problem words presented simultaneously in horizontal orientation above, at, and below the fixation cross. The problem words remain in view until the solution is given or for a specified time limit, which varies with the experiment. Our research has involved a number of variations on this basic procedure. See Fig. 1 for a diagram of the variations on the basic procedure.

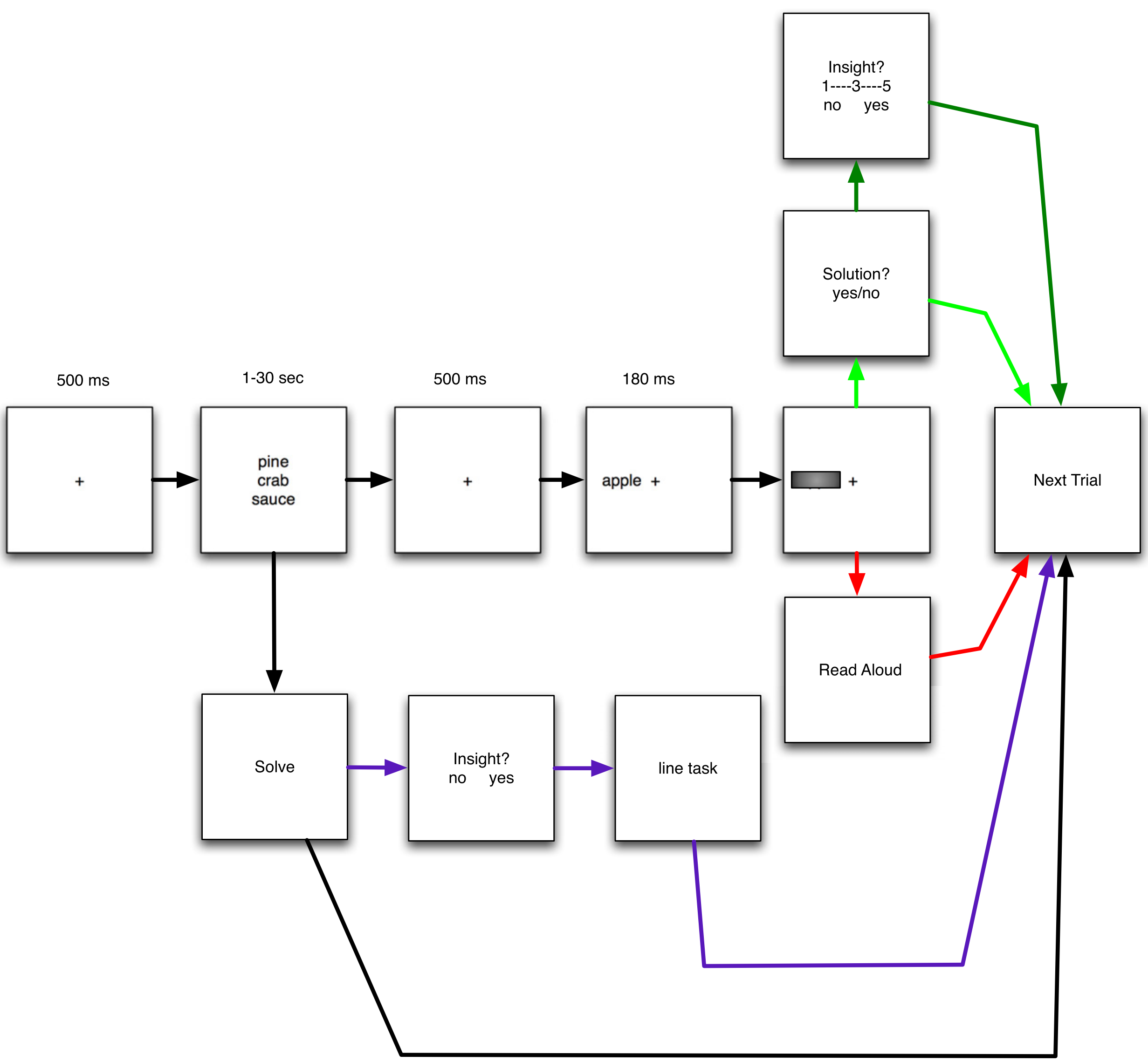

Fig. 1. Variations on the basic experimental procedure. Black, basic procedure; red, solution priming; green, solution decision; violet, fMRI/EEG. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

5.1. Visul hemifield presentation: position and timing considerations

In our initial set of experiments using the CRA problems we used a visual-hemifield presentation paradigm with either a word naming or solution recognition task [17]. The visual-hemifield paradigm refers to presenting stimuli so that they occur in only one visual hemifield and thus are initially projected to only one cerebral hemisphere. The total visual field is the sum of the right and left *hemifields*. Just as the visual field is divided into two hemifields, the retina is divided into two *hemiretina*. The axons of ganglion cells exit the eyes via the *optic nerve*, partially cross at the *optic chiasm*, and form two *optic tracts*, so that the information in the right visual hemifield (rvf) of each eye initially travels to the brain's left hemisphere and the information in the left visual hemifield (lvf) of each eye initially travels to the brain's right hemisphere. In normal people information is quickly communicated between the hemispheres via the corpus callosum, however, numerous studies have demonstrated qualitatively different patterns of semantic priming for words presented to the rvf versus the lvf, suggesting some independent processing by each hemisphere despite an intact corpus callosum (for a review see [48]).

To insure that the stimuli actually are being presented to the desired hemifield it has become standard practice to position the most central edge of stimuli $\geqslant 1°$ eccentric of the person's presumed fixation point. To do this one must determine how far from the fixation the stimuli must be positioned to be $\geqslant 1°$ of visual angle.

The visual angle is dependent on two factors: (1) The actual size of the object and (2) the distance the object is from the eye. In our case, the size of the "object" is the blank space between the central fixation and the inner edge of the stimulus. The distance the object is from the eye is the distance between the participant's eye and the computer display. Therefore, when using a visual hemifield presentation paradigm it is important to position both the stimulus on the display and participant's head so that the stimulus is $\geqslant 1°$ of visual angle from the participant's point of fixation.

When the participant's task is to read laterally presented words it is good practice to present the words so that they do not extend beyond approximately 5° of visual angle to the left or right of the fixation point. Parts of the words occurring beyond this limit become difficult to read. This is more problematic for words in the left visual hemifield because it is the beginnings of those words that become difficult to read.

To determine the appropriate position of stimuli on the display one must take into account several practical constraints. For example, the size of the table on which the display rests will determine how far the participant can be placed from the display. To maintain the proper distance for the desired visual angle we used a simple chin rest or binocular viewer, which we designed and built. This chin rest or viewer was then attached to the table so that when the subject placed his/her chin in the rest his/her eyes were the correct distance from the display.

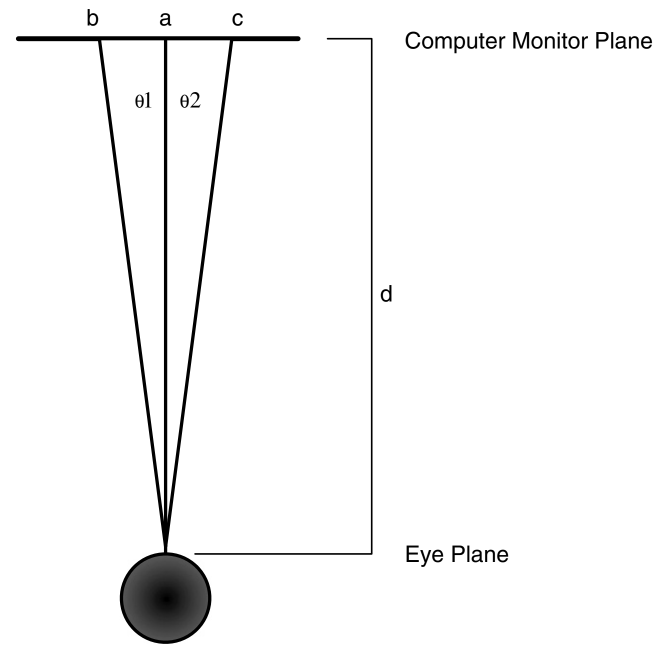

Fig. 2. Measurements necessary for determining visual angle.

We chose to have the most central edge of the stimuli be 1.5° from the fixation point. This meant that we positioned the participants' eyes 46 cm from the computer display and the most central edge of the stimuli 1.2 cm from the fixation point.[2]

When words are used as stimuli one must decide on what font and font size one wants to use to maximize readability. Care should be taken to choose a font and size that is easy to read but not so big that the outermost edge of the longest stimulus is beyond 5°–6° from the fixation point. Some have argued that a fixed width font, such as Monaco or Courier, is a better choice than a variable width font, such as Times, because it is easier to control the physical length of the words by simply controlling the number of letters. However, we feel any highly readable font can be used as long as the distance from the fixation to the ends of the words is known for each word. We used 24-point Times. Words in 24-pt Times are similar in length to words in 18-pt Courier (e.g., of the words we used the longest word in 18-pt Courier—terminal—was 3 cm, whereas the longest in 24-pt Times—common—was 3 cm). A longest word length of 3 cm meant that no target extended more than 5.2° from the fixation point.

It should be noted that if one plans to present the experiment on more than a single non-identical display one must

[2] If a different visual angle, viewing distance and/or stimulus size is desired the following formulas can be used to make the relevant calculations (Refer to Fig. 2): d = distance from the viewer to the display (d) ab (or ac) = distance from the fixation point (a) to the most central edge of stimulus (b). Then visual angle ($\theta 1$) is calculated by dividing distance (ab) by distance (d) and taking the arctangent of the result: $\mathrm{atan}(\mathrm{ab}/d)$ If one wants to know the distance between (ab) given that ($\theta 1$) is a given angle take the tangent of $\theta 1$ and multiply it by the distance (d): $\tan(\theta 1) \times d$.

keep in mind that pixels are different sizes and in different relative positions on different displays so the relevant positions of participant and stimuli may need to be recalculated for each display.

Timing variables are also important in visual-hemifield presentation experiments. To insure that the stimuli are presented to only one *hemiretina* the stimuli must be presented for a duration that is too short for the participant to move his eyes and fixate on the stimulus. In most cases if a stimulus is presented for a duration of less than 180 ms participants will not be able to move their gaze from the central fixation point and re-fixate on the stimulus.

A second measure, which prevents both iconic memory and an afterimage on the display from extending the stimulus beyond its intended duration, is the use of a mask. A mask is simply another stimulus that immediately replaces the target stimulus. We used a letter-fragment pattern mask or a rectangular mask of the same color and brightness as the target stimuli.

5.2. Variations on the basic visual hemifield presentation procedure

5.2.1. Target naming (priming for solutions)

For each trial of our target naming (priming) experiments [17,18], participants tried to solve one problem, then read aloud (name) one target word. Each trial began with a central fixation cross, which then was erased and replaced by the three problem words presented simultaneously in normal horizontal orientation above, at, and below the center of the display. Participants attempted to produce the solution word within a time limit (Over four different experiments the time limit varied from 2 to 15 s). After either a solution was produced, or the time limit expired, the problem words were erased, a tone sounded, and the fixation cross was re-presented. A target word was then presented for 180 ms at the vertical center of the display and with its inner edge 1.5° of visual angle from fixation. The target word was immediately replaced by a letter-fragment pattern mask, which remained on the display for 120 ms. Participants had 3 s from the offset of the mask to read aloud the target word. Half of the target words were solutions to the problem just seen and half were unrelated words; half of each of these groups was presented to the left visual hemifield, and the other half to the right. The unrelated target words were the solutions to problems 72 trials away (e.g., Problem 1 occurred with either its own solution or the solution to Problem 73). The participants saw each target word only once over the course of the experiment. Across participants, condition of target words was rotated so that all target words occurred equally often as both solutions and unrelated words and in both visual hemifields. Latency (Response Time—RT) to begin naming the target word aloud was measured. After the participants had named the target word, the experimenter pressed a key to record whether the response was correct. Participants were tested individually. Prior to the experiment, they were given five practice problems with target words. Further explanation of the task was given if required. Participants' head movement was restricted by the requirement to view the display through a binocular viewer mounted on the table.

5.2.1.1. Interpretation. The fundamental assumption underlying the priming paradigm is that people make a response more quickly if they are already prepared (primed) to make that response. Thus, more rapid naming of solution words than unrelated words is taken as an indication that the solution words were more activated (or accessible) than the unrelated word. Because words are typically read more quickly when presented to the rvf-LH than when presented to the lvf-RH we compared naming times for solution words to naming times for unrelated words within each visual hemifield rather than across hemifields.

Importantly for our hypothesis, the amount of priming depended on the hemifield to which the target words were presented. Participants showed greater priming (i.e., reading latencies decreased more) for solution words (relative to solution-unrelated words) presented to the lvf-RH than for those presented to the rvf-LH.

Because priming was found when the targets for unsolved were presented to the lvf-RH, but not when they were presented to the rvf-LH, we concluded that at that point in time the solutions were available in the RH, but not in the LH even though the participants had not yet been able to produce the solution.

5.2.2. Solution decisions (speed of recognition of solutions)

Our solution decision experiments [17,18] involved the same materials and procedure as the target naming experiments, except that instead of naming the target word participants indicated whether the target word was the solution to the problem. After the participant offered a solution, or the solution period ended without a solution, a target word was shown for 180 ms then masked, the word SOLUTION? was then presented, and the participants indicated whether the target word was or was not the solution. RT from the onset of the solution decision event until the participant responded was recorded. This was a direct test of participants' ability to recognize solutions. Half the participants responded with their left hands, and half with their right. Instead of using a binocular viewer, as in the target naming experiment, participants' heads were positioned in a chin rest.

5.2.2.1. Interpretation. Because the responses differed for solution and unrelated targets (solution words required a "yes" response, whereas unrelated words required a "no" response) we could not use priming. Instead we compared the hemispheric difference in raw RT, keeping in mind that participants normally display a rvf-LH advantage when responding to words.

We compared solution decision times for solution words presented to the rvf-LH with decision times for those presented to the lvf-RH. The same comparison was done for unrelated words. Latencies of correct responses were analyzed. Most important, after unsolved problems, participants responded more quickly to lvf-RH words than they did to rvf-LH words. This result is in contrast to the typical rvf-LH advantage for responding to words, and was found for both hits ("yes" responses to solutions) and correct rejections ("no" responses to unrelated targets).

Once again the more rapid responses to target words presented to the lvf-RH supported our hypothesis that solution related information would be more available in the right hemisphere than the left hemisphere. The results also led us to speculate that the information available in the right hemisphere might play an important role in producing solutions, not just recognizing solutions when they are encountered.

5.2.3. Solution decisions with insight ratings

The procedure for this experiment [19] was identical to the solution decision procedure except participants were additionally required to indicate whether the solution decision was accompanied by a feeling of insight. After responding to the SOLUTION? prompt participants saw the word RATING? with a rating scale of 1–5 underneath. The ratings were described as follows: "A rating of 1 means that at first, you did not know whether the word was the answer, but after thinking about it strategically (for example, trying to combine the single word with each of the three problem words) you figured out that it was the answer. A rating of 3 means that you did not immediately know the word was the answer, but you did not have to think about it much either. A rating of 5 means that when you saw the word you suddenly knew that it was the answer ("It popped into my head"; "Of course!" "That's so obvious"; "It felt like I was already thinking that"). Ratings of 2 and 4 indicate feelings somewhere in between. It is up to you to decide what rating to give each of your responses. There are no right or wrong answers". The order of the ratings was reversed for half of the participants. Examples of the Aha! experience were described. Awareness of decision processes (such as using a strategy) was emphasized as a criterion for low-insight ratings, and lack of awareness ("I just knew, I do not know how I knew") was emphasized as the criterion for high-insight ratings.

5.2.3.1. Interpretation. The main focus of this experiment was to determine whether the participants' feelings of insight, as indexed by the rating scale, had to do with solution-related activation, as indexed by solution priming (naming solutions faster than naming unrelated target words) for problems they had not yet solved. Participants' insight ratings correlated better with solution priming for lvf-RH targets. Contrasts revealed a reliable lvf-RH advantage in solution priming only on trials for which the participants rated their solution decisions as most insightful.

5.3. Functional magnetic resonance imaging (fMRI)

Investigating problem solving with fMRI presents some unique advantages and challenges. The advantages consist of the ability to connect patterns of neural activity to cognitive processes. Principal among the challenges is that all problem solving follows a strict sequence of events (e.g., problem solving effort always precedes generating a solution). In addition, our experiments require participants to make insight judgments, which always follow a solution. Separating the neural activity for events that follow a strict sequence, and events that are close together in time, is a difficult challenge.

Other challenges include that one cannot control which problems will be solved, how much time will be needed to reach a solution, or whether a problem is solved with or without insight.

5.3.1. Meeting the challenges of fMRI

In an effort to meet the challenges of using fMRI in problem solving research we began by eliminating as many confounds as possible. To eliminate the confound of using different problems to elicit insight and non-insight solutions we use a large number of the same type of problem (i.e., CRA problems, described above) any one of which can elicit either an insight or non-insight solutions from individuals within a group of solvers. In our procedure both types of solutions are followed by identical response events—indicating whether the solution was with insight or non-insight.

5.3.1.1. Event-related designs. Because, one cannot strictly control which problems will be solved, how much time will be needed to reach a solution, or whether a problem is solved with or without insight an event-related design is preferred over a blocked design [71]. The popularity of event-related designs has increased in recent years [72–75]. In contrast to traditional blocked designs, where multiple trials of a particular condition are grouped together in blocks, event-related designs allow different trial types (for example, insight and non-insight solutions) to be presented in arbitrary sequences.

The use of an event-related design for insight research requires the fluid classification of events as insight or non-insight solutions on a solution-by-solution basis. Though it is somewhat controversial, we have found participants' self-reports of insight work well for this purpose.

5.3.1.2. "Jittering" events. A significant challenge in designing and analyzing event-related fMRI experiments is how to optimize the accuracy of the estimated event-related responses. fMRI analysis involves looking for correlations between experiment events and changes in neural activity, therefore, if an event (such as solving a problem) is highly correlated with another event (such as pressing a button to indicate whether the solution was with insight), and the events occur close together in time, the neural activity overlaps and it becomes difficult to separate for the two events. There are two relatively straightforward ways to reduce this problem: (1) separate the events in time, and (2) randomly vary (*jitter*) the inter-event intervals (ISI). The first approach reduces the problem of overlapping neural activity but does nothing about the high correlation between the events. The effect of the second approach is to reduce the correlation between the events, which increases the ability to separate the brain's activity for separate events.

It has been shown that the accuracy of event-related fMRI response estimates depends on the entire distribution of ISIs not only the mean ISI. Substantial improvement in our ability to separate neural activity associated with different events can be achieved by *jittering* events in a trial, relative to a fixed ISI design with the same mean ISI [76]. Numerous studies have shown highly reliable event-related response estimates using mean ISIs of one second or less (see, e.g., [72–74,77]).

When possible we jitter response events and subsequent trial onsets, to allow deconvolution of hemodynamic responses [76,77]. For instance, in experiments in which participants are required to produce a solution, they first press a solution button, then wait for a period of varying length (2, 4, 6, or 8 s, randomized across all trials) before being prompted to give the solution and seeing the next response prompt.

Randomized intervals between trials (Inter-trial intervals ITI)—Jittering—deconvolves correlated events (and makes it less likely that the MRI scan will always be at the same brain slice for the same task though this is not likely with events with variable durations like ours).

5.3.1.3. Responses. Another challenge is the use of verbal reports of problem solutions. Because it is absolutely critical to ensure that participants produced correct solutions, we have required participants to verbalize their solutions. Overt verbal responses have now been used in many studies, with some concluding that overt verbal responses produce no more head movement than do covert responses (e.g., [78,79]). Nonetheless, challenges remain [80]. In our recent experiments [21], we separate the verbalization from the solution itself, by inserting jittered rest periods between the button press indicating solution and the "Solution?" prompt indicating participants should verbalize. Thus, even artifacts due to tongue movement should be deconvolved from signal corresponding to the solution and button press. Further, we take every measure possible to maintain head position, remind participants to remain as still as possible before each block, correct as much as possible for head motion, and remove participants whose data (from orthogonal contrasts, such as motor cortex activity associated with button presses to other steps of the experiment) indicate head motion.

5.4. fMRI procedure

Following practice, participants attempted 124 compound remote associate problems during FMRI scanning. Each trial began with the task label, "Compound", presented on liquid crystal diode goggles for 0.5–2.5 s. A gating signal from the scanner triggered the central presentation of three problem words, which persisted until participants solved the problem or 30 s elapsed. If participants solved the problem, they made a bi-manual button press, after which the word "Solution?" prompted them to verbalize their solution. After 2 s the word "Insight?" prompted participants to press buttons indicating whether they solved the problem with or without insight [20].

Prior to the experiment participants were told the following: "A feeling of insight is a kind of 'Aha!' characterized by suddenness and obviousness. You may not be sure how you came up with the answer, but are relatively confident that it is correct without having to mentally check it. It is as though the answer came into mind all at once—when you first thought of the word, you simply knew it was the answer. This feeling does not have to be overwhelming, but should resemble what was just described." The experimenter interacted with participants until this description was clear. This subjective rating could be used differently across participants (or even across trials), blurring condition boundaries; yet the distinct neural correlates of insight observed across the group demonstrate that there was some consistency.

5.4.1. Interpretation

The strongest insight effect was that insight solutions were associated with greater neural activity in the RH aSTG than non-insight solutions. There was no insight effect anywhere within temporal cortex of the LH.

After RH aSTG, the second largest area showing an insight effect in FMRI signal was the medial frontal gyrus in the LH. There also was an insight effect in small clusters in or near bilateral amygdala or parahippocampal gyrus. An amygdalar response may be expected, given the emotional sensation of the insight experience [81]. Hippocampal or parahippocampal involvement is also plausible, if memory interacts with insight solutions differently from how it interacts with non-insight solutions [22]. For instance, insight problems may encourage distinct memory encoding [82] or may require distinct retrieval.

The involvement of the RH rather than the LH for insight solutions cannot be attributed to greater difficulty in producing insight solutions: subjects produced insight solutions at least as quickly as they produced non-insight solutions. It also is not likely that RH aSTG is involved only in output or in emotional response following insight solutions, because neural activity in this area also increased when subjects first encountered each problem. Thus, RH aSTG is involved in processing the problem words both initially and at solution.

We have proposed that insight requires several components, including the detection of competing processes and switching from one solution strategy or set of associations to another. Our recent data suggest recruitment of a network of brain areas when people produce insight solutions, including midline areas such as ACC and medial frontal gyrus [20,21], which have been implicated in cognitive control [83,84].

6. Issues and areas for improvement

6.1. Determining whether insight occurred

There have been some challenges to the use of RAT or CRA items as insight problems, however, these challenges seem to revolve around two related issues: (1) should a problem be called an insight problem only if it always requires an insight to reach solution, and (2) how should researchers determine whether a problem has been solved with insight? It appears that the point of greatest contention is whether it is better to determine whether insight has occurred by relying on researchers *a priori* categorizations of problems as insight or non-insight and ignore the experiences of solvers, or rely on solvers' reports of their solving experiences as a measure of whether insight has occurred. We strongly believe that the solver is in a much better position than any observer to judge whether she has been reached a solution with or without insight. However, some have objected that the feeling of insight reported by participants is merely a measure of the speed of the solution, or the positive emotion that accompanies the solution, not of a different problem solving mechanism. We argue that this is not the case because we have found no evidence that solutions reported as being produced with insight require any less time than solutions reported without insight, and we have found differences in both hemispheric activation and neural activation in areas not thought to be connected to emotional responses.

We also strongly believe that these are not mutually exclusive positions. Researchers should select or create problems based on the factors they believe lead to insight or non-insight solutions. They should then use solvers' reports of the solving experience as a manipulation check to determine whether the manipulated factors actually lead to insight or non-insight solutions. If we are interested in the processes that lead to insight, the failure to assess whether a problem was solved with insight represents a fundamental flaw in experimental design.

6.1.1. Improving solvers' reports

Having taken the position that solvers' reports are an important piece of data we recognize that there is room for improvement in how they are collected. We also recognize that at some time in the future overt subjective reports may not be necessary, but that time has not yet arrived. How can solvers' reports be improved?

One improvement would be to improve the description of insight and non-insight given participants. Agreement among researchers on the central features of insight solutions would greatly improve the use of participants' reports of insight. Descriptions might then avoid the use of terms such as insight, analytic, trial-and-error, etc. altogether and focus on phenomena thought to characterize insight, such as suddenness of solution or switching interpretation. We also believe that counterbalancing descriptions so that in one case they emphasize insight and in the other analytic problem solving would reduce concerns about demand characteristics of subjective reports.

When using participants' self-reports of their solving experience one must decide on the number of alternative responses to use. We found that with a 5-point scale (1 = strong non-insight, 3 = neutral, 5 = strong insight) participants tended to use the middle values of 2–4 [19]. We were also concerned that with a 5-point scale participants might use different points on the scale to indicate the same levels of insight (e.g., one participant might use only values of 1–3 whereas another participant might use only values 3–5 so that 3 for one participant is equivalent to 5 for another participant). We have also used a 2-point scale (insight or non-insight) [20], however, without a third choice participants are forced to assign solutions to either insight or non-insight, weakening the distinction between the solution types in the results. Therefore, we are presently using a 3-point scale as it allows an "other" category but does not provide too wide of a range of responses to the participants. We have used a variety of descriptions of the other category where other includes, "I already knew the solution", "The solution did not feel like either insight or non-insight", "I had a little insight about how to solve the problem, but then I still had to work out the solution" The solution was the first thing I considered", and "I just guessed".

6.2. Studying other populations

Certain types of brain damage would, of course, preclude conducting problem-solving research. However, research involving participants with certain types of brain damage could prove very revealing. For example, people with damage to their RH often miss the point of complex discourse and have trouble organizing stories into related events [85,86], show impaired comprehension of figurative language and are sometimes described as being too literal [87,88], and have difficulty understanding jokes [89]. Therefore, we predict that participants with RH damage would have relatively little difficulty with non-insight solutions but would show decrements in the ability to produce insight solutions. Participants with LH damage would show marked decrements in the ability to produce non-insight solutions. The location and extent of the damage could predict the precise decrements found.

7. Conclusions

We believe that our research has contributed to the understanding of insight in several ways. First, by using a visual-hemifield paradigm and event-related neuroimaging, we have found general RH activation that is related to insight, and more specific RH-aSTG involvement in insight solutions. These findings provide evidence that distant associations (coarse coding) in the RH may play an important role in insight solutions. These distant associations might allow for the restructuring critical for insight.

Second, we believe that our use of solvers' reports of their solving experiences on a solution-by-solution basis is important. Whether solvers experience a solution as an insight or a non-insight has rarely been assessed. We see this as an unfortunate oversight because very few problems always produce an insight solution in all solvers. If we fail to determine whether insight has occurred how can we be certain that our data inform us about the processes of insight? Third, our development and testing CRA problems demonstrates that it is not necessary to rely on traditional "insight" and "non-insight" problems to do research on insight. CRA problems can be solved with or without insight, and can be solved quickly enough so that a large number of problems are solved in a one-hour session. The use of CRA problems, and the development of other problems with these properties, opens up research possibilities, such as event-related fMRI, that were difficult to pursue in the past.

We believe that our research is merely an early contribution to efforts at revealing the neural components of insight. Understanding how, when, and where the brain produces insight solutions might prove beneficial in many ways. For example, a better understanding of the mechanisms of insight might allow people to develop their creativity to a fuller extent or improve methods of education by allowing teachers to design lessons so that students are more likely to have insights. We believe that, because insight appears to be a general phenomenon or mechanism of cognition, there will be many unanticipated benefits from a greater understanding of the neural mechanisms of insight.

"A scientific understanding of creativity does not destroy our wonder at it, nor make creative ideas predictable. Demystification does not imply dehumanization" [30].

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