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The right hemisphere maintains solution-related activation for yet-to-be-solved problems

MARK JUNG BEEMAN and EDWARD M. BOWDEN
Rush Medical College, Chicago, Illinois

In five experiments, we examined the time course of hemispheric differences in solution activation for insight-like problems. We propose that solving insight problems requires retrieval of unusual interpretations of problem elements, and that right-hemisphere (RH) coarse semantic coding is more likely than left-hemisphere (LH) fine semantic coding to maintain semantic activation of such interpretations. In four experiments, participants attempted word problems for 7 sec (Experiments 1A and 1B) or 2 sec (Experiments 2A and 2B), and 750 msec later responded to lateralized target words. After 7 sec of solving effort, Experiment 1A participants showed greater solution-related priming (i.e., they named solutions faster than unrelated words) for left visual field-RH (lvf-RH) targets than for right visual field-LH (rvf-LH) targets, and Experiment 1B participants made faster solution decisions on target words presented to the RH, as previously demonstrated following 15 sec of effort. After 2 sec of solving effort in Experiment 2A, women showed symmetric solution-related priming, although men showed a slight lvf-RH advantage in priming; and in Experiment 2B participants made equally quick solution decisions for targets presented to the LH and to the RH. In Experiment 3, participants viewed the problems for 1,250 msec then named lateralized target words; they showed symmetric solution-related priming. These experiments demonstrate solution activation initially in both hemispheres, but maintained solution activation only in the RH.

We examine two component processes of problem solving: activation of information relevant to the solution, which may lead the solver to the correct solution path, and recognition of the solution when it is encountered or generated. It is clear that these two component processes are important for all problem solving, but they may play unique roles in solving insight-like problems, which require the retrieval of unusual interpretations, or seemingly distantly related information, to achieve solutions.

We suggest that insight problems contain features that bias retrieval toward solution-irrelevant interpretations of critical words in the problems, and away from interpretations that would lead to solution. We further suggest that the cerebral hemispheres activate information differently. According to our theory, the left hemisphere (LH) engages in fine semantic coding, strongly focusing activation on a single interpretation of a word and a few close associates, whereas the right hemisphere (RH) engages in coarse semantic coding, weakly and diffusely activating alternative meanings and distant associates (for a review, see Beeman, 1998).

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Thus, the present experiments are driven by two hypotheses: (1) Problems that produce the subjective experience of insight misdirect or fail to direct retrieval (Bowden, 1997); and (2) due to the lack of directing cues, relatively coarse semantic coding in the RH is more likely than relatively fine semantic coding in the LH to activate (or maintain activation of) solution-relevant information (Beeman, 1993, 1998; Beeman et al., 1994). These hypotheses were supported by previous results showing a RH advantage both in solution-related priming and in solution decision time following relatively long solution efforts (Bowden & Beeman, 1998). We aim to replicate and extend these earlier results.

Evidence for Hemispheric Differences in Processing

Support for the RH coarse semantic coding theory comes from a number of different sources. For example, despite the normal LH advantage in processing language, in divided visual field studies normal comprehenders can show greater priming—speed or accuracy benefits—for target words presented to the left visual field (lvf)-RH than for target words presented to the right visual field (rvf)-LH, following certain prime types. Specifically, greater lvf-RH priming occurs when a target word is distantly related to, or related to an unusual interpretation of, a preceding prime word or words (Beeman et al., 1994; Burgess & Simpson, 1988; Chiarello, Burgess, Richards, & Pollock, 1990; M. E. Faust & Gernsbacher, 1996; Nakagawa, 1991). Similarly, people more easily recognize pairs of remotely associated words as related if one of the pair is presented to the lvf-RH (Rodel, Cook, Regard, & Landis, 1992). Moreover, patients with RH brain damage (who rely to a greater extent than normals on their intact LH) tend to focus on the most direct denotative interpretations of words, whereas patients with LH damage (who rely more on their intact RH) tend to focus on metaphoric or connotative meanings (Brownell, Potter, & Michelow, 1984). Patients with RH damage also can have difficulty drawing inferences (Beeman, 1993; Brownell, Potter, Bihrle, & Gardner, 1986), and normal participants show inference-related priming earlier in the lvf-RH than in the rvf-LH (Beeman, Bowden, & Gernsbacher, 2000).

Neuroimaging studies show RH activation when participants comprehend metaphors (Bottini et al., 1994) and generate novel uses of verbs (Abdullaev & Posner, 1997; Seger, Desmond, Glover, & Gabrieli, 2000). Task manipulations that are thought to increase the demand for semantic integration of discourse selectively increase fMRI signal in the RH (Robertson et al., 2000; St. George, Kutas, Martinez, & Sereno, 1999). The combined evidence suggests that complementary processing by both hemispheres is necessary to comprehend complex discourse (for review, see Beeman & Chiarello, 1997). In general, the RH seems better suited to process complex discourse connected by distant semantic associations than to process single words or word pairs (for review, Beeman, 1998). Thus, it is a small step to hypothesize that the RH may also play an important role in solving verbal problems that require similar semantic processing (e.g., insight problems).

The Possible Role of Hemispheric Differences in Problem Solving

If the LH uses fine semantic coding, it will strongly activate a small semantic field of information closely related to the contextually biased interpretation of problem words. Though normally effective, this activation pattern makes the LH vulnerable to misdirecting features of insight problems. If the RH engages in coarse semantic coding, it should maintain diffuse activation of alternative meanings and more distant associates, including solution-relevant concepts, as well as misdirected and solution-irrelevant information. Initially, the solver may not be able to take advantage of solution activation in the RH because the activation is weak and diffuse and may be blocked or overshadowed by stronger, more focused, but misdirected, activation in the LH (along with weak activation of the same concepts in the RH). If activation of alternative meanings and more distant associates persists in the RH, then this activation might eventually prove useful for recognizing or generating the solution if misdirected activation subsides.

Fiore and Schooler (1998) have argued that "the sudden recognition of an alternative approach that leads to the solution of a problem that previously seemed insoluble—may rely on cognitive processes associated with the RH" (p. 367). They examined differences in participants' ability to benefit from hints for nine insight problems depending on whether the hints were presented to the right or left visual field. They used two different delays (immediate vs. 2 min) to examine the effect of reaching impasse on the use of hints. Hints presented to the lvf-RH helped more than hints to the rvf-LH, and the magnitude of the RH advantage was greater in the delay than in the no-delay condition, especially after the 2-min delay. This study provides empirical support for the hypothesis that the RH may be involved in processing that leads to solving insight problems, especially when solvers encounter new relevant information after unsuccessfully working on the problem for 2 min. However, participants were equally adept at recognizing new information as a hint when presented to either hemisphere, so there was no evidence of greater RH solution activation prior to the hints.

Recent evidence suggests that problem solvers do exhibit hemispheric differences in semantic activation related to solutions of insight-like problems (Bowden & Beeman, 1998). In two experiments participants attempted to solve compound remote associate problems, patterned after some items on the Remote Associates Test (Mednick, 1962), which was originally developed as a test of creativity. Similar problems have been widely used to study insight and creative thinking (e.g., Bowers, Regehr, Balthazard, & Parker, 1990; Dallob & Dominowski, 1993; Dorfman, 1990; Schooler & Melcher, 1995; Shames, 1994; Smith & Blankenship, 1989). Problem solvers' success on the Remote Associates Test reliably correlates with their success on classic insight problems (Dallob & Dominowski, 1993; Schooler & Melcher, 1995).

The compound remote associate problems consisted of three stimulus words for which participants were asked to generate a fourth word that, when combined with each of the three stimulus words results in word pairs that are used in everyday language (e.g., *right/cat/carbon*—COPY). (See Bowden & Beeman, 2000b, for the complete set of problems.) Problem solvers can experience compound remote associate problems as insight or noninsight problems, according to subjective ratings (Bowden & Beeman, 2000a). Participants attempted to produce the solution within 15 sec. After producing the solution, participants showed greater solution-related priming (faster naming latencies for solution words than for unrelated words) for lvf-RH than for rvf-LH targets. After 15 sec of unsuccessful effort, participants showed solution-related priming only in the lvf-RH (Bowden & Beeman, 1998, Experiment 1). Furthermore, after 15 sec of unsuccessful effort, participants made faster solution decisions for lvf-RH target words than for rvf-LH target words (Bowden & Beeman, 1998, Experiment 2). This result is unusual in that normal right-handed participants almost always respond faster to words presented to the rvf-LH rather than to the lvf-RH. In combination, these results demonstrated that, in a problem-solving context, solvers had greater activation of solution-related information in the RH than in the LH, and that they could use this activation to recognize solutions to as yet unsolved insight problems.

In the experiments reported here, we examine the time course of solution activation in the hemispheres. We replicate our previous experiments, but give participants either 7 sec (Experiments 1A and 1B) or 2 sec (Experiments 2A and 2B) to produce the solution, or examine priming after just 1 sec of effort with instructions not to overtly generate solutions (Experiment 3). One key question these experiments address is whether the RH advantage in solution activation is the result of bottom-up processing differences or of more slowly unfolding processes related to comprehension and problem solving. Some research suggests that in response to a single word, both hemispheres initially activate both close and remote associates, but that the LH quickly (within 750 msec) selects the dominant or contextually relevant associations and "deactivates" all others (Burgess & Simpson, 1988; Koivisto, 1997), perhaps through attentional mechanisms (Nakagawa, 1991). In our previous studies (e.g., Bowden & Beeman, 1998), participants were given 15 sec to work on each problem. It is possible that the hemispheric differences in activation of the solution were present immediately after the presentation of a problem (due to bottom-up activation that differs between the hemispheres). In contrast, the differences might have developed over time due either to differences in the way the hemispheres inhibit or enhance initially similar activation, or to hemispheric differences specific to problem solving.

We also examined sex differences because the degree of language laterality has sometimes been shown to be greater in men than in women for both visual hemifield studies (Luh & Levy, 1995) and neuroimaging studies (Pugh et al., 1997; Shaywitz et al., 1995; cf. Buckner et al., 1996; Frost et al., 1999; Gur et al., 1994).

EXPERIMENT 1A

In Experiment 1A, participants attempted to solve compound remote associate problems within 7 sec. After solving the problems, or after 7 sec of effort, they named (read aloud) solution words or unrelated words presented to the rvf-LH or to the lvf-RH. Seven seconds (plus a 750-msec stimulus onset asynchrony [SOA]) was selected as ample time for solvers to settle into solution strategy for most problems, and thus for solution activation to reflect somewhat long-term semantic activation. Results were expected to replicate those observed after 15 sec of solving effort (Bowden & Beeman, 1998) and to serve as a basis for comparison for Experiments 2A, 2B, and 3, in which we examined activation at shorter intervals.

Solution-related priming (when participants name solutions faster than unrelated words) would demonstrate semantic activation of the solution. Even if participants manifest the normal rvf-LH advantage for word reading, we can examine differential activation in the hemispheres by comparing priming for solution words presented to the lvf-RH with priming for solution words presented to the rvf-LH. Participants often manifest qualitatively different patterns of semantic priming for words presented to each visual hemifield, suggesting some independent processing despite an intact corpus callosum (for a review, see Beeman & Chiarello, 1998).

Greater priming for solution words presented to lvf-RH would reinforce our contention that the RH is more likely to activate, or sustain activation of, more distantly associated meanings (or less common interpretations), which, in the case of insight-like problems, could eventually be useful in reaching solutions. Priming for the solutions to problems that have not yet been solved would further suggest that solvers have semantic activation of solutions, without awareness (or at least without recognizing that the word is indeed the solution).

Method

Participants. Thirty-two students (16 women, 16 men) from the University of Wisconsin, Parkside, and the University of Illinois, Chicago, participated in Experiment 1A for partial course credit. All participants were strongly right-handed (Oldfield, 1971) and native speakers of American English.

Materials. The problems were 144 compound remote associate problems, patterned after some items on the Remote Associates Test (Mednick, 1962). For all of the items, each of three words in a problem could form a compound word or phrase with the solution word (e.g., *high/district/house*—SCHOOL), providing participants with a consistent task (for full list and solving rates, see Bowden & Beeman, 2000b). Recognizing solutions to these simple problems can lead to an insight experience (Bowden & Beeman, 2000a). Compound remote associate problems have two advantages over more complex problems: They are compact, allowing centralized presentation of an entire problem, and they have single-word solutions, allowing presentation of solution or unrelated target words to a single visual hemifield.

Procedure. For each trial, participants tried to solve one problem, then read aloud one target word. Each trial began with a central fixation cross presented on a 15-in. Apple monitor by a Powerbook 165 computer, then three problem words were presented simultaneously in normal horizontal orientation above, at, and below the center of the screen. Participants tried to produce the solution word within 7 sec. After participants produced a solution, or after 7 sec, the problem words were erased, a tone sounded for 250 msec, and the fixation cross reappeared for 500 msec (for a total SOA of 7,750 msec). Then a target word was presented horizontally to the left or right of fixation for 180 msec, with the inner edge (right side of last letter for lvf-RH words, left side of first letter for rvf-LH words) 1.5 deg of visual angle from fixation. Participants had a maximum of 3 sec to name (read aloud) the target word. Relatedness and visual hemifield of the target words were completely crossed. The unrelated target words were the solutions to problems 72 trials away (e.g., the first problem occurred with either its own solution, or with the solution to Problem 73), with targets to companion trials appearing in the same visual field, and of course being either both related or both unrelated. Problems were arranged in pseudorandom order, and hemifield by relatedness condition was balanced across four material sets, each viewed by equal numbers of participants. Participants saw each target word only once over the course of the experiment.

Participants were tested individually, positioned in a chin rest/head holder a constant distance from the screen. They were given five practice problems with target words. Further explanation of the task was given if necessary.

Results

On average, participants solved 21.1% ($SD = 5.8$) of the problems within the 7-sec time limit and correctly read 89.3% ($SD = 6.1$) of the target words. Analyses were performed on participants' latencies and accuracies for both solved and unsolved problems. (Comprehensive information about performance on particular items is available in Bowden & Beeman, 2000b). For all statistical comparisons (F and t tests) reported in this paper, a $p <$ .05 level of significance was adopted. The data from 5 participants were replaced because they had too many missing responses (more than 2.5 SD below the mean; i.e., < 74% of possible correct responses were recorded). Missing responses were due to the participant speaking too quietly to trigger the microphone, making the response too late, not making any response, or making an incorrect response. For each participant, outlier latencies (exceeding 3.0 SD from the participant's mean) were excluded. There were no sex effects or sex × hemifield interactions for either solved or unsolved problems (Fs < 1.0), but sex was included as a factor in the remaining analyses.

See Table 1 for mean naming latencies. For unsolved problems, participants showed the expected LH advantage in response latency, naming target words presented to the rvf-LH 58 msec more quickly than target words presented to the lvf-RH [$F(1,30) = 77.75$, $MS_e = 109{,}395$]. Participants also showed overall priming, reading solution words 37 msec more quickly than they read unrelated words [$F(1,30) = 22.77$, $MS_e = 43{,}218$].

Participants showed significant priming (49 msec) for solution words presented to the lvf-RH [$F(1,30) = 30.12$, $MS_e = 38{,}171$] and for solution words presented to the rvf-LH [25 msec, $F(1,31) = 8.59$, $MS_e = 9{,}726$]. A reliable target type × hemifield interaction [$F(1,30) = 9.35$, $MS_e = 4{,}680$] reflected a 24-msec lvf-RH advantage in solution-related priming.

For solved problems, there were main effects of hemifield and relatedness (Table 1). Participants showed the expected LH advantage in naming latency, naming rvf-LH target words 20 msec more quickly than lvf-RH target words [$F(1,30) = 3.90$, $MS_e = 12{,}720$, $p < .06$]. Participants also showed overall priming, naming solution target words 79 msec more quickly than they named unrelated target words [$F(1,30) = 15.16$, $MS_e = 123{,}504$]. Hemifield and relatedness interacted marginally [$F(1,30) = 4.06$, $MS_e = 14{,}620$, $p < .06$]. This reflected a 43-msec RH-advantage in solution-related priming. Participants showed reliable priming (84 msec) for solution words presented to the lvf-RH [$F(1,30) = 17.87$, $MS_e = 111{,}556$] and for solution words presented to the rvf-LH [41 msec, $F(1,30) = 4.84$, $MS_e = 26{,}569$].

EXPERIMENT 1B

As previously demonstrated following 15 sec of solution effort (Bowden & Beeman, 1998), solvers in the present study manifest a RH advantage in solution-related priming after 7 sec of solving effort, despite the typical LH advantage for raw reaction time. In Experiment 1B, we tested whether the solution activation observed in Experiment 1A might be useful for the second component process of problem solving—recognizing the solution. Previously, after 15 sec of solving effort, solvers showed a RH advantage in raw reaction time for accepting solutions and rejecting distractors. Given the RH advantage in solution-related priming following 7 sec of solving effort, we again expected that solvers would make solution decisions faster for lvf-RH than for rvf-LH targets.

Method

Forty students (24 women, 16 men) participated in Experiment 1B. All participants were strongly right-handed (Oldfield, 1971) and native speakers of American English. The materials and procedure were the same as those of Experiment 1A except that instead of naming the target word, participants indicated with a buttonpress whether the target word was or was not the solution to the problem. Solution decision tests problem solving more directly than does reading the target words aloud. However, we cannot examine priming because solution words require a "yes" response, whereas unrelated words require a "no" response, and it might be the case that participants simply make one type of response faster than the other. Instead, we must examine the hemispheric difference in raw response times, keeping in mind that, as a group, right-handed participants nearly always display a rvf-LH advantage when responding to words. Half the participants responded with their left hands, half with their right hands, and response hand did not interact with any variables of interest.

Results

On average, participants solved 21.6% ($SD = 7.5$) of the problems within the 7-sec time limit and correctly responded to 93.7% ($SD = 9.0$) of the target words. Five participants were replaced—2 because they had a strong bias to respond "no" to target words (more than 80% of responses), 1 for failure to solve any problems, and 2 because of equipment failure. There were no sex effects, and sex did not interact with other variables (all Fs < 1.0), but sex was included as a factor in all analyses.

Table 1
Mean Naming Latencies in Milliseconds for Experiment 1A for Unrelated Words and Solutions, After 7 Sec of Solving Effort, by Visual Hemifield of Presentation and Solution Outcome

	Unsolved Problems			Solved Problems		
Target Word	rvf-LH	lvf-RH	RH Advantage	rvf-LH	lvf-RH	RH Advantage
Unrelated	659	730		653	694	
Solution	635	681		612	611	
Priming	25*	49*	24*	41*	84*	43*

*$p < .05$.

Table 2
Mean Solution Decision Latencies in Milliseconds for Experiment 1B, After 7 Sec of Solving Effort, by Hemisphere and Decision Outcome

	Unsolved Problems		
Response Type	rvf-LH	lvf-RH	RH Advantage
Correct Rejections	1,772	1,740	32
Hits	1,769	1,704	65
			M: 49*

*$p < .05$.

Decision latency. We examined response latencies for correct solution decisions following unsolved problems, and these are listed in Table 2. (It makes little sense to examine solution decisions after participants have already produced the solution, and in any case no differences were present).

After failing to solve problems, participants made hits (responding "yes" when the target word was the solution) just 7 msec more quickly than they made correct rejections (responding "no" when the target word was not the solution), ($F < 1.0$). There was a significant main effect of hemifield of presentation: Participants responded 49 msec more quickly to words presented to the lvf-RH than they did to words presented to the rvf-LH [$F(1,38) = 7.41$, $MS_e = 87{,}783$]. Response type and hemifield of presentation did not interact ($F < 1.0$).

Decision accuracy. We cannot draw strong conclusions from the accuracy data because right-handed people generally read a greater proportion of target words presented to the rvf-LH than to the lvf-RH (with equal exposure durations, as used here), so that solution decisions for lvf-RH targets are guesses more often than for rvf-LH targets. For example, in Experiment 1A participants correctly read 95.1% ($SD = 3.94$) of target words presented to the rvf-LH and 83.4% ($SD = 9.91$) of those presented to the lvf-RH [$F(1,31) = 56.41$, $p < .001$]. Nevertheless, a sensitivity analysis (d') from signal detection theory was used to examine accuracy of recognition responses. As with previous analyses, only unsolved problems were examined. Participants responded with greater sensitivity to target words presented to the rvf-LH ($d' = 1.91$, $SD = .69$; 76.2% correct) than to the lvf-RH [$d' = 1.42$, $SD = .72$; 68.5% correct; $F(1,39) = 20.58$, $MS_e = 5.8$]. Importantly, the lvf-RH advantage for response latency was not correlated with the rvf-LH advantage for accuracy [$r(40) = .04$]. Thus, participants were not sacrificing accuracy for speed when responding to lvf-RH target words. These results are similar to those from our earlier experiment (Bowden & Beeman, 1998, Experiment 2). Moreover, in another study participants read the target words aloud and then made solution decisions. For trials on which participants correctly named the target words, there were no accuracy or sensitivity differences across the hemispheres (Bowden & Beeman, 2000a).

Summary of Experiments 1A and 1B

Results after 7 sec of solving time replicated results after 15 sec of solving time (Bowden & Beeman, 1998). In Experiment 1A, when participants failed to solve problems within the 7-sec limit, they showed significantly greater priming for lvf-RH target words than for rvf-LH target words. After solving problems, participants showed a marginally reliable RH advantage in solution priming. In Experiment 1B, following unsolved problems participants made solution decisions significantly faster for lvf-RH target words than for rvf-LH target words. In both experiments, there was no sex effect, and sex did not interact with other variables.

EXPERIMENTS 2A AND 2B

In Experiments 2A and 2B, participants were allowed only 2 sec to attempt solution. Two seconds was determined to be enough time to initiate a solution strategy, but generally not enough time to produce a solution. The time limit (plus warning tone and fixation, for a total SOA of 2,750 msec) was short for a study of problem solving, but much longer than that used in most priming studies of simple word comprehension. Thus, solution-related activation may reflect initial problem-solving processes, rather than pure bottom-up semantic activation, but may still differ from activation resulting from later solving efforts. Participants were encouraged to attempt to solve each problem before the target word was presented, and feedback indicated that they did so. Although it is possible that the short solving time could cause participants to adopt different strategies from those adopted with longer solving time, an experiment with time limit varying randomly, to discourage such strategies, would lose considerable statistical power due to fewer observations per condition cell.

Method

Participants. Forty students (20 women, 20 men) participated in each experiment (2A and 2B) for partial course credit. All participants were University of Wisconsin, Parkside, students, were strongly right-handed according to a handedness survey (Oldfield, 1971), and were native speakers of American English.

Materials and Procedure. The materials and procedure were the same as those of Experiments 1A and 1B except that participants were allowed 2 sec of solving time before the warning tone and target words were presented (total SOA of 2,750 msec).

Experiment 2A Results

On average, participants solved 10.6% ($SD = 6.8$) of the problems within the 2-sec time limit and correctly read 90.4% ($SD = 4.6$) of the target words. Analyses were performed only on unsolved problems because there were too few observations per condition for the solved problems. Five participants were replaced because they had too many missing responses (more than 2.5 *SD* below the mean; i.e., < 79%), resulting in too few observations per

Table 3
Mean Naming Latencies in Milliseconds for Experiment 2A for Unrelated Words and Solutions, After 2 Sec of Solving Effort, by Visual Hemifield of Presentation

	Unsolved Problems		
Target word	rvf-LH	lvf-RH	RH Advantage
Unrelated	605	654	
Solution	574	616	
Priming	31*	38*	7

$p < .05$.

condition. Missing responses were due to the participant speaking too quietly to trigger the microphone, making the response too late, not making any response, or making an incorrect response. There was no main effect of sex ($F < 1.0$), but sex did marginally interact with the hemifield × relatedness interaction, and it was included as a factor in all analyses.

In terms of naming latencies, there were significant main effects of hemifield of presentation and type of target word (solution vs. unrelated). See Table 3 for mean response times. Participants showed the expected LH advantage in response latency for naming: They read rvf-LH target words 54 msec more quickly than lvf-RH target words [$F(1,38) = 42.91$, $MS_e = 81{,}450$]. They also showed priming, reading solution target words 45 msec more quickly than they read unrelated target words [$F(1,38) = 32.80$, $MS_e = 47{,}334$].

Participants showed significant priming for solutions presented to both visual hemifields—38 msec for lvf-RH solution words [$F(1,38) = 21.24$, $MS_e = 28{,}388$] and 31 msec for rvf-LH solution words [$F(1,38) = 21.37$, $MS_e = 19{,}375$]. Priming did not interact with hemifield of presentation ($F < 1.0$). In other words, the lvf-RH advantage (7 msec) was not reliable. There was a marginal three-way interaction (hemifield of presentation × target type × sex) for response latency [$F(1,38) = 3.51$, $p < .07$, $MS_e = 2{,}805$]. Men showed a marginally reliable 24-msec RH priming advantage [$F(1,19) = 4{,}23$, $p < .06$, $MS_e = 2{,}714$], whereas women showed a nonreliable 10-msec LH priming advantage ($F < 1.0$). In nine experiments to date investigating hemispheric differences with these problems, this is the only time even a marginal sex difference has appeared (Bowden & Beeman, 1998; Bowden & Beeman, 2000a).

Experiment 2B Results

On average, participants solved 5.5% ($SD = 6.5$) of the problems within the 2-sec time limit and made a buttonpress response to 97.5% ($SD = 2.5$) of the target words. Again, analyses were performed only on correct responses following unsolved problems. The data from 4 participants were replaced because they had a strong bias to respond "no" to target words (more than 80% of responses).

Decision latency. See Table 4 for mean response latencies. There was a significant main effect of response type: Participants made hit responses (responding "yes" when the target word was the solution) 256 msec more quickly than they made correct rejections [responding "no" when the target word was not the solution; $F(1,38) = 22.50$, $MS_e = 2{,}329{,}315$]. No other effects or interactions were reliable (all Fs < 1.0).

Decision accuracy. Again, it is difficult to draw strong conclusions from the accuracy data because participants can read more rvf-LH target words than lvf-RH target words, so solution decisions for lvf-RH target words more often reflect guessing. In Experiment 2A, after unsolved problems, participants correctly read 93.9% ($SD = 5.2\%$) of target words presented to the rvf-LH and 84.8% ($SD = 10.8\%$) of those presented to the lvf-RH [$F(1,39) = 41.15$, $p < .0001$]. A sensitivity analysis (d') from signal detection theory was used to examine accuracy of recognition responses. As with previous analyses, only unsolved problems were examined. Participants responded with marginally greater sensitivity in the rvf-LH ($d' = 1.98$, $SD = .63$; 78.6% correct) than in the lvf-RH [$d' = 1.77$, $SD = .70$; 76.4% correct; $F(1,39) = 3.43$, $p < .08$, $MS_e = 0.8$]. The rvf-LH advantage for response accuracy was not correlated with a response latency asymmetry [in either direction, $r(40) = -.02$]. Thus, participants were not sacrificing accuracy for speed when responding to lvf-RH target words. These results are similar to those from our earlier experiments (Experiment 1B and Bowden & Beeman, 1998, Experiment 2).

Summary of Experiments 2A and 2B

In Experiment 2A, only men showed marginally greater response latency priming for lvf-RH presentation of solutions than for rvf-LH presentation following 2 sec of solving effort. In contrast, in Experiment 1A, after 7 sec of solving effort, women and men both showed a reliable RH advantage in priming, and a previous experiment showed that after 15 sec of solving effort, women showed a highly reliable RH advantage in priming (Bowden & Beeman, 1998). In Experiment 1B, there was no reliable hemispheric difference in response latency to judge whether a target word was the solution to the problem. Again, this is in contrast to results after 7 sec (Experiment 1B) or 15 sec (Bowden & Beeman, 1998) of solving effort, when participants show reliable RH advantages.

EXPERIMENT 3

Previous experiments revealed robust hemispheric differences in solution-related priming with 7- or 15-sec solving periods, and nonsignificant differences with over

Table 4
Mean Solution Decision Times in Milliseconds for Experiment 2B, After 2 Sec of Solving Effort, by Hemisphere and Decision Outcome

	Unsolved Problems		
Response Type	rvf-LH	lvf-RH	RH Advantage
Correct Rejections	1,696	1,698	−3
Hits	1,449	1,434	14
			M: 6

$p < .05$.

2 sec. The question remains whether hemispheric differences would exist following problem presentation and virtually no solving period. Therefore, in Experiment 3 we examined solution-related priming 1,250 msec after problem onset.

Method

Thirty-two students (16 women, 16 men) from the University of Wisconsin-Parkside participated in Experiment 3. All participants were strongly right-handed (Oldfield, 1971) and native speakers of American English. The materials and procedure were the same as those of Experiments 1A and 2A except that participants were shown each triad for only 1 sec before the target word was presented, followed by simultaneous tone and fixation for 250 msec, followed by the target (total SOA of 1,250 msec). Also, participants were instructed to try to solve the problems, but not to voice solution attempts. One second was selected because participants would have enough time to read all three words in each triad, and barely initiate a problem-solving strategy. This SOA is longer than most simple word priming experiments, but very short for problem solving.

Results

On average, participants correctly read 89.2% (*SD* = 11.1) of the target words. The data from 3 participants were replaced because reading accuracy was more than 2.5 *SD* below the mean (89.2%). Data from an additional participant were excluded because she showed unusually large priming across both hemispheres (315 msec, more than 3.5 *SD* from mean priming), suggesting an unusual strategy. Including her data affects the numeric strength, but not the pattern or statistical reliability of priming. There were no sex effects, and sex did not interact with hemifield (all *F*s < 1.0), but it was included as a factor in all analyses.

See Table 5 for mean response latencies. Thirty-one remaining participants showed the expected LH advantage in response latency for reading (naming): Target words presented to the rvf-LH were read 57 msec more quickly than target words presented to the lvf-RH [$F(1,29) = 27.22$, $MS_e = 102{,}799$]. Participants also showed overall priming, reading solution target words 45 msec more quickly than they read unrelated target words [$F(1,29) = 22.97$, $MS_e = 62{,}439$]. No other main effects or interactions were reliable (*F*s < 1.0). Men showed a 7-msec RH priming advantage, whereas women showed a 10-msec LH priming advantage; neither was reliable.

Table 5
Mean Naming Latencies in Milliseconds for Experiment 3 for Unrelated Words and Solutions, After 1 Sec of Solving Effort, by Visual Hemifield of Presentation

	Unsolved Problems		
Target word	rvf-LH	lvf-RH	RH Advantage
Unrelated	696	752	
Solution	649	708	
Priming	46*	45*	−2

*$p < .05$.

Time Course Analyses

Qualitatively different results were obtained in the different experiments, for which the only substantive difference was the length of time for which participants considered the compound remote associate problems. Therefore, participants' mean latencies from all experiments (including the 15-sec experiments previously published) were submitted to mixed-factor analyses to examine whether solving time reliably interacted with the relatedness × hemifield interaction. Figures 1 and 2 illustrate the trends in solution-related priming and solution decision latency.

For naming latencies obtained at 1.25, 2.75, 7.75, and 15.75 sec following problem onset, solving time (experiment) reliably interacted with the relatedness × hemifield interaction [$F(3,130) = 3.05, p = .03, MS_e = 2{,}627$]. This reflects a RH advantage in solution-related priming following 15 and 7 sec of solving effort, but not after 1 or 2 sec of solving effort. Also, for solution decision latencies at 2.75, 7.75, and 15.75 sec, solving time reliably interacted with hemifield [$F(1,104) = 3.92, p < .03, MS_e = 48{,}175$]. This reflects a RH advantage in decision latencies following 15 and 7 sec of solving effort, but not after 2 sec.

GENERAL DISCUSSION

These experiments paint the following picture of semantic activation in the hemispheres while solvers attempt compound remote associate problems: Initially, both hemispheres activate a broad scope of information, which is likely to include solution-related information. Therefore, up to 3 sec after problem presentation, solution-related priming occurs in both visual hemifields, and solvers make solution decisions equally quickly for rvf-LH and lvf-RH target words. Soon, however, for problems that they have not solved, semantic activation in the LH begins to focus, at the expense of solution-related information. (It seems likely that if LH semantic activation focused on solution-related information, solvers would produce the solution.) In contrast, RH semantic activation continues to be diffuse and sensitive to semantic overlap, and thus solution-related activation persists, even for problems the solvers have not yet solved. Thus, after 7 sec of effort, solution-related priming is greater in the RH, and solvers make solution decisions more quickly for lvf-RH targets than for rvf-LH targets. After 15 sec of effort, solution-related priming persists only in the RH (Bowden & Beeman, 1998). The fact that problem solvers maintain solution activation for problems they have not yet solved is consistent with the belief that unconscious processing contributes to insight solutions (see Bowden, 1997). Similarly, solution-related priming has previously been documented for obscure words that participants could not produce in response to the word definitions (Yaniv & Meyer, 1987; cf. Connor, Balota, & Neely, 1992).

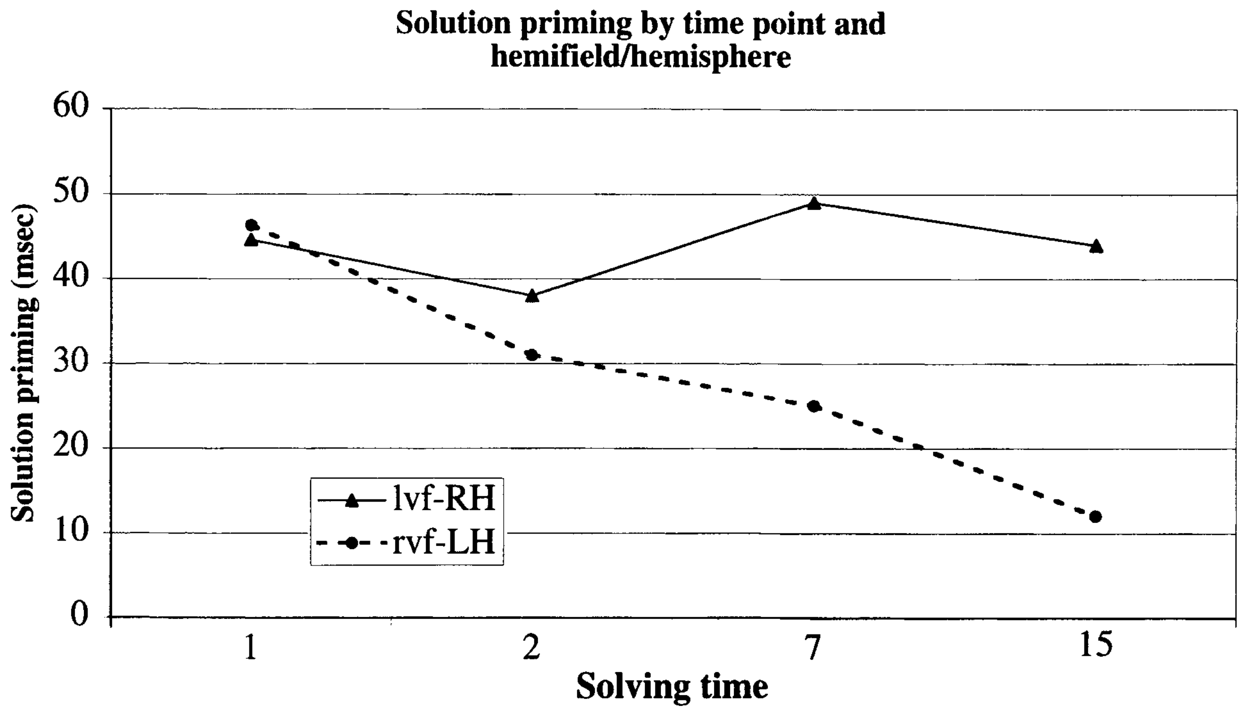

Figure 1. Solution-related priming for target words presented to the rvf-LH or to the lvf-RH, after 1, 2, 7, or 15 sec of solving effort, from Experiments 3, 2A, 1A, and Bowden and Beeman (1998) Experiment 1, respectively.

These experiments extend the literature in several important ways. First, the data replicate and extend our previous results showing RH advantages in both solution-related priming and raw solution decision latency following 15 sec of solution effort. The current data suggest that this RH advantage emerges over time, as solution-related activation fades in the LH. These data with compound remote associate problems complement data on hemispheric differences while solvers attempt more classic insight problems (Fiore & Schooler, 1998). In that study, male solvers attempted nine insight problems, and hint words were laterally presented beginning soon after the problem presentation, or only after a 2-min delay. Hint words were presented for 165 msec in the lvf-RH and 115 msec in the rvf-LH to allow for roughly equal identification. Although solvers benefited more from lvf-RH hints after the long delay, they identified words as hints equally well in either hemifield. Thus hint efficacy could be attributed to hemispheric differences in strategies for utilizing hints rather than hemispheric differences in semantic activation per se. In the present study, using the 144 compound remote associate problems allowed tight control over timing and more power for detecting small differences in priming, although the problems used were not classic insight problems like those used by Fiore and Schooler (1998). These studies provide converging evidence for an important role of the RH in solving insight and insight-like problems. In another recent study, solvers only demonstrate a significant RH advantage in solution-related priming for compound remote associate problems when they rate solution recognition as an insight experience, and not when they rate their recognition as noninsight (Bowden & Beeman, 2000a).

The present experiments also relate to the literature on hemispheric differences in semantic priming in simple word-reading contexts, without any problem-solving context. Our data are consistent with the general picture that the RH activates some information more strongly than the LH does (for review, see Chiarello, 1998; Faust, 1998), perhaps in part because the LH focuses on the dominant or contextually relevant meanings of input words (Burgess & Simpson, 1988; M. E. Faust & Gernsbacher, 1996; Nakagawa, 1991; Titone, 1998). The data also fit the RH coarse semantic coding theory (Beeman, 1998; Beeman et al., 1994). For most language tasks, the LH's ability to quickly narrow the focus of activation is advantageous. However, under certain circumstances (e. g., when an unusual meaning is intended), the LH may focus activation on an incorrect interpretation or association. When this happens the diffuse activation maintained in the RH could allow the person to access alternative interpretations. Thus, the RH's ability to maintain broader semantic activation over time facilitates the reinterpretation of discourse.

Extended to problem solving, the RH coarse semantic coding theory predicts that, because insight problems misdirect solvers, the LH will focus on interpretations that do not lead to solution, whereas the RH maintains solution-related (as well as misdirected) activation. Coarse semantic coding also predicts that, because RH solution activation is diffuse, it may be overshadowed by stronger,

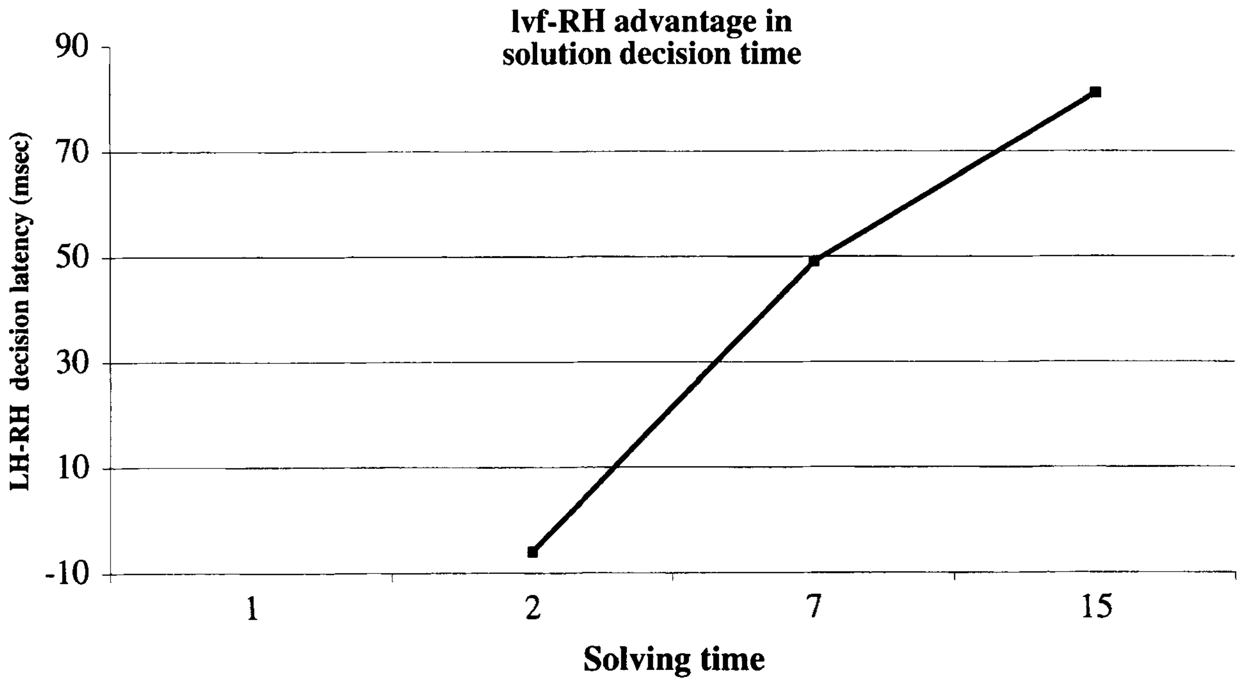

Figure 2. lvf-RH advantage in raw solution decision latency, after 1, 2, 7, or 15 sec of solving effort, from Experiments 2B, 1B, and Bowden and Beeman (1998) Experiment 2, respectively.

more focused activation in the LH, or may be too weak to be generated as a solution. However, when solution candidates are presented to problem solvers the RH activation can help in judging whether those candidates are indeed solutions (as shown in Experiment 2B above, and Experiment 2 of Bowden & Beeman, 1998). That is, at the very least, RH activation can be used to help recognize the solution if or when it is encountered. It is also possible that, at some point, problem solvers could use this activation to help generate solutions.

It should be noted that these solution priming experiments manifest a pattern similar to that observed in previous priming experiments with no problem-solving context, but over a much longer time. Participants sometimes show priming for distantly related targets, or targets reflecting unusual prime interpretations, in the LH at short (e.g., 35-msec) delays following a single-word prime, but after a longer (750-msec) delay, only the RH shows such priming. Even with three-word primes, where all three words are distantly related to the target, there is a RH advantage in priming as early as 750 msec (Beeman et al., 1994). In contrast, the RH advantage in solution-related priming did not emerge after 2,750 msec in the present experiments. This suggests that some aspect of the problem-solving process is driving the hemispheric difference. The fact that the LH shows strong solution-related priming at 1,250 and 2,750 msec could also be due to the type of stimuli used. Whereas summation priming stimuli were chosen specifically to be distantly related to the target words (Beeman et al., 1994), some of the problem words in the compound remote associate problems may be moderately or even closely related to the solution. Although such problem words cause activation in both hemispheres, this activation does not lead directly to solution because other activation exists as well, and the activation may be linked to only one problem word rather than all three (e.g., activation for high school but not for school district).

One possible wrinkle in this depiction is that the RH and LH patterns may diverge more quickly in men than in women, with men showing an earlier loss of solution-related priming in the LH (after 2,750 msec). Although the data for this are quite weak, this pattern is consistent with some literature suggesting slightly stronger lateralization in men. It contradicts the idea that men have language representation only in the LH, whereas women have it in both hemispheres.

In summary, when a person is attempting to solve a problem that either fails to direct or misdirects retrieval (e.g., an insight-like problem), initially both the LH and RH have solution-relevant activation. However, solution-related activation in the LH appears to fade quickly, perhaps as activation focuses on misdirected information. In contrast, RH semantic processing maintains activation of solution-relevant information, just as it is more likely to maintain activation of distantly related information or unusual interpretations during discourse comprehension (Beeman, 1998). This RH activation is weak, diffuse, and perhaps overshadowed by stronger misdirected activation in the LH. Therefore, RH activation may persist in the absence of awareness, but still be useful for recognizing the solution, and it appears to be related to the experience of insight when solvers recognize a solution (Bowden & Beeman, 2000a).

REFERENCES

Abdullaev, Y. G., & Posner, M. I. (1997). Time course of activating brain areas in generating verbal associations. *Psychological Science*, **8**, 56-59.

Beeman, M. J. (1993). Semantic processing in the right hemisphere may contribute to drawing inferences from discourse. *Brain & Language*, **44**, 80-120.

Beeman, M. J. (1998). Coarse semantic coding and discourse comprehension. In M. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 255-284). Mahwah, NJ: Erlbaum.

Beeman, M. J., Bowden, E. M., & Gernsbacher, M. A. (2000). Right and left hemisphere cooperation for drawing predictive and coherence inferences during normal story comprehension. *Brain & Language*, **71**, 310-336.

Beeman, M. J., & Chiarello, C. (1997). Complementary right and left hemisphere language comprehension. *Current Directions in Psychological Science*, **6**, 2-8.

Beeman, M. J., & Chiarello, C. (1998). *Right hemisphere language comprehension: Perspectives from cognitive neuroscience*. Mahwah, NJ: Erlbaum.

Beeman, M. J., Friedman, R. B., Grafman, J., Perez, E., Diamond, S., & Lindsay, M. B. (1994). Summation priming and coarse semantic coding in the right hemisphere. *Journal of Cognitive Neuroscience*, **6**, 26-45.

Bottini, G., Corcoran, R., Sterzi, R., Paulescu, E., Schenone, P., Scarpa, P., Frackowiak, R. S. J., & Frith, C. D. (1994). The role of the right hemisphere in the interpretation of figurative aspects of language: A positron emission tomography activation study. *Brain*, **117**, 1241-1253.

Bowden, E. M. (1997). The effect of reportable and unreportable hints on anagram solution and the aha! experience. *Consciousness & Cognition*, **6**, 545-573.

Bowden, E. M., & Beeman, M. J. (1998). Getting the right idea: Semantic activation in the right hemisphere may help solve insight problems. *Psychological Science*, **9**, 435-440.

Bowden, E., & Beeman, M. J. (2000a). *Aha! Insight experience correlates with solution activation in the right hemisphere*. Manuscript submitted for publication.

Bowden, E., & Beeman, M. J. (2000b). *One hundred forty-four compound remote associate problems: Short insight-like problems with one-word solutions*. Manuscript in preparation.

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

Brownell, H. H., Potter, H. H., Bihrle, A. M., & Gardner, H. (1986). Inference deficits in right brain-damaged patients. *Brain & Language*, **27**, 310-321.

Brownell, H. H., Potter, H. H., & Michelow, D. (1984). Sensitivity to lexical denotation and connotation in brain-damaged patients: A double dissociation? *Brain & Language*, **22**, 253-265.

Buckner, R. L., Bandettini, P. A., O'Craven, K. M., Savoy, R. L., Petersen, S. E., Raichle, M. E., & Rosen, B. R. (1996). Detection of cortical activation during averaged single trials of a cognitive task using functional magnetic imaging. *Proceedings of the National Academy of Sciences*, **93**, 14878-14883.

Burgess, C., & Simpson, G. (1988). Hemispheric processing of ambiguous words. *Brain & Language*, **33**, 86-104.

Chiarello, C. (1998). On codes of meaning and the meaning of codes: Semantic access and retrieval within and between hemispheres. In M. J. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 141-160). Mahwah, NJ: Erlbaum.

Chiarello, C., Burgess, C., Richards, L., & Pollock, A. (1990). Semantic and associative priming in the cerebral hemispheres: Some words do, some words don't ... sometimes, some places. *Brain & Language*, **38**, 75-104.

Connor, L. T., Balota, D. A., & Neely, J. H. (1992). On the relation between feeling of knowing and lexical decision: Persistent subthreshold activation or topic familiarity? *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **18**, 544-554.

Dallob, P. I., & Dominowski, R. L. (1993, April). *Erroneous solutions to verbal insight problems: Effects of highlighting critical material*. Paper presented at the annual meeting of the Western Psychological Association.

Dorfman, J. (1990). *Metacognitions and incubation effects in insight problem solving*. Unpublished doctoral dissertation, University of California, San Diego.

Faust, M. (1998). Obtaining evidence of language comprehension from sentence processing. In M. J. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 161-186). Mahwah, NJ: Erlbaum.

Faust, M. E., & Gernsbacher, M. A. (1996). Cerebral mechanisms for suppression of inappropriate information during sentence comprehension. *Brain & Language*, **53**, 234-259.

Fiore, S. M., & Schooler, J. W. (1998). Right hemisphere contributions to creative problem solving: Converging evidence for divergent thinking. In M. J. Beeman & C. Chiarello (Eds.), *Right hemisphere language comprehension: Perspectives from cognitive neuroscience* (pp. 349-371). Mahwah, NJ: Erlbaum.

Frost, J. A., Binder, J. R., Springer, J. A., Hammeke, T. A., Bellgowan, P. S. F., Rao, S. M., & Cox, R. W. (1999). Language processing is strongly left lateralized in both sexes: Evidence from fMRI. *Brain*, **122**, 199-208.

Gur, R. C., Ragland, J. D., Resnick, S. M., Skolnick, B. E., Jaggi, J., Muenz, L., & Gur, R. E. (1994). Lateralized increases in cerebral blood flow during performance of verbal spatial tasks: Relationship and performance level. *Brain & Cognition*, **24**, 244-258.

Koivisto, M. (1997). Time course of semantic activation in the cerebral hemispheres. *Neuropsychologia*, **35**, 497-504.

Luh, K. E., & Levy, J. (1995). Interhemispheric cooperation: Left is left and right is right, but sometimes the twain shall meet. *Journal of Experimental Psychology: Human Perception & Performance*, **21**, 1243-1258.

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

Nakagawa, A. (1991). Role of anterior and posterior attention networks in hemispheric asymmetries during lexical decisions. *Journal of Cognitive Neuroscience*, **3**, 315-321.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, **9**, 97-113.

Pugh, K. R, Shaywitz, B. A., Shaywitz, S. E., Constable, R. T., Skudlarski, P., Fulbright, R. K., Bronen, R. A., Shankweiler, C. P., Katz, L., Fletcher, J. M., & Gore, J. C. (1997). Cerebral organization of component processes in reading. *Brain*, **119**, 1221-1238.

Robertson, D. A., Gernsbacher, M. A., Guidotti, S. J., Robertson, R. R. W., Irwin, W., Mock, B. J., & Campana, M. E. (2000). Functional neuroanatomy of the cognitive process of mapping during discourse comprehension. *Psychological Science*, **11**, 255-260.

Rodel, M., Cook, N. D., Regard, M., & Landis, T. (1992). Hemispheric dissociation in judging semantic relations: Complementarity for close and distant associates. *Brain & Language*, **43**, 448-459.

St. George, M. Kutas, M., Martinez, A., & Sereno, M. I. (1999). Semantic integration in reading: Engagement of the right hemisphere during discourse processing. *Brain*, **122**, 1317-1325.

Schooler, J. W., & Melcher, J. (1995). The ineffability of insight. In S. M. Smith, T. B. Ward, & R. A. Finke (Eds.), *The creative cognition approach* (pp. 249-268). Cambridge, MA: MIT Press.

Seger, C., Desmond, J., Glover, G., & Gabrieli, J. (2000). *Right hemisphere involvement in processing distant semantic relationships*. Manuscript in preparation.

Shames, V. A. (1994). *Is there such a thing as implicit problem-solving?* Unpublished doctoral dissertation, University of Arizona.

Shaywitz, B. A., Shaywitz, S. E., Pugh, K. R., Constable, R. T., Skudlarski, P., Fulbright, R. K., Bronen, R. A., Fletcher, J. M., Shankweiler, C. P., Katz, L., & Gore, J. C. (1995). Sex differences in the functional organization of the brain for language. *Nature*, **373**, 607-609.

Smith, S. M., & Blankenship, S. E. (1989). Incubation effects. *Bulletin of the Psychonomic Society*, **27**, 311-314.

Titone, D. (1998). Hemispheric differences in context sensitivity during lexical ambiguity resolution. *Brain & Language*, **65**, 361-394.

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

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