

## Evidence for dissociable neural mechanisms underlying inference generation in familiar and less-familiar scenarios <sup>☆</sup>

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Accepted 11 March 2005

Available online 20 April 2005

### Abstract

In this study, we investigated whether the left and right hemispheres are differentially involved in causal inference generation. Participants read short inference-promoting texts that described either familiar or less-familiar scenarios. After each text, they performed a lexical decision on a letter string (which sometimes constituted an inference-related word) presented directly to the left or right hemisphere. Response-time results indicated that hemisphere of direct presentation interacted with type of inference scenario. When test stimuli were presented directly to the left hemisphere, lexical decisions were facilitated following familiar but not following less-familiar inference scenarios, whereas when test stimuli were presented directly to the right hemisphere, facilitation was observed in both familiar and less-familiar conditions. Thus, inferences may be generated in different ways depending on which of two dissociable neural subsystems underlies the activation of background information.

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*Keywords:* Inferences; Familiarity; Hemisphere asymmetries; Text comprehension; Background knowledge; Semantic associations

### 1. Introduction

Inferences we generate during reading are influenced by our familiarity, i.e., background knowledge, with the topics described in the text. However, little is known about the number or neural implementation of inference-generation processes. In the research presented here, we investigated the extent to which inference-generation processes differ depending on the amount of background knowledge the reader has of the scenario

depicted in the text and, in particular, whether the left and right hemispheres may be differentially involved in inference generation for familiar and less-familiar scenarios.

A major initial component of inference generation is the activation of information during comprehension that is not explicitly described in the text. To maintain coherence during comprehension, a reader must be able to connect incoming information in the text with information currently active in working memory (Kintsch & van Dijk, 1978; van Dijk & Kintsch, 1983). If the immediately preceding text or information in working memory does not provide a causal explanation for the current event, the comprehender will activate inference concepts based on background knowledge that successfully bridge the coherence gap (Fletcher & Bloom, 1988; Graesser, Bertus, & Magliano, 1995; Graesser, Haberlandt, & Koizumi, 1987; McKoon & Ratcliff, 1986, 1989; Meyers, Shinjo, & Duffy, 1987; Potts, Keenan, &

<sup>☆</sup> This research was supported by the Center for Cognitive Sciences at the University of Minnesota through a grant from the National Institute of Child Health and Human Development (HD-07151), by the Guy Bond Endowment for Reading and Literacy, and by a Golestan fellowship at the Netherlands Institute for Advanced Study in the Humanities and Social Sciences to Paul van den Broek.

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Golding, 1988; van den Broek, 1990, 1994; van den Broek & Lorch, 1993). For instance, after encountering the sentences, “*Laurie left early for the birthday party. She spent an hour shopping at the mall.*” readers will be compelled to explain why Laurie shopped at the mall. When a sufficient explanation for the focal event has not been explicitly provided in the text, readers often maintain coherence by constructing an inference supported by background knowledge (in the example, the inference that Laurie went to buy a birthday present).

A comprehender’s familiarity with relevant background information can affect the context in which individual words and combinations of words are interpreted, thereby facilitating specific inferences. For instance, inferences about the meaning of words in ambiguous passages are influenced by a reader’s familiarity with the topics in those passages. Weight lifters interpreted an ambiguous passage containing the words “held,” “lock,” “strong,” and “break” as a wrestling match whereas musicians interpreted the passage as a prison scenario (Anderson, Reynolds, Schallert, & Goetz, 1976). Similarly, baseball experts were faster and more accurate than baseball novices in judging inferences relevant to baseball in a discourse, but not to elements that were not part of the game (Spilich, Vesonder, Chiesi, & Voss, 1979). Findings such as these indicate that individual or group differences in background knowledge help predict the inferences generated by different comprehenders.

It is unknown, however, whether such effects stem from a single, unified process or from multiple, distinct processes. In the current study, we examined whether the familiarity of a causal inference scenario (familiar vs. less-familiar) would have different effects in two hypothesized neural subsystems contributing to inference generation. One possibility is that a single neural system underlies the processes involved in generating inferences both from familiar background knowledge and also from less-familiar background knowledge (i.e., knowledge that has been less experienced by the reader). Another possibility is that inferences constructed from less-familiar inference scenarios are generated by a process that differs from another process that can generate inferences from familiar scenarios. The latter theory stems from interesting findings of hemispheric asymmetries in inference making. Both cerebral hemispheres appear to contribute to the generation of inferences, but subsystems in the left hemisphere (LH) and subsystems in the right hemisphere (RH) may contribute in different ways to different kinds of inferential processing depending on the type of background knowledge that is needed to generate a particular inference.

There is some evidence that semantic processing in the RH is either responsible for or heavily involved with the inference making process in readers (for a review see Lehman & Tompkins, 2000). For example,

Beeman (1993) measured facilitation of inference-related concepts with a lexical decision task during story comprehension in patients with RH damage and control subjects. Although readers without RH damage exhibited a facilitation effect in the form of faster lexical decisions for inference-related probes than for unrelated probes, no such facilitation was observed for RH-damaged patients. This suggests that semantic activation that contributes to inference facilitation normally takes place in a RH subsystem. A similar conclusion was drawn by Beeman, Bowden, and Gernsbacher (2000). Furthermore, processing in the RH can contribute to the generation of inferences from relatively unfamiliar background knowledge. In support of this, RH-damaged patients had difficulty generating the alternate, less-preferred (i.e., less-familiar) inference from a sentence after reading a second sentence that reinforced the alternate interpretation (Brownell, Potter, Bihrlé, & Gardner, 1986). Similarly, RH-damaged patients also tend to choose more literal interpretations of idiomatic expressions rather than correct metaphorical interpretations (Meyers & Linebaugh, 1981) and have difficulty understanding metaphoric meanings of ambiguous words (Brownell, Simpson, Bihrlé, Potter, & Gardner, 1990). Also, at least some of the scenarios used by Beeman (1993) seem to have probed inferences generated from relatively unfamiliar background information (e.g., priming “overflow” from cleaning a mess after a bathtub faucet was left running). Therefore the effects observed by Beeman (1993) may be consistent with the notion that a RH semantic subsystem is capable of generating inferences from less-familiar knowledge.

There also is evidence that semantic processing in the LH contributes to inference generation. For example, readers with an intact LH but a damaged RH did not demonstrate an inference deficit as compared with normal controls for inferences dependent on familiar world knowledge (Purdy, Belanger, & Liles, 1992). Similarly, RH-damaged patients generated inferences as well as readers without brain damage when an ambiguous sentence elicited a dominant (i.e., familiar) inference (Brownell et al., 1986). Also, in classification experiments with a split-brain patient, the LH was less capable than the RH at deciding that previously unseen information was in fact new information if those items were in the same category as previously presented (i.e., familiar) information. One interpretation is that the LH stores less veridical memories than the RH, indicating that the LH is more effective than the RH at making generalizations and inferences (Metcalf, Funnell, & Gazzaniga, 1995). Such findings suggest that an undamaged LH is capable of making inferences, contributing to the processing of inferences generated from familiar background knowledge. In addition, highly familiar and organized background knowledge such as

scripts facilitated lexical decisions to targets that were presented to either the LH or RH, but facilitation by scripts was greatest for targets presented to the LH (Faust & Babkoff, 1997). There is little, if any, evidence that the LH contributes significantly to the generation of inferences from unfamiliar background knowledge. In fact, some findings argue against this possibility. For example, RH-damaged individuals with intact left hemispheres did not infer non-literal sarcasm as well as LH-damaged patients and individuals without brain damage (Giora, Zaidel, Soroker, Batori, & Kasher, 2000). Because sarcasm is situation-dependent, a non-literal inference of a sarcastic statement is therefore much less-familiar than a literal interpretation of the statement. Therefore, the LH may be less able than the RH at generating inferences from rather unfamiliar scenarios.

Considering the findings reviewed above, we suggest that dissociable neural subsystems perform different processes that each contribute to inference making. By dissociable neural subsystems, we mean functionally defined entities that perform at least partially distinct processes in anatomically and physiologically separable brain areas (Marsolek, 2003). We hypothesize that a LH semantic subsystem contributes to coherence inferences that are generated from background knowledge of familiar inference scenarios but does not contribute to coherence inferences generated from less-familiar scenarios. In contrast, a RH semantic subsystem contributes to coherence inferences that are generated from background knowledge of relatively unfamiliar scenarios as well as inferences generated from background knowledge of familiar scenarios.

For the purposes of this study, we draw a distinction between familiar and less-familiar semantic information involved in causal inference generation. To clarify this distinction, we suggest that an event becomes more familiar as the aspects of that event are routinely experienced over time, either in person or by hearing/reading about the event being experienced by others. Presumably, the greater the familiarity—in terms of past expe-

riences—the stronger the associations among the relevant stored concepts that can produce an inference. For example (see Table 1), a scenario about opening a book, spending some time, and then feeling ready to take an exam induces the inference, “study.” The *occurrence of studying* in the context of that scenario is routinely experienced (at least by our participants) and hence highly familiar. A scenario about a CIA agent picking up a photograph of a suspect, spending some time, and then feeling able to identify the suspect in person also induces the inference “study.” However, the *occurrence of studying* in that particular context, even though possible, tends to be less routinely experienced and hence less familiar.

## 2. Experiment 1

In this experiment, we varied the familiarity of scenarios in short inference-promoting texts (familiar inference vs. less-familiar inference), and we assessed the on-line activation of coherence–inference concepts, as measured in a lexical decision task, by presenting target inference words directly to the left or right hemisphere. To obtain a baseline measure of lexical decision performance with these words, we recorded response times for the same target words in a neutral (i.e., non-inference) condition also. We compared performance in the neutral condition against performance in two inference conditions (in which the preceding text promoted an inference to the target word, using either familiar or less-familiar background knowledge). In this article, we refer to faster lexical decision performance in the inference conditions than in the neutral condition as *inference facilitation*.

To our knowledge, this is the first study to examine familiarity effects on inference facilitation in an on-line task. We predicted that, when test items are presented directly to the left hemisphere, inference facilitation would be observed following familiar scenarios but not following less-familiar scenarios. In contrast, when test items are presented directly to the right hemisphere, inference facilitation would be observed following both familiar scenarios and less-familiar scenarios. If the predicted properties of one hypothesized semantic subsystem (e.g., inference facilitation from familiar but not less-familiar scenarios) are exhibited when test stimuli are presented directly to one hemisphere (e.g., the LH), and the predicted properties of another hypothesized semantic subsystem (e.g., inference facilitation from both familiar and less-familiar scenarios) are observed when test stimuli are presented directly to the other hemisphere (e.g., the RH), this provides evidence that different neural circuitry underlies the two hypothesized subsystems (e.g., Marsolek & Burgund, 1997).

Table 1  
Example item

Condition	Sentences
Familiar	With his exam coming up, the student opened his book. After three hours, he was sure he knew the material quite well.
Less-familiar	The CIA agent picked up the photograph of the suspect. After a few minutes, he felt confident that he could identify the man on the street.
Neutral	The children arrived for their first day of elementary school dressed in new clothes. They were excited to meet their new teacher, see their old friends, and play outside.

Note. The associated target word is *study*.

## 2.1. Method

### 2.1.1. Participants

Thirty-six males from the University of Minnesota participated in the experiment for extra credit an Introductory Psychology class. All were native speakers of English who had normal or corrected-to normal vision. All participants were right-handed, with a mean laterality quotient of 0.89 and range of 0.50–1.00 on the Edinburgh Handedness Inventory (Oldfield, 1971). Only right-handed males were tested in this experiment and in Experiment 2 because they tend to exhibit stronger hemispheric asymmetries than do females and left-handed males (e.g., Hellige, 1993a).

### 2.1.2. Materials

Forty-eight inference items (which were followed by genuine English words) and 48 filler items (which were followed by pronounceable non-words) were constructed for the experiment. For each of the 48 target words, the preceding inference item consisted of two sentences that described a brief scenario and could take on three different forms to represent three different inference conditions (familiar, less-familiar, and neutral; see Table 1 for an example of an item in each condition). All materials are available online (<http://levels.psych.umn.edu/stimuli/inference.pdf>). For both familiar and less-familiar inference items, the first sentence provided general background information about the protagonist(s) and the problem or goal. The second sentence required that the reader make a causal inference to bridge a coherence break following the first sentence (except in the neutral condition). The familiar inference items described a scenario that was familiar to readers, and the less-familiar items described a scenario that was less familiar than the familiar scenario. In the neutral condition, the two sentences were constructed so that the target inference was *not* required for the comprehension of the second sentence. About half of these items were modified from pre-existing materials with coherence inferences (Potts et al., 1988). The range of number of syllables for the second sentence across texts was 14–28, with an average of 19.

Forty-eight inference target words (44 verbs, four nouns) were used to follow the 48 inference items and 48 pronounceable non-words were used to follow the 48 filler items. The non-words were equated with the target words in number of letters. In deciding between the past tense and present tense of each verb, the verb form having the highest estimated word frequency was used (Carroll, Davies, & Richman, 1971).

**2.1.2.1. Inference items.** A pilot study was conducted with 26 participants to ensure that familiar passages were indeed more familiar than less-familiar passages. Familiarity ratings were assessed in the following manner. The familiar and less-familiar inference texts and

the associated target words (in bold capital letters) were printed in a booklet. Participants judged the familiarity of each scenario, and they were encouraged to think of familiarity as *how often* they have seen, read about, thought about, or experienced the scenario *in which the event word (in bold) occurs*. To illustrate, consider the example item; participants were asked to rate how familiar they were with students studying for an exam vs. CIA agents studying a photograph. Ratings were made on a 7-point Likert scale with 1 = not familiar, 4 = somewhat familiar, and 7 = very familiar. Different booklets with the experimental items were created so that each participant would see each target word preceded by one text representing one of the two inference conditions (familiar vs. less-familiar). In the final set of items, all familiar items were judged as being significantly more familiar (5.87) than the less-familiar items (4.60),  $F(1,47) = 77.90$ ,  $MSe = .501$ ,  $p < .001$ .

### 2.1.3. Design

Each participant silently read the 96 items (48 experimental items with targets and 48 filler items with pronounceable non-words). The forty-eight target words were randomly assigned to one of six sets consisting of eight words each. The average number of letters of the target words (5.1, 4.8, 5.0, 5.0, 5.1, and 4.9, for the six sets, respectively) and the average word frequency of the target words (86, 84, 92, 70, 89, and 89, for the six sets, respectively) in estimated words per million as found in Carroll et al. (1971) were not reliably different between the sets of items. Six between-subjects counterbalancing conditions were created by assigning the six sets of words to the six experimental conditions (visual field  $\times$  familiarity) in six different ways (in a Latin-square manner). These assignments of sets to experimental conditions were counterbalanced across subjects so that each target word represented each condition an equal number of times across subjects. The trial orders were randomized for each participant, intermixing word and non-word trials as well as word trials representing different conditions. Each participant saw the same filler items. Also, half of the participants were instructed to respond with their right hand, and the other half with their left hand.

### 2.1.4. Procedure

Participants were told that they were taking part in an experiment involving the comprehension of text. They were instructed to read each text, and then perform a lexical decision task and a recall task. Before a trial began, participants placed their thumbs on the left-most button, their index fingers on the middle button, and their second finger on the right-most button of the button response box. The button response box was held at approximately a 45° angle to the participant to comfortably accommodate this finger placement. Placement was identical for the left-hand- and right-hand-response groups. The

participant was seated 50 cm from the screen, and the distance from the participants' eyes was kept constant by having participants rest their heads in a chin rest attached to the table in front of the computer monitor.

The sequence of events for a trial was as follows. The first sentence was presented as a whole in the center of the computer screen in 18-point Times New Roman, each clause being presented on a separate line. The first clause of each item was always displayed starting two lines above the vertical center of the screen. Participants were instructed to read this sentence at their own pace without rereading. In order to advance from the first sentence to the second sentence, participants pressed the right-most key on the button box. The second sentence was presented in the same manner as the first. After participants read the second sentence at their own pace without rereading, they again pressed the right-most key on the button box. Immediately afterward, a red plus symbol (+) in 24-point Helvetica was presented for 500 ms in the center of the screen. Given that inference facilitation is generally observed only after a significant delay between the text and the target word (between 250 and 750 ms depending on the type of presentation and task: see Potts et al., 1988; Till, Mross, & Kintsch, 1988), we chose a stimulus onset asynchrony (500 ms) that is well represented in inference studies with similar methodologies. Immediately after the 500-ms fixation-point presentation, the target letter string (also in 24-point Helvetica) was presented to either the participant's left or right visual field for 176 ms. Such a brief presentation time prevented the possibility of attention-based saccades to the targets.

Participants were instructed to fixate their eyes and attention on the central plus symbol when it appeared, which was immediately prior to the presentation of the target. The distance between this central fixation and the inner edge of the longest target word was 1 cm subtending 1.15° of visual angle, and the distance between the center of each letter string and the fixation point was 2.18 cm subtending 2.5° of visual angle. These eccentricities were chosen to assure that the letter strings were presented directly to the intended hemisphere (see Brysbaert, 1994; Bunt, Minckler, & Johanson, 1977). Furthermore, previous research has shown that participants erroneously fixate more than 1° from the central fixation point only on less than 1% of trials when given instructions similar to ours (Jordan, Patching, & Milner, 1998).

Participants were instructed to decide whether the presented letter string was a real English word, and were told to respond as quickly and accurately as possible. Responses were to be given by pressing the middle button on the button box with the index finger for "yes" answers and by pressing the left-most button with the thumb for "no" answers. Response time and accuracy were collected by the computer program and feedback for wrong responses was given by a loud beep lasting

250 ms. After the participant responded, he was instructed to continue to the next item or, for a predetermined 25% of the items, was told to summarize the text he had just read in a provided booklet. The frequency with which items in each condition were to be summarized was equal between conditions. The summarization task was included to encourage participants to comprehend and remember the passages. On average, participants completed the instruction phase, three practice trials, and 96 experimental trials in 45 min.

### 2.1.5. Apparatus

Stimulus presentation and data collection were controlled by a Power Macintosh 7500/100 computer utilizing PsyScope version 1.2 software (Cohen, MacWhinney, Flatt, & Provost, 1993). Responses were made and self-paced text presentation was accomplished on a three-button response box accurate to within one millisecond. An Apple multiple scan C5 display monitor was used to present the stimuli.

### 2.2. Results

Response times for correct responses to the target words and accuracy rates were collected and analyzed. To minimize the possibility of including outliers in the analyses, response times shorter than 200 ms were eliminated. For each of the three experimental conditions within a visual field, the longest 1% of the response times was not included in the analyses (see Ratcliff, 1993; for details of this procedure). One participant was replaced because his accuracy in one of the conditions was less than 50%. In all analyses,  $F_1$  refers to tests against an error term based on subject variability and  $F_2$  refers to tests against an error term based on item variability (see Clark, 1973). An alpha level of .05 was used for all statistical tests that follow. All unreported effects were not significant.

We measured inference facilitation by calculating difference scores per subject (for by-subject analyses) or per item (for by-item analyses) between both the familiar and less-familiar inference conditions and the neutral baseline condition.<sup>1</sup> Response times and accuracy rates

<sup>1</sup> Repeated measures analyses of variance were also conducted on the mean response times (before subtraction) to examine lexical decision performance. The only interesting result in these analyses that is not reflected in the analyses of inference facilitation is that response times were longer when targets were directly presented to the RH (971 ms) than when directly presented to the LH (917 ms),  $F_1(1,24) = 12.83$ ,  $MSe = 12,533$ ,  $p < .005$ ;  $F_2(1,42) = 7.86$ ,  $MSe = 22,662$ ,  $p < .005$ , replicating previous results that lexical decisions (Leiber, 1976), and word recognition more generally (Beaumont, 1982; Mishkin & Forgy, 1952), are more efficient when stimuli are presented directly to the left hemisphere than to the right. Accuracy results reflected the effects found for lexical decision response times. Participants were more accurate to targets directly presented to the LH (96%) than to targets directly presented to the RH (93%),  $F_1(1,24) = 5.76$ ,  $MSe = .014$ ,  $p < .05$ ;  $F_2(1,42) = 10.87$ ,  $MSe = .010$ ,  $p < .005$ .

Table 2

Mean response times (RT, in ms) and accuracy rates (AR, in percentages) for lexical decisions to target words as a function of condition, and visual field-hemisphere

Condition	Visual field-hemisphere			
	rvf-LH		lvf-RH	
	RT	AR	RT	AR
Familiar	859 (39)	96 (1.3)	953 (49)	97 (1.5)
Less-familiar	935 (51)	97 (0.9)	946 (47)	92 (2.3)
Neutral	956 (46)	96 (1.3)	1014 (51)	89 (2.7)

Note. Values in parentheses represent standard errors. rvf-LH: right visual field, left hemisphere; lvf-RH: left visual field, right hemisphere.

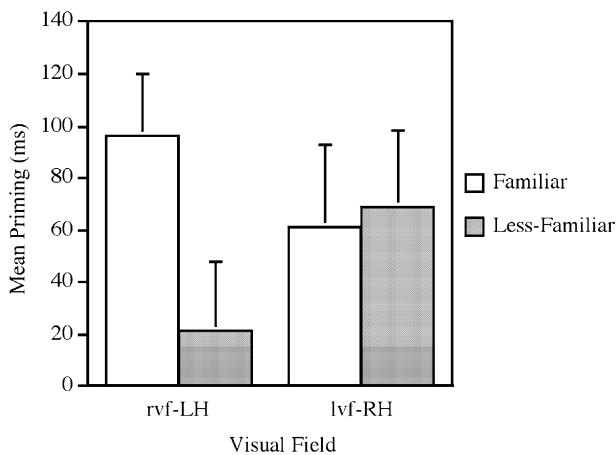


Fig. 1. Mean inference-facilitation scores as a function of condition and visual field-hemisphere. rvf-LH: right visual field, left hemisphere; lvf-RH: left visual field, right hemisphere. Error bars depict standard errors.

before subtraction are shown in Table 2. Fig. 1 displays the facilitation scores. Two repeated-measures analyses of variance were conducted on mean facilitation scores, one for response times and the other for accuracy data. The independent variables were type of scenario (familiar and less-familiar) and hemisphere of direct letter-string presentation (left and right). Response hand and subject counterbalancing condition were entered as between-subjects variables in the analyses by subjects (see Pollatsek & Well, 1995; for a discussion of using counterbalancing variables). The item counterbalancing condition was entered as a between-items variable in the analyses by items.

### 2.2.1. Response times

Mean response-time facilitation scores for the inference target words in each visual field are depicted in Fig. 1. Type of scenario (familiar and less-familiar) interacted with hemisphere of direct target presentation,  $F_1(1, 24) = 7.72$ ,  $MSe = 7997$ ,  $p < .05$ ;  $F_2(1, 42) = 9.73$ ,  $MSe = 15,271$ ,  $p < .005$ . Simple-effect contrasts revealed

that after direct LH presentations, facilitation was greater for targets in the familiar condition (96 ms) than for targets in the less-familiar condition (21 ms),  $F_1(1, 24) = 12.72$ ,  $MSe = 7997$ ,  $p < .005$ ;  $F_2(1, 42) = 9.72$ ,  $MSe = 15,271$ ,  $p < .005$ . There was no significant facilitation difference between familiar and less-familiar conditions in the RH (61 vs. 69 ms, respectively),  $F_1(1, 24) = .13$ ,  $MSe = 7997$ ,  $p = .72$ ;  $F_2(1, 42) = 1.67$ ,  $MSe = 15,271$ ,  $p = .21$ . There was a main effect for familiarity of scenario. Facilitation was greater for targets following the familiar texts (79 ms) than for targets following the less-familiar texts (45 ms). This result was statistically reliable in the subjects analysis,  $F_1(1, 24) = 4.87$ ,  $MSe = 7997$ ,  $p < .05$ ,  $F_2(1, 42) = 1.44$ ,  $MSe = 17,708$ ,  $p = .24$ . Also, there was a main effect for the item-counterbalancing condition in the analysis by items,  $F_2(5, 42) = 17.65$ ,  $MSe = 40,731$ ,  $p < .005$ .<sup>2</sup> This item-counterbalancing variable also interacted with the type of scenario,  $F_2(5, 42) = 11.07$ ,  $MSe = 17,708$ ,  $p < .05$ , and contributed to a significant three-way interaction with hemisphere of direct target presentation and type of scenario  $F_2(5, 42) = 16.29$ ,  $MSe = 15271$ ,  $p < .05$ .

One-tailed paired-difference  $t$  tests were conducted on the facilitation scores to determine if observed facilitation effects were significantly above zero. In these analyses,  $t_1$  refers to tests against an error term based on subject variability, and  $t_2$  refers to tests against an error term based on item variability. Facilitation was significantly greater than zero for familiar targets presented to the LH (96 ms),  $t_1(35) = 4.06$ ,  $Se = 23.69$ ,  $p < .005$ ;  $t_2(47) = 2.86$ ,  $Se = 33.23$ ,  $p < .005$ , and for familiar targets presented to the RH (61 ms) in the analysis by subjects,  $t_1(35) = 1.93$ ,  $Se = 31.67$ ,  $p < .05$ ;  $t_2(47) = 1.14$ ,  $Se = 37.90$ ,  $p = .13$ . There was also significant facilitation for less-familiar targets presented to the RH (69 ms),  $t_1(35) = 2.32$ ,  $Se = 29.60$ ,  $p < .05$ ;  $t_2(47) = 2.06$ ,  $Se = 36.87$ ,  $p < .05$ , but not for less-familiar targets presented to the LH (21 ms),  $t_1(35) = .783$ ,  $Se = 26.90$ ,  $p = .22$ ;  $t_2(47) = .474$ ,  $Se = 34.37$ ,  $p = .32$ .

### 2.2.2. Accuracy

Accuracy facilitation scores were greater for targets presented to the RH (5.7%) than for targets presented to the LH (0.5%),  $F_1(1, 24) = 5.09$ ,  $MSe = .019$ ,  $p < .05$ ;  $F_2(1, 42) = 5.49$ ,  $MSe = .024$ ,  $p < .05$ . This result should be interpreted with caution, however,

<sup>2</sup> Variability between the properties of the items used in the different item counterbalancing conditions was minimized as much as possible. The observed differences in facilitation among the counterbalancing conditions could be the result of differences in average word frequency. Facilitation scores for each item counterbalancing condition were somewhat, though not significantly, correlated with average estimated word frequency of each of the item counterbalancing conditions,  $r = .691$ ,  $p < .10$ .

because accuracy of responses to targets presented to the LH was close to ceiling (see Table 2), thus possibly masking any condition differences. Most important for this analysis, type of scenario (familiar, less-familiar) did not interact significantly with hemisphere of direct target presentation,  $F_1(1,24) = 3.11$ ,  $MSe = .007$ ,  $p = .09$ ;  $F_2(1,42) = 3.5$ ,  $MSe = .008$ ,  $p = .07$ , indicating that there was no tradeoff between speed and accuracy of responses.

### 2.3. Discussion

In Experiment 1, when target words were presented directly to the LH, inference facilitation was observed after reading familiar scenarios but not after reading less-familiar scenarios; whereas when target words were presented directly to the RH, inference facilitation was observed after reading either familiar or less-familiar scenarios. Furthermore, for less-familiar scenarios, inference facilitation was greater when targets were presented to the RH than to the LH. These results support the hypothesis that dissociable neural subsystems underlie semantic processing that contributes to inference generation, and only one of them contributes to inference generation in less-familiar scenarios.

## 3. Experiment 2

Our interpretation of the results from Experiment 1 assumes that the inference facilitation scores reflect activation of the target concepts from the generation of inferences that bridge the gap between the two sentences in each scenario. However, it is conceivable that instead they reflect activation of the target concepts from relatively simple and direct lexical associations between individual words in the scenarios and the targets, without reflecting coherence inference generation per se.<sup>3</sup> Experiment 2 was conducted to test this alternative explanation. The procedure was the same as that used in Experiment 1, except that participants were presented with only the first or the second sentence of the texts before they made lexical decisions to the targets. If the results replicate the pattern of results observed in Experiment 1, then the inference facilitation measured in Experiment 1 likely was due to local lexical associations rather than coherence inference generation. If the results indicate no significant levels of inference facilitation, this would support the hypothesis that the results in Experiment 1 reflect coherence inference generation.

<sup>3</sup> We thank one of the reviewers of the manuscript for suggesting this interpretation and the experimental test of it.

### 3.1. Participants

Thirty-six males from the University of Minnesota participated in the experiment for extra credit an Introductory Psychology class. All were native speakers of English who had normal or corrected-to normal vision. All participants were right-handed, with a mean laterality quotient of 0.87 and range of 0.50–1.00 on the Edinburgh Handedness Inventory (Oldfield, 1971).

### 3.2. Materials, design, procedure, and apparatus

The materials, design, procedure, and apparatus were the same as those used in Experiment 1, with one exception. For half of the participants, only the first sentence of each scenario was presented, and for the other half of the participants, only the second sentence of each scenario was presented, before lexical decisions were made to the target stimuli (as in Experiment 1).

### 3.3. Results

Response times for correct responses to the target words and accuracy rates were collected and analyzed in the same manners as in Experiment 1 (see Table 3).

#### 3.3.1. Response times

In contrast with the results in Experiment 1, there was no significant interaction between type of scenario (familiar and less-familiar) and hemisphere of direct target presentation,  $F_1(1,24) = 0.58$ ,  $MSe = 12,073$ ,  $p = .45$ ;  $F_2(1,42) = 0.64$ ,  $MSe = 17,912$ ,  $p = .42$ . As in Experiment 1, there was a main effect for the item-counterbalancing condition in the analysis by items,  $F_2(5,42) = 8.31$ ,  $MSe = 44,460$ ,  $p < .005$ . This item-counterbalancing variable also interacted with the type of scenario,  $F_2(5,42) = 9.98$ ,  $MSe = 30,697$ ,  $p < .005$ , and contributed to a significant three-way interaction with hemisphere of direct target presentation and type of scenario  $F_2(5,42) = 6.55$ ,  $MSe = 17,912$ ,  $p < .005$ .

One-tailed paired-difference *t* tests were conducted on the facilitation scores to determine if observed facilitation

Table 3

Mean response times (RT, in ms) and accuracy rates (AR, in percentages) for lexical decisions to target words as a function of condition, and visual field-hemisphere

Condition	Visual field-hemisphere			
	Rvf-LH		lvf-RH	
	RT	AR	RT	AR
Familiar	912 (47)	95 (1.1)	934 (43)	93 (2.2)
Less-familiar	908 (46)	94 (1.6)	950 (51)	92 (2.5)
Neutral	921 (41)	91 (2.4)	949 (41)	87 (2.5)

*Note.* Values in parentheses represent standard errors. rvf-LH: right visual field, left hemisphere; lvf-RH: left visual field, right hemisphere.

effects were significantly above zero. Results did not show inference facilitation for any of the conditions. Facilitation was not significantly greater than zero for familiar targets presented to the LH (10 ms),  $Se = 22.40$ , for familiar targets presented to the RH (15 ms)  $Se = 20.81$ , for less-familiar targets presented to the LH (13 ms),  $Se = 23.35$ , nor for less-familiar targets presented to the RH (0 ms),  $Se = 25.03$  (all  $t$ 's  $< 1$ , critical  $t = 1.86$ ). Furthermore, facilitation scores did not significantly differ between targets presented after the first sentence and targets presented after only the second sentence in any of the textual or visual field conditions (all  $t$ 's  $< 1$ ).

### 3.3.2. Accuracy

There were no significant main effects or interactions in the accuracy facilitation data.

### 3.4. Discussion

In Experiment 2, lexical decisions were made to targets following reading of only one of the sentences in each of the two-sentence scenarios used in Experiment 1. Because of this, any facilitation of lexical decision performance in the familiar or less-familiar condition compared with the neutral condition likely would be due to local lexical associations between words in the sentences and the targets, not to coherence inference generation. The results from Experiment 2 indicate no such facilitation. This finding is consistent with previous studies showing that control passages containing words semantically related to an inference, but contextually unrelated to the inference, do not activate inferences as strongly as passages that are contextually appropriate for the inference (McKoon & Ratcliff, 1989). Such results support the notion that presentation of both sentences, thus introducing the coherence break, was necessary in Experiment 1 to produce facilitation for the inference target words.

## 4. General discussion

The results of this study demonstrate that the left and right hemispheres play different roles in the generation of inferences during reading depending on the familiarity of the inference scenario. When target words were presented directly to the LH, inference facilitation was observed after reading familiar scenarios but not after reading less-familiar scenarios; whereas when target words were presented directly to the RH, inference facilitation was observed after reading either familiar or less-familiar scenarios. Thus, online generation of inferences likely involves both hemispheres of the brain, but a RH semantic subsystem may be needed for effective causal inference generation for relatively unfamiliar scenarios.

A RH subsystem could effectively contribute to less-familiar inference generation because of the type of semantic activation that it supports. To offer an explanation, we first review evidence of differences in the kinds of semantic activation that take place in the two hemispheres. Second, we suggest that these different kinds of semantic activation differentially affect inferences that can be made. Third, we suggest that inferences generated from familiar and less-familiar scenarios, in particular, should be affected by the different kinds of semantic activation evidenced in the previous research.

Distinct types of semantic activation—both useful for inference generation—may occur in the two hemispheres (Beeman, 1998; Beeman & Chiarello, 1998). Although there has been some evidence for equivalent semantic priming in the two hemispheres (Burgess & Simpson, 1988; Eglin, 1987; Walker & Ceci, 1985), other evidence indicates that the kinds spreading activation that should be useful for generating inferences differ between the left and right hemispheres (Chiarello, 1985; Chiarello, Burgess, Richards, & Pollock, 1990). In particular, considerable evidence indicates that the RH is involved in the processing of distant and less-familiar associations (Chiarello et al., 1990; Seger, Desmond, Glover, & Gabrieli, 2000). Similarly, summation priming from three distantly related words to an inference word (e.g., FOOT, CRY, and GLASS to the word CUT) was greater when test words were presented directly to the RH than when they were presented directly to the LH (Beeman, Bowden, Hassenfeld, & Shivde, 1996). Moreover, although priming from strongly related words (e.g., SCISSORS to the word CUT) was greater than summation priming when test words were presented directly to the LH, summation priming was at least as great as the strongly related priming when test words were presented directly to the RH (Beeman et al., 1994). Thus, a relatively restricted range of meanings and relatively direct associations may be activated in a subsystem that operates effectively in the LH, whereas a wider, more diffuse range of meanings may be activated in a subsystem that operates effectively in the RH.

Such hemisphere asymmetries in semantic activation may affect the type of inferences that can be generated. This idea is plausible because semantic associations in a text are related to the specificity of the to-be-generated inference (McKoon & Ratcliff, 1989). For example, a text that includes features that are associated with and only with the inference concept highly constrains a particular inference. In contrast, a text that includes features that are weakly associated with the target inference can converge on the inference target, but may have other potential outcomes. In the examples that we described earlier, the CIA agent could have “perused” or “contemplated” the photograph rather than

“study” it per se (in the less-familiar condition), but the student very likely “studied” the book (in the familiar condition; see Table 1).

These differences in associative activation may account for the differences in the use of familiar versus less-familiar background information to generate inferences. For example, the word “scissors” activates the concept “cut” effectively in the LH because the very strong relation between the two general concepts allows (even relatively localized) activation to take place from “scissors” to “cut.” Presumably, the activated information stems from the strong, familiar association between the two words, an association gleaned from countless previous experiences. It would *not* stem from only a distinctive, relatively specific past experience with those two concepts. Thus, it is conceivable that coherence inferences involving familiar (frequently encountered) scenarios may be activated in a LH subsystem because they depend on strong associations (and not by convergence of weakly related associations). In contrast, the activation of a more diffuse range of word meanings in a subsystem in the RH may allow even weakly related concepts to be activated, as well as strongly related concepts (Beeman, 1998). For example, the word triad “foot/cry/glass” activates the concept “cut” effectively in the RH because diffuse activation from “foot,” “cry,” and “glass” can converge on “cut.” Presumably, the activated information stems from three weak associations that *combine* to constrain one distinctive instantiation of the meaning of “cut.” The information would stem from a small number of particular, relatively specific past experiences with that particular combination of concepts. Thus, coherence inferences involving such less-familiar (infrequently encountered) scenarios (in addition to inferences involving familiar scenarios) could take place effectively in a RH subsystem because of weak converging concepts.

If the familiarity of inference scenarios is indeed related to the degree of semantic strength or similarity between the inference text and the target word, one would expect that the familiar items used in this study should be, as a whole, more strongly related to the target than the less-familiar items. To test this possibility, the strength of association between the text passage and the inference target was computed using Latent Semantic Analysis via web interface (<http://lsa.colorado.edu/>). Latent Semantic Analysis (LSA) is a statistical method that represents the meaning of a word or passage by analyzing the word or passage's context in large corpora of texts (see Landauer & Dumais, 1997; Landauer, Foltz, & Laham, 1998). Similarity values (–1.00 to 1.00) calculated by LSA has been shown to accurately simulate passage-to-word priming data (Landauer & Dumais, 1997). In the present study, we used LSA

to compute the similarity between the inference texts and the target inference word. In the analysis, the results demonstrated that the familiar texts were more similar to the inference target than the less-familiar inference texts.<sup>4</sup> Therefore, the observed hemisphere asymmetries in familiar vs. less-familiar inference scenarios may result at least in part from differences between LH- and RH-subsystems in the treatment of semantic associations (in a particular sentence context) between the text and inference word.

These semantic associations and the inferences derived from them are necessarily dependent on sentence context, as suggested by results from Experiment 2. A potential explanation is illustrated with a couple of examples. For a scenario involving “scissors” to activate the concept “cut,” the text must provide a context in which the scissors is understood as a cutting device (as opposed to a paper weight, for instance) and in which the appropriate causal necessity and sufficiency may be inferred. Similarly, for a scenario involving “foot,” “cry,” and “glass” to activate the concept “cut,” the text must provide a context in which those terms are understood as referring to an individual's foot (as opposed to a unit of measurement), a cry from that individual, and glass that is broken, respectively, and in which the appropriate causal necessity and sufficiency may be inferred. Therefore, the present study is not restricted to priming of isolated words, but helps to further knowledge about hemispheric contributions to inference processing by providing a textual context.

It is important to note that previous inference priming studies have been conducted in which targets were presented directly to each hemisphere in normal participants. Beeman et al. (2000) conducted a study in which participants listened to stories and responded to visually presented inference target words at different points in a short narrative. Results demonstrated that inference facilitation for the RH occurred prior to the coherence break (i.e., at a point when readers may generate a predictive inference), little if any RH facilitation occurred at the coherence break, and both the RH and LH showed facilitation at a point after the coherence break. In a related study, when predictive and coherence inferences were strongly constrained by causality, inference targets presented to either hemisphere were facilitated. However, when targets were weakly constrained, the RH showed greater facilitation than the LH, suggesting that the RH may be better able to make connections between more weakly constrained information (Virtue, van den Broek, & Linderholm, 2005).

<sup>4</sup> Average similarity values were greater for familiar items (.42) than for less-familiar items (.38),  $t(47) = 2.42$ ,  $p = .01$ . Average similarity values for both familiar and less-familiar items were greater than for neutral items (.31),  $t(47) = 6.57$ ,  $p < .005$ ;  $t(47) = 5.33$ ,  $p < .005$ , respectively.

The findings from the present study are important for additional reasons. A multiple subsystems theory of inference generation has implications for current models of text comprehension. Recent models explicitly address how the semantic activation of concepts and context enter into the inferential process (e.g., the Construction–Integration model, Kintsch, 1988; the Landscape model, van den Broek, Young, Tzeng, & Linderholm, 1998). Our results suggest an important addition to these models. In general, the models include a single mechanism for concept activation. Given our results, they may account for human performance more accurately by incorporating separable mechanisms of concept activation for restricted versus diffuse semantic activation. Such a modification to models of comprehension would be similar to modifications in the domain of visual-form recognition; dual-subsystems models of visual-form recognition may account for human performance more accurately than traditional single-system models (Marsolek, 1999; Marsolek & Burgund, 1997).

Interestingly, one of the original motivations for the Construction–Integration Model (Kintsch, 1988) was that a model with multiple processes should account for performance more effectively than single-system schema- or script-based accounts of comprehension. In order for comprehension to operate at peak efficiency, sufficient constraints must exist to generate an appropriate inference, but flexibility must also be maintained to adapt to the changing mental representation, to allow for revisions, and to create multiple layers of interpretation. To accomplish this, the model includes a single activation phase in which word meanings are activated and inferences are produced without regard to the discourse context, followed by a phase that integrates activated concepts from a previous reading cycle into the current representation. Our results lead to an interesting speculation. It may be more effective for different subsystems to generate activation of concepts and potential inferences in parallel, instead of as a single system. Restricted semantic activation likely enables inferences from familiar scenarios, and diffuse semantic activation likely enables inferences from less-familiar scenarios, and the two kinds of semantic activation likely are contradictory (both cannot occur simultaneously in a common processor). Hence, both may be performed more efficiently in separate subsystems.

Several previous studies have examined hemispheric differences similar to those reported in the present article. For example, the LH has been shown to be more sensitive to linguistic constraint than the RH, implying that language processing by constraint is a function of the linguistic-dominant LH (Faust & Kravetz, 1998). In addition, coherence-building inferences supported by relatively weak causal constraint are facilitated more strongly in the RH than in the LH (Virtue et al., 2005). Finally, the ability to activate less familiar and more dis-

tantly related information to solve insight problems is greater in the RH than in the LH (Beeman & Bowden, 2000). We suggest that these results are in line with our hypothesis that dissociable semantic subsystems operate asymmetrically and contribute in different ways to inference making and to related aspects of comprehension.

We should note that the participant-controlled reading times in our experiments may have encouraged re-reading or certain other strategies (despite our instructions not to re-read) which could have added noise to the timing between inference generation and the on-line tests. However, the alternative of computer-controlled presentations of the sentences would have created a highly unnatural reading situation. Not only are reading deadlines unnatural, but there is evidence supporting the notion that some inferences take some time to complete (Magliano, Baggett, Johnson, & Graesser, 1993; Till et al., 1988). Because we want this research to be as applicable as possible to educational psychology and to the teaching of successful reading strategies, we need the task to be as much like natural reading as possible. Furthermore, self-paced reading is not without precedent; other influential studies investigating the on-line activation of inference generation have successfully used participant-controlled reading times for inferences (e.g., Potts et al., 1988).

In summary, our evidence suggests that there are two separable mechanisms in the generation of causal inferences. One mechanism may be relatively sensitive to constraints of context and previous background knowledge, generating inferences based on relations among strongly related concepts. The other may be less affected by such constraints and generate inferences from a wider, less strongly related set of concepts given the appropriate context. These mechanisms operating in parallel bestow flexibility to inference making, enabling both familiar and less-familiar inferences to be generated. Such processes thereby increase the chances that a reader is able to create a coherent representation of the text, in which various parts of the text as well as the reader's background knowledge are integrated.

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