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Error monitoring in the hemispheres: the effect of lateralized feedback on lexical decision

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Abstract

Does each hemisphere have its own system for monitoring and responding to errors? Three experiments investigate the effect of presenting lateralized accuracy feedback in a bilateral lexical decision task. We presented feedback after each trial in either the left visual field (LVF) or right visual field (RVF). In Experiment 1 the feedback stimuli were faces smiling or frowning, in Experiment 2 we used colored squares, and Experiment 3 tested the effect of verbal feedback. Negative feedback presented in the LVF tended to improve performance on the following trial, while the same negative feedback in the RVF tended to disrupt performance on the following trial. This result was strongest with the faces as feedback, was less pronounced with colored squares, and disappeared with verbal feedback. The results are interpreted as suggesting a right hemisphere superiority for error monitoring that depends on the mode of feedback. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

As humans, we are prone to making all sorts of errors – slips of the tongue, miscalculations, typographic mistakes, or fumbled footballs. The ability to monitor and compensate for these errors is an essential part of our fallible cognitive systems. However, relatively little is known about the neural mechanisms of error monitor-

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ing. Even less is known about how the two hemispheres of the brain differ in their ability to detect and respond to errors.

In 1977, Rabbitt and Rodgers posed the question “What does a man do after he makes an error?” (Rabbitt & Rodgers, 1977). One generality that comes out of Rabbitt’s work on serial choice reaction time tasks is that people tend to slow down after they’ve made an error (Rabbitt, 1966a,b; Rabbitt & Phillips, 1967; Rabbitt & Rodgers, 1977; Rabbitt & Vyas, 1970). This happens in the absence of performance feedback, indicating that people monitor their own performance in these tasks. They seem to know, at least implicitly, that they have made an error. The cause of this slowdown is not clear. It may be related to ongoing processing of the error, suppression of the tendency to correct errors, or it may even be an artifact of whatever caused the error in the first place (Gehring, Goss, Coles, Meyer, & Donchin, 1993; Rabbitt & Rodgers, 1977).

Recent ERP data provide evidence that there is actually error-related processing in the brain. In several choice reaction time paradigms, a negative-going deflection in the EEG was observed only on trials that were errors (Gehring, Coles, Meyer, & Donchin, 1995). This potential is known as the error-related negativity (ERN). The ERN begins immediately after the response and peaks at 100–150 ms post-response. Gehring et al. (1995) showed that the ERN is larger when accuracy is made important to participants by means of a reward system. Larger ERNs are associated with weaker error responses as measured by a dynamometer, and a greater probability of a correct response on the following trial. Taken together, these data suggest that the ERN reflects a neural system concerned with the detection and compensation for errors. However, it is not clear what the anatomical substrate for this system is. The poor spatial resolution of EEG does not allow for accurate localization, although the ERN seems to be stronger at frontal and central scalp electrodes. It is hypothesized that the potential may be originating in the anterior cingulate, which is known to play a role in attention-related tasks (Vogt, Finch, & Olson, 1992). Dehaene, Posner, and Tucker (1994) used source dipole localization techniques to estimate the source of the ERN, and confirmed that the anterior cingulate is a likely source.

Carter, Braver, Barch, Botvinick, and Cohen (1998) have an alternate interpretation of the ERN. They propose that anterior cingulate activity is not related to the occurrence of errors, but rather that it reflects conditions of increased response competition. If the cingulate monitors competition between ongoing processes, we would expect it to show error-related activity inasmuch as errors are a result of response competition. Using fMRI they demonstrated that during conditions of high response competition the anterior cingulate was activated for both correct and incorrect trials. However, a recent fMRI study by Kiehl, Liddle, and Hopfinger (2000) claims to show error-related activity in the anterior cingulate.

There are, then, no definite conclusions that can be drawn about the neural mechanisms for monitoring. We approach this issue from the perspective that each hemisphere can function as an independent cognitive unit, complete with its own perceptual, motoric, and linguistic abilities (Zaidel, Clarke, & Suyenobu, 1990). This view leads to questions about the ability of each hemisphere to contribute to monitoring. It is possible that each hemisphere has its own independent executive control, including the ability to monitor errors and adjust performance accordingly. Another possibility is that one hemisphere may be specialized for the monitoring of errors. Although the ERN does not appear asymmetric, if the source is a midline structure like the anterior cingulate, hemispheric differences might not be detectable in the ERP data.

Zaidel (1987) has argued for distinct error processing modules in the two hemispheres based on evidence from the lexical decision task. In lexical decision, participants must decide whether a string of letters is a real English word or not. Lateralized versions of this task usually fit a “direct access” model, meaning that each stimulus is processed by the hemisphere that receives it directly (Zaidel et al., 1990), thus making it a suitable task to investigate each hemisphere’s role in error monitoring. Stein and Zaidel (1987) administered a version of this task in which participants were encouraged to correct their errors by a reward system. The results showed that the pattern of error correction responses was markedly different than that of initial responses. Whereas initial responses showed the typical lexical decision pattern of a right visual field (RVF) advantage, and faster responses to words than to non-words, the error correction responses showed no visual field advantage, and faster responses to non-words. The different characteristics of error correction responses were interpreted as evidence that error correction is performed by a distinct error correction module rather than by recomputation in the system that made the initial decision. Furthermore, error correction also appeared to fit the direct access model, which means that each hemisphere was able to independently monitor errors. Error correction was performed equally well by both hemispheres overall, but the right hemisphere (RH) showed an early monitoring advantage that decreased with practice, while the monitoring performance of the left hemisphere (LH) increased with practice. Stein and Zaidel (1987) suggest that this initial RH superiority in error correction may be due to a general advantage in processing feedback about the external environment.

Iacoboni, Rayman, and Zaidel (1997) made a similar suggestion based on their analysis of how the previous trial affects the current trial in a lateralized lexical decision task. In this experiment, accuracy improved on left visual field (LVF) trials following errors, while performance on RVF trials following errors was unaffected. An improvement after error may be interpreted as an appropriate compensatory response, reflecting a shift in strategy, allocation of resources, or some other adjustment towards better performance. Thus, the increase in accuracy in the LVF following errors may reflect a RH error processing advantage.

The present experiments are designed to investigate each hemisphere’s ability to respond to external feedback about its performance. If each hemisphere has a different response to feedback information, this would provide further evidence for hemispheric modularity and independence of executive control in the two hemispheres. Notice that by giving feedback about performance we are bypassing the issue of hemispheric differences in *detecting* errors in favor of investigating differences in *compensation for* errors. Thus, in conditions where participants are receiving feedback, we are measuring what we call *explicit monitoring*. The hemispheres are explicitly informed of their performance and must react accordingly. In contrast, in conditions where no feedback is given, we can measure *implicit monitoring*, the extent to which participants react to errors in the absence of explicit feedback.

Few studies have addressed hemispheric reactions to feedback. The most relevant line of work is that of Derryberry (1989, 1990) who investigated the effects of feedback in the context of emotional arousal. Since these experiments bear closely on our research, they will be described in detail.

Derryberry (1989) used positive and negative feedback presented both centrally and laterally in a lateralized simple reaction time task in order to examine the effects of different emotional states as feedback for the hemispheres. Positive feedback was provided after fast trials, and negative feedback was provided after trials that were inaccurate or slow. By manipulating the reaction time criteria for positive feedback, Derryberry created some blocks containing mostly negative feedback, and others with mostly positive feedback. Experiments 1 and 2 used feedback presented centrally. The main result was that in mostly negative feedback blocks, the reaction time was faster to RVF targets, while in mostly positive feedback blocks the reaction time was faster to LVF targets. Comparing these conditions to a control in which no feedback was presented led to the interpretation that negative emotion interferes with RH performance, while positive emotion facilitates RH performance. Experiment 3 replicated these results with lateralized feedback stimuli. In this experiment, the feedback stimuli were letter grades, with ‘A’ serving as positive feedback, ‘C’ as neutral feedback, and ‘F’ as negative feedback. Reaction time analysis showed that responses were faster in the LVF after positive feedback, and faster in the RVF after negative feedback, with no difference occurring after neutral feedback. Thus, positive feedback shifted performance in favor of the RH, while negative feedback shifted performance in favor of the LH.

Manipulations of the time between the feedback signal and the target stimulus showed that the feedback effects were greatest at 500 ms SOAs and less at 250 or 740 ms SOAs. Derryberry interpreted these results as indicating a “phasic arousal” mechanism activated by the RH. There is extensive evidence that the RH is sensitive to emotional processing and may control arousal mechanisms (Davidson, 1995; Tucker & Williamson, 1984). Tucker and Williamson (1984) have proposed more specifically that the RH responds in opposite ways to positive and negative emotions. According to Tucker and Williamson, right frontal regions become activated in negative mood states and serve to inhibit posterior perceptual regions of the brain, while positive moods decrease activity in the right frontal lobe leading to less inhibition. Derryberry considers the feedback in his experiments to elicit emotional responses, and suggests that the RH role in emotional control may account for his results.

Derryberry (1990) further explored the mechanism of this feedback effect by manipulating stimulus-response compatibility. The aim was to specify the locus of this emotional interference. The reasoning goes that if the interference is perceptual, then manipulating stimulus-response mappings should not interact with feedback effects. However, if the interference affects the RH at a motor or pre-motor level then this manipulation should interact with the feedback effects. There were three experiments in this paper that all used the same computer-based reaction time task with letters as feedback. Results showed that spatial compatibility did indeed interact with the feedback effects. Derryberry (1990) interprets these findings to "provide additional evidence that feedback-related emotional states modulate information processing within the right hemisphere" (p. 1268). These data are also used to form a more sophisticated interpretation of the feedback mechanism. Derryberry reasons, in line with Tucker and Williamson (1984), that the negative feedback leads to increased right frontal activity. However, in contrast with Tucker and Williamson, he claims that the resulting inhibition from the frontal lobe affects the communication between perceptual and motor systems, thus explaining the interaction with S-R compatibility in his results.

There are, however, alternate interpretations of these results. It is not clear that an "emotional" state was elicited by the feedback stimuli. Derryberry refers to the emotion resulting from negative feedback as frustration, but this state does not fall obviously along the positive-negative mood axis the RH has been associated with. Secondly, the nature of the feedback signals must be considered. The letters "A" and "F" are used to indicate good and poor performance, respectively, and "C" is used as a middle baseline. Feedback with the letter "C" may not be an appropriate baseline. The subjects in these experiments were college students to whom a "C" may represent unsatisfactory performance. Moreover, in this task if subjects are striving to respond as quickly as possible, a "C" may indicate failure to achieve the fastest category. Thus, the axis that has been interpreted as corresponding to positive-negative emotion may instead reflect increasing error awareness. In this view, reaction times following positive feedback may be considered a baseline in which no error has been detected. Then, the slowing of RH reaction times following "C" and "F" feedback may be interpreted as reflecting increased failure-related processing. Our experiments use a content-neutral stimulus as a control to ensure there is no success- or failure-related processing.

Other experiments that have investigated hemispheric responses to feedback have substantial interpretational difficulties. Kostandov (1988) used three different types of feedback in a lateralized task that required participants to distinguish time intervals between stimuli. Unfortunately, participants always used the left hand to respond that the interval was short and the right hand to indicate that it was long, which makes it difficult to draw conclusions about each hemisphere's role in processing the feedback.

The present experiments use a bilateral version of the lateralized lexical decision task to investigate hemispheric response to feedback. In bilateral lexical decision, a distractor stimulus accompanies the target stimulus, but is lateralized to the opposite visual field. Bilateral conditions have been shown to increase hemispheric independence (Iacoboni & Zaidel, 1996). Feedback was lateralized to ensure at least initial processing by the contralateral hemisphere. In Experiment 1, the feedback stimuli consisted of a woman's face either smiling or frowning to indicate the accuracy of the previous trial. Experiment 2 attempts to replicate the results of Experiment 1 using less meaningful stimuli, colored squares, as feedback. Experiment 3 examines the effect of using verbal feedback which may be considered a LH biased stimulus.

2. Experiment 1

2.1. Method

2.1.1. Participants

Twelve male and 12 female UCLA undergraduate students participated in this study for partial course credit. All participants learned English as their first language and were strongly right-handed as determined by a modified Oldfield–Edinburgh handedness inventory. All had normal or corrected-to-normal vision.

2.1.2. Materials and apparatus

Two lists of three, four, five, and six letter strings were created, each consisting of 64 English nouns and 64 pronounceable non-words. Words were counterbalanced for spelling-sound regularity and for frequency. For each participant, each list was randomized and strings from one list were paired with strings of equal length from the other list to create 128 trials each with a target and distractor. Thus, one list served as the LVF stimuli and the other served as the RVF stimuli. Which list was presented to which visual field was counterbalanced across participants. Items that occurred as targets in one block served as distractors in the other block.

Participants sat with their chin in a chinrest so that their eyes were 57.3 cm from a computer monitor controlled by an Apple IIsi computer. Their hands were positioned so that the middle and index fingers of both hands rested on switches on a response box positioned at the midline, with palms facing each other. The switches were aligned vertically so that the index fingers rested on the two top switches and the middle fingers rested on the two bottom switches. Stimuli were presented using the MacProbe software developed by Dr Steven Hunt.

2.1.3. Procedure

Eight of the participants (four male, four female) were randomly assigned to the control (“no feedback”) condition; the other 16 served in the experimental (“feedback”) condition. A fixation cross remained at the center of the screen throughout the experiment and participants were instructed to keep their eyes focused on it. Letter strings were presented in lower-case black letters on a gray background for 150 ms. On each trial, one string was presented to the left of fixation and one to the right of fixation, with the more central edge of each stimulus at 1.5° of visual angle from fixation. The strings were printed in 24 point bold Helvetica font. One of the letter strings was underlined, indicating the target. On half of the trials, the target was in the RVF and in the other half the target was in the LVF. The participant was instructed to respond to the underlined string by pressing both of the top switches to indicate it was a word and both of the bottom switches to indicate a non-word. Thus, the responses were made bimanually.

Each participant received 24 practice trials, then completed two blocks of 128 trials each. Participants in the feedback condition completed one block in which feedback was presented only to the RVF and one block in which feedback was presented only to the LVF. The order of these blocks was counterbalanced across participants. Feedback was only presented in the visual field where the target letter string had just been. For example, in a LVF feedback block, participants would receive feedback in the LVF after each trial in which the target was in the LVF, and would receive a meaningless control stimulus in the RVF on each trial in which the target was in the RVF. The feedback was presented 225 ms after the response and remained on the screen for 150 ms. The feedback stimulus consisted of a digitized grayscale photograph of a woman's face. The pictures subtended 2.3° of visual angle in width and 2.7° in height, with the innermost edge at 1.5° from fixation. The face was smiling if the response just made was accurate, and frowning if the response just made was inaccurate. Several control stimuli were created by scrambling the frowning and happy pictures so that they were unrecognizable. Control participants were presented with a scrambled picture after every trial.

2.2. Results

All data points greater than three standard deviations away from the mean of each cell were discarded.

2.2.1. Lexical decision variables

The data for the control participants were submitted to a 2 (visual field of target: left, right) × 2 (wordness of target: word, non-word) repeated measures ANOVA for both latency and percent error. All three of the expected findings (Measso & Zaidel, 1990) were significant: a RVF advantage (RVFA) ($F(1,7) = 5.75$, $P < 0.05$ for latency and $F(1,7) = 14.1$, $P < 0.01$ for percent error), a wordness advantage ($F(1,7) = 19$, $P < 0.01$ for latency, not significant for percent error) and an interaction between wordness and visual field ($F(1,7) = 13.86$, $P < 0.01$ for latency and $F(1,7) = 5.66$, $P < 0.05$ for percent error). Planned comparisons revealed that the interaction fit the standard pattern, where word responses showed fewer errors than non-word responses in the RVF ($F(1,7) = 13.77$, $P < 0.01$), but not in the LVF ($F(1,7) = 0.119$, $P > 0.5$). Thus, there seem to be no effects of a meaningless visual stimulus after each trial.

2.2.2. Explicit monitoring

Two analyses were performed on the feedback group data. The first was a comparison of the LVF and RVF feedback blocks with a 2 (visual field of target: left, right) × 2 (wordness: word, non-word) × 2 (feedback block: LVF feedback, RVF feedback) ANOVA for both percent error and latency data. The three usual findings were again significant in these data: a RVFA ($F(1,15) = 9.34$, $P < 0.01$ for latency and $F(1,15) = 22.03$, $P < 0.001$ for percent error), a wordness advantage ($F(1,15) = 95.71$, $P < 0.001$ for latency and $F(1,15) = 5.83$, $P < 0.05$ for percent error) and a wordness × visual field interaction ($F(1,15) = 22.14$, $P < 0.001$ for latency and $F(1,15) = 7.87$, $P < 0.05$ for percent error). Interestingly, there was a main effect of feedback block on percent error ($F(1,15) = 6.30$, $P < 0.05$), with participants responding with fewer errors in the LVF feedback blocks (23.6%) than in RVF feedback blocks (26.6%). Feedback block interacted with visual field of target in both percent error ($F(1,15) = 14.42$, $P < 0.005$) and latency ($F(1,15) = 39.13$, $P < 0.001$). In LVF feedback blocks, participants were faster responding to LVF targets (741 ms) than to RVF targets (751 ms), while in the RVF feedback blocks participants responded faster to RVF targets (711 ms) than to LVF targets (769 ms). According to planned comparisons, only the RVF feedback difference was significant ($F(1,15) = 56.807$, $P < 0.001$). Percent error also shifted in favor of the visual field that was receiving feedback. In the RVF feedback condition, there was a large difference between LVF targets (34.4%) and RVF targets (18.8%). Planned comparisons revealed that this difference was significant ($F(1,15) = 53.45$, $P < 0.001$). In the LVF feedback condition, however, there was no significant difference between LVF and RVF error rates.

There was also a three-way interaction between feedback block, wordness, and visual field of target for latency ($F(1,15) = 46.06$, $P < 0.001$). Planned comparisons revealed that this interaction was due to a normal wordness × visual field interaction in the RVF feedback blocks, with words significantly faster than nonwords only in the RVF ($F(1,15) = 235.78$, $P < 0.001$), but a different pattern in the LVF feedback blocks. In the LVF feedback blocks, words were faster than nonwords in both the LVF ($F(1,15) = 89.45$, $P < 0.001$) and in the RVF ($F(1,15) = 111.03$, $P < 0.001$).

The second analysis looked at the effect that positive and negative feedback had on the subsequent trial. Data were analyzed in a 3 (type of feedback on previous trial: none, positive, negative) × 2 (feedback block: LVF feedback, RVF feedback) repeated measures ANOVA. There was a main effect of feedback block for percent error ($F(1,15) = 13.247$, $P < 0.01$). Responses were more accurate in LVF feedback blocks (23.1% errors) than in RVF feedback blocks (28.3% errors). There was no main effect of feedback type, but there was an interaction between feedback type and block for percent error ($F(2,30) = 5.90$, $P < 0.01$) (see Fig. 1).

According to planned comparisons, the error rate following negative feedback presented in the LVF (20.2%) was significantly lower than after positive feedback presented in the LVF (25.8%) ($F(1,30) = 4.720$, $P < 0.05$). The error rate following feedback presented in the RVF, however, was actually higher after negative (32.6%) compared to positive (27.2%) feedback, although this difference was not significant.

Analysis of the latency data showed no significant main effect of block, and no main effect of previous trial feedback type. There was no significant interaction between the two variables, but planned comparisons were performed in order to examine the effects of feedback within each visual field since these effects were of theoretical interest. The comparisons revealed that reaction time following negative feedback presented in the RVF (779 ms) was slower ($F(1,30) = 5.20$, $P < 0.05$) compared with trials following no feedback in the RVF (742 ms). Latency following positive RVF feedback trials was not significantly different (731 ms) from the no feedback condition. There were no effects of feedback type on latency when feedback was presented to the LVF and thus there is no evidence that the increase in accuracy following negative feedback to the LVF is due to a speed-accuracy tradeoff.

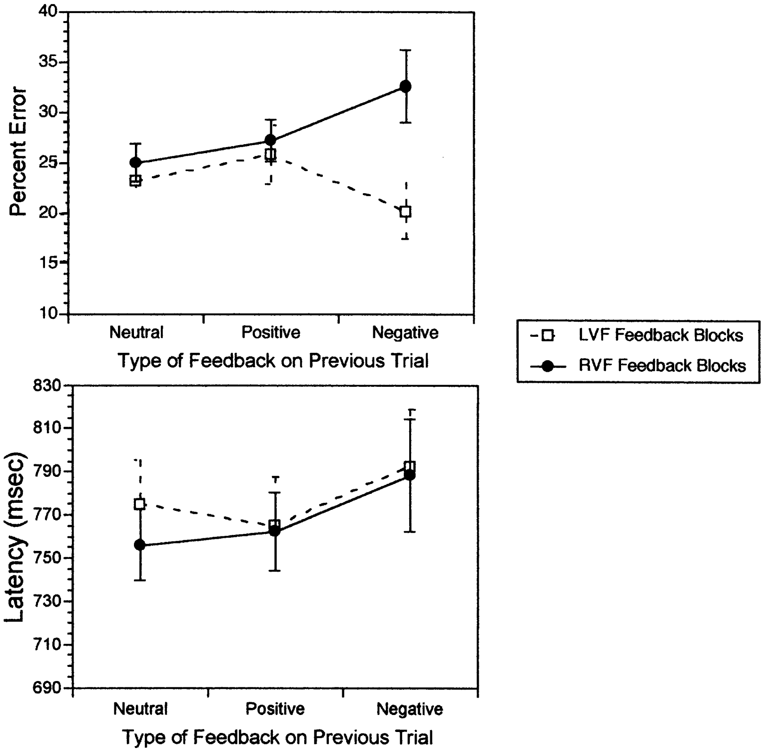

Fig. 1. Experiment 1: interaction between type of feedback on previous trial and feedback block.

2.2.3. Implicit monitoring

This analysis involves the control blocks in which no meaningful feedback was given. Is there a similar pattern of results after errors even when no feedback is given? We analyzed the control blocks with a 2 (correctness of previous trial: correct, incorrect) × 2 (visual field of previous trial: left, right) × 2 (visual field of present trial: left, right) repeated measures ANOVA for percent error and latency. Participants were not significantly slower on trials following errors (790 ms) than trials following correct responses (783 ms). Nor was there any difference in error rate on trials following errors (19.0%) compared to correct responses (19.7%). Previous trial correctness did not significantly interact with previous trial visual field or present trial visual field and thus we did not find evidence of implicit monitoring.

2.3. Discussion

The control participants showed the standard lexical decision pattern, indicating that the presence of a meaningless stimulus after the response did not affect performance. Nor did control participants show any evidence of implicit monitoring; the characteristic slowdown after error trials observed by Rabbitt and Vyas (1970) was not seen here. This may be explained by the presence of the scrambled control stimulus after each trial. This intertrial distraction served to space the trials temporally as compared to most serial reaction time tasks. Also, whatever minimal processing of the scrambled picture took place may have masked any error-related slowing.

Adding meaningful feedback to the task changed the pattern of performance. Participants made fewer errors and responded faster in the visual field that was receiving the feedback. This result is not surprising; participants often reported being more attentive to the field in which they were receiving feedback information.

The finding that negative feedback presented to the RH caused an decrease in error rate while the same feedback presented to the LH increased latency on the following trial provides evidence that feedback is processed independently by each hemisphere. If the feedback information were shuttled across the corpus callosum to a specialized component in one hemisphere regardless of where it was presented, we would expect to see similar patterns in response to negative or positive feedback regardless of where it was presented. Instead we have an almost complete reversal of effect depending on hemifield of presentation.

The differential effects of feedback presented to the two visual fields can be interpreted as indicating a RH superiority for error monitoring in this task. Feedback to the RH seems to initiate a more appropriate response; LVF feedback blocks were more accurate overall and negative feedback led to a compensatory response as indicated by the increase in accuracy on the next trial. This result is consistent with the finding by Stein and Zaidel (1987) of initial RH superiority in detecting errors, and with the previous trial analysis of Iacoboni et al. (1997). This interpretation is also consistent with the finding by Derryberry (1989, 1990) of RH sensitivity to feedback, although in his experiments negative feedback presented to the RH led to a slowing in reaction times. The lexical decision task in the present experiment may allow for more flexibility in strategy readjustment than Derryberry's simple reaction time task. That task did not allow for measurement of error rate as a dependent variable.

If the RH initiates compensatory mechanisms, this may explain the effects on wordness. The pattern following feedback to the LH was no different from the typical pattern observed in this task; there was a wordness advantage that was greater in the RVF. Presenting feedback to the RH, however, resulted in an unusual pattern in which the wordness advantage was the same in both visual fields. The altered pattern suggests a shift in strategy initiated by the RH.

A RH superiority in error monitoring is consistent with the neuropsychological observation that some forms of anosognosia are more often associated with damage to the RH than to the LH (Bisiach & Geminiani, 1990). Anosognosia is the denial of disability following brain damage. Often when patients have damage to the inferior parietal lobe they refuse to admit that the left side of their body is paralyzed. Anosognosia has often been interpreted as a disorder of self-monitoring (Bisiach & Geminiani, 1990; Goldberg & Barr, 1990; Heilman, 1990; Ramachandran, 1995). Goldberg and Barr (1990) point out that monitoring requires at least three components: external feedback about the environment, an internal model of the intention of an act, and a comparator mechanism to compare the intention with the feedback. Ramachandran hypothesizes that there is such a comparator module located in the RH. According to Ramachandran (1995), the RH has a general "anomaly detector" that "detects anomalies or discrepancies, and generates a paradigm shift if the discrepancy is too large" (p. 39). An earlier version of this hypothesis is due to D. Zaidel (1994). The results from the lexical decision task are consistent with the notion of a specialized error detector located in the RH.

It might be argued, however, that the apparent RH advantage in responding to feedback is due to a superior ability to process faces or facial emotions (Adolphs, Damasio, Tranel, & Damasio, 1996; Nakamura et al., 1999). Experiment 2 uses neutral colored squares instead of faces to address this issue.

3. Experiment 2

The purpose of this second experiment was to clarify the results of Experiment 1 by providing a lateralized feedback stimulus that was "hemisphere-neutral". The ideal feedback stimulus for this experiment is one that both hemispheres can identify with equal ease. We chose to use square patches of different colors to indicate right and wrong answers. In addition, in contrast to Experiment 1, we used a within-subjects design to allow for better cross-conditional analyses.

3.1. Method

3.1.1. Participants

A total of 32 UCLA undergraduate students (16 male, 16 female) participated in this study for partial course credit. All participants learned English as their first language and were strongly right-handed as determined by a modified Oldfield–Edinburgh handedness inventory. All had normal or corrected-to-normal vision.

3.1.2. Materials and apparatus

The chinrest setup, response box, computer, and computer software were identical to those used in Experiment 1. Since this experiment requires participants to complete four blocks of trials, new word lists were created. These word lists were adapted from Iacoboni and Zaidel (1996). Two lists of 96 stimuli pairs were created, counterbalanced for regularity and frequency. Each pair was matched for length, and consisted of three, four, five, and six letter strings. Words that were targets in one block became distractors in another to create the four blocks.

3.1.3. Procedure

The bilateral lexical decision procedure was the same as for Experiment 1, with two changes. First, the feedback stimuli were replaced with solid colored squares of the same size (2.3° wide by 2.7° high). Three colors were used. A black square served as the control/neutral stimulus. Participants were told that the black square did not provide any information about their performance. A blue square and a yellow square served as the meaningful feedback. Half of the participants saw a blue square after each correct trial and a yellow square after each incorrect trial. The colors were reversed for the other half of the participants. The second change was that after a practice block of 24 trials, each participant completed four blocks of 96 trials each. One block was a control in which a black square appeared after each trial in the same visual field as the target. Thus, in the control block participants did not receive any explicit feedback. Participants also completed a RVF feedback block and a LVF feedback block corresponding to the two experimental conditions in Experiment 1. Again, in RVF feedback blocks colored squares indicating correctness appeared after all RVF targets, while black squares appeared after all LVF targets. In LVF feedback blocks meaningful feedback was presented only after LVF targets, and black squares appeared after all RVF targets. In a fourth block, participants were presented with meaningful feedback after *both* LVF and RVF trials.

3.2. Results

All data points that were greater than three standard deviations away from the mean of each cell were discarded.

3.2.1. Lexical decision variables

The first analysis looked at the lexical decision pattern across the four blocks with a 2 (visual field of target: left, right) × 2 (wordness: word, non-word) × 4 (feedback block: control, LVF feedback, RVF feedback, both) repeated measures ANOVA for both percent error and latency. Once again, we obtained the classic lexical decision pattern. There was a significant RVFA overall ($F(1,31) = 96.44$, $P < 0.0001$), with 17.3% errors in the RVF and 28.9% in the LVF. Participants were also significantly faster when targets were in the RVF (754 ms) as opposed to the LVF (809 ms) ($F(1,31) = 30.98$, $P < 0.0001$). There was also a wordness advantage in percent error ($F(1,31) = 6.78$, $P < 0.05$) and latency ($F(1,31) = 84.07$, $P < 0.0001$). In addition, we again found an interaction between wordness and visual field in percent error ($F(1,31) = 22.663$, $P < 0.0001$) and latency ($F(1,31) = 84.56$, $P < 0.0001$). There was no main effect of feedback block, and feedback block did not significantly interact with any other variable in the accuracy data. However, in the latency data, feedback block interacted with visual field ($F(3,93) = 6.16$, $P < 0.001$) and with wordness ($F(3,93) = 3.84$, $P < 0.05$).

A series of post-hoc comparisons using the Bonferroni correction was used to examine these interactions. The interaction between visual field and feedback block showed the same pattern as in Experiment 1, where reaction times were slower in the visual field not receiving feedback. Thus, in the RVF feedback blocks, LVF trials were significantly slower than LVF trials in the control block ($F(1,93) = 17.26$, $P < 0.001$), while RVF trials were not significantly slower compared with control blocks. In the LVF feedback blocks, RVF trials were slower than RVF trials in control blocks ($F(1,93) = 17.11$, $P < 0.001$), whereas LVF trials were not significantly slower compared to the control blocks. There was no significant slowdown in either visual field in the “both” blocks.

Analysis of the wordness × block interaction revealed that the presence of feedback in a block slowed down the processing of words, but not of non-words. Each of the three feedback blocks showed significantly slower reaction time to word targets as compared with control blocks (LVF feedback blocks, $F(1,93) = 13.52$, $P < 0.001$; RVF feedback blocks, $F(1,93) = 18.66$, $P < 0.001$; "both" blocks, $F(1,93) = 15.03$, $P < 0.001$). None of the three blocks showed a significant difference in reaction time to non-word targets as compared with control blocks.

3.2.2. Explicit monitoring

The second set of analyses looked at the effect of feedback on the following trial. The LVF feedback blocks and RVF feedback blocks contained trials with all three types of feedback (positive, negative, and neutral), whereas the "both" blocks did not contain any trials with neutral feedback. For this reason, we analyzed the "both" blocks separately. A 2 (feedback block: LVF feedback, RVF feedback) × 3 (type of feedback on previous trial: none, positive, negative) repeated measures ANOVA was conducted on the error and latency data from the LVF and RVF feedback blocks. One participant did not have any valid trials in one of the cells due to a small number of errors in the RVF feedback block and was not included in this analysis.

The data are shown in Fig. 2. In the accuracy data, there was no significant main effect of block or of previous trial feedback type. Also, although the pattern looks remarkably similar to the one obtained in Experiment 1, the interaction between feedback block and previous trial feedback type was not significant. Motivated by the results of Experiment 1, we looked at the trials following negative feedback with a planned comparison, and found that participants made significantly fewer errors when the negative feedback had been presented to the LVF (22.3%) as opposed to the RVF (28.1%) ($F(1,60) = 5.789$, $P < 0.02$). The latency data showed no significant main effect of feedback block, but there was a significant main effect of previous trial feedback type ($F(2,60) = 4.188$, $P < 0.02$). This reflected an error-related slowdown such that trials following negative feedback (906 ms) were about 100 ms slower than trials following positive (798 ms) or neutral (812 ms) feedback. There was no significant interaction between feedback block and previous trial feedback type, but there is some evidence that the error-related slowdown was greater when negative feedback was presented to the RVF. A planned comparison revealed a marginally significant difference between response times following negative feedback presented to the RVF (963 ms) compared to those following negative feedback presented to the LVF (848 ms) ($F(1,60) = 3.74$, $P < 0.06$). Thus, as in Experiment 1, negative feedback presented to the RVF tends to slow down and *decrease* accuracy on subsequent trials, whereas negative feedback presented to the LVF tends to slow down and *increase* accuracy on subsequent trials.

The "both" blocks were then analyzed with a 2 (type of feedback on previous trial: positive, negative) × 2 (visual field of previous trial: left, right) repeated measures ANOVA for percent error and for latency. The error data revealed no main effect of type of feedback or of visual field, but a significant interaction between the two ($F(1,31) = 4.58$, $P < 0.05$). These data are plotted in Fig. 3. A planned comparison shows that there is a significant difference between error rate following LVF nega-

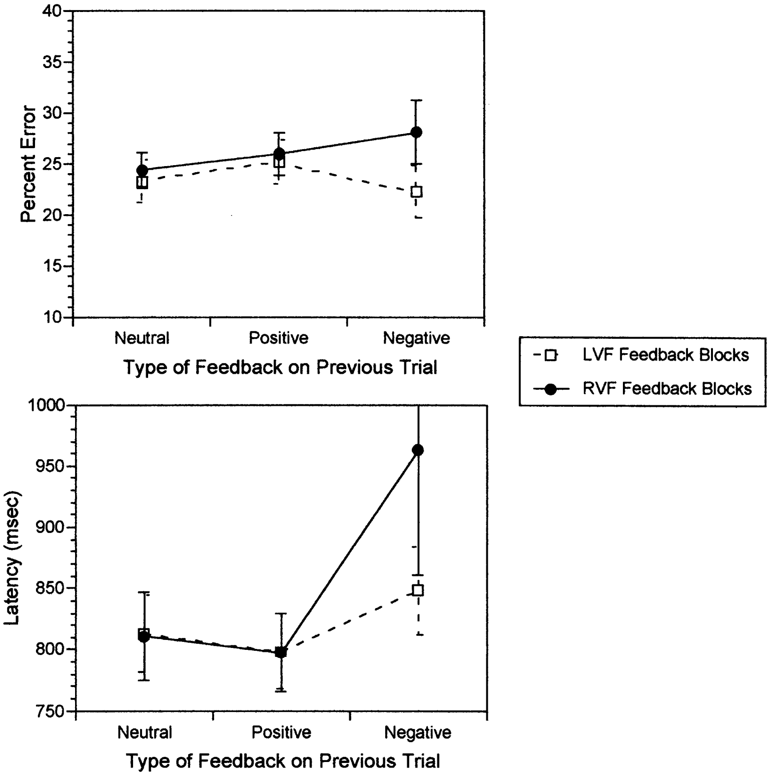

Fig. 2. Experiment 2: interaction between type of feedback on previous trial and feedback block for LVF and RVF feedback blocks.

tive feedback as compared to RVF negative feedback ($F(1,31) = 6.923$, $P < 0.05$). This result is in the opposite direction as that found in the other blocks, with errors following RVF negative feedback less frequent (20.5%) than following LVF negative feedback (25.3%). The latency data showed a main effect of previous trial feedback type ($F(1,31) = 14.36$, $P < 0.001$), reflecting slower responses after negative feedback (853 ms) compared to positive feedback (787 ms). There were no further significant effects or interactions.

3.2.3. Implicit monitoring

To test for implicit monitoring, we subjected the error rate and latency data from the control blocks to a 2 (correctness of previous trial: correct, incorrect) × 2 (visual field of previous trial: left, right) repeated measures ANOVA. No significant results were found for either error or latency data.

3.3. Discussion

The effect of colored squares as feedback in Experiment 2 was similar to the effect

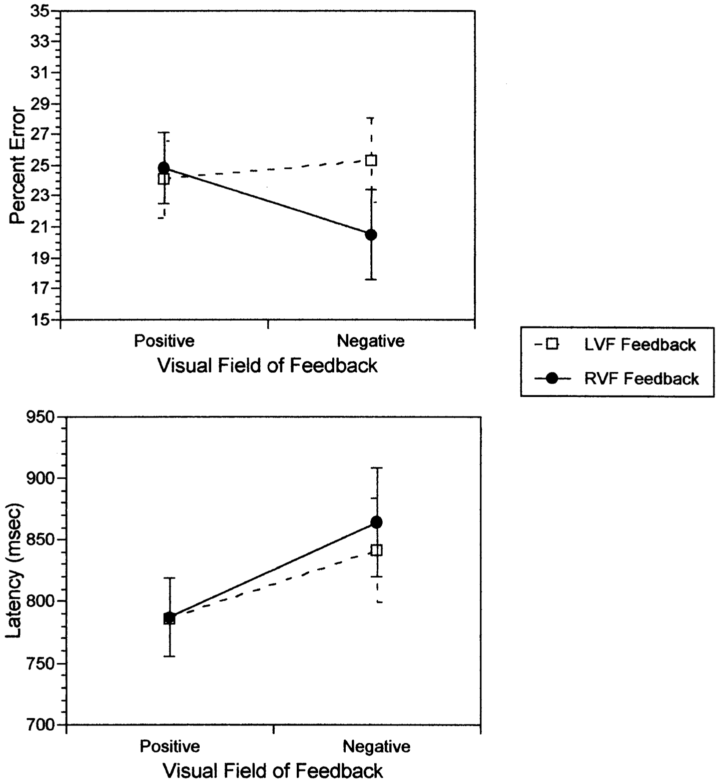

Fig. 3. Experiment 2: interaction between type of feedback on previous trial and visual field of feedback during "both" blocks.

of the faces in Experiment 1. When negative feedback is presented to the RVF, performance is worse on the following trial compared to when negative feedback is presented to the LVF. Participants show a greater slowdown and increased error rate following negative feedback presented to the RVF or LH. It appears that this effect is dependent on the presence of the feedback stimulus itself, since we obtained no evidence of implicit monitoring.

We may learn something about the locus of the feedback effect from these data. In comparison to the control blocks, reaction times to word targets were slower in the three feedback blocks. Non-word trials were not any slower in the feedback blocks. This suggests that the presence of feedback may initiate a shift in strategy that affects word processing but not non-word processing. This idea also supports the independence of word and non-word processing (Iacoboni & Zaidel, 1996).

There are two important differences between the results of Experiments 1 and 2. First, the interaction between block and type of feedback on previous trial was not significant in the second experiment. The visual field differences in feedback response were more robust when the feedback stimuli were faces as opposed to colored squares. Second, the “both” blocks did not show the same pattern, indicating that the blocked nature of feedback was essential for the effect. Perhaps the mixed nature of the “both” blocks clouded the contribution of each hemisphere to error monitoring. This suggests that the error monitors in both hemispheres are not independent of each other.

The attenuated interaction between feedback type and block suggested that the faces may have been a more effective RH feedback stimulus than the squares. Each hemisphere may be sensitive to different types of feedback. For example, it is possible that the LH is able to utilize verbal feedback more efficiently than the right. To test this idea, we ran a third experiment using verbal feedback.

4. Experiment 3

4.1. Method

4.1.1. Participants

For this experiment, 32 different UCLA undergraduate students (16 male, 16 female) participated for partial course credit. All participants learned English as their first language and were strongly right-handed as determined by a modified Oldfield–Edinburgh handedness inventory. All had normal or corrected-to-normal vision.

4.1.2. Materials and apparatus

The chinrest setup, response box, computer, and computer software were identical to those used in Experiments 1 and 2. The word lists were identical to those used in Experiment 2.

4.1.3. Procedure

The procedure was the same as Experiment 2 except that the feedback stimuli were changed to the words “none” for the control stimulus, “good” for a correct response, and “error” for an incorrect response. These words were chosen because they all appeared approximately the same length on the computer screen. We avoided using the word “right” to indicate a correct response due to its other meaning as the opposite of “left”. The feedback stimuli, like the lexical decision targets, were printed in black 24 point bold Helvetica font.

4.2. Results

Once again, data points that were greater than three standard deviations away from the mean of each cell were discarded.

4.2.1. Lexical decision variables

We conducted a 2 (visual field of target: left, right) × 2 (wordness of target: word, non-word) × 4 (feedback block: control, LVF feedback, RVF feedback, both) repeated measures ANOVA for both percent error and latency data. These data too showed the classic lexical decision pattern. There was a main effect of visual field in percent error ($F(1,31) = 56.98$, $P < 0.0001$), with fewer errors in the RVF (16.1%) than in the LVF (26.7%). Participants also responded faster to RVF targets (749 ms) than to LVF targets (781 ms) ($F(1,31) = 48.52$, $P < 0.0001$). There was a significant main effect of wordness in latency ($F(1,31) = 48.52$, $P < 0.0001$), and a trend towards a wordness advantage in percent error ($F(1,31) = 3.50$, $P < 0.08$). The wordness by visual field interaction was again significant for percent error ($F(1,31) = 47.00$, $P < 0.0001$) and latency ($F(1,31) = 16.46$, $P < 0.001$).

4.2.2. Explicit monitoring

We first examined the LVF and RVF feedback blocks with a 2 (feedback block: LVF feedback, RVF feedback) × 3 (type of feedback on previous trial: positive, negative, neutral) repeated measures ANOVA on the percent error and latency data. These data are shown in Fig. 4. The results of this experiment look markedly different from Experiments 1 and 2. In the error rate data, there were no significant main effects or interactions. There was no difference between error rate following LVF negative feedback (20.9%) and error rate following RVF negative feedback (21.0%). In the latency data, there was no main effect of feedback block, and no significant interaction between feedback block and type of feedback. There was,

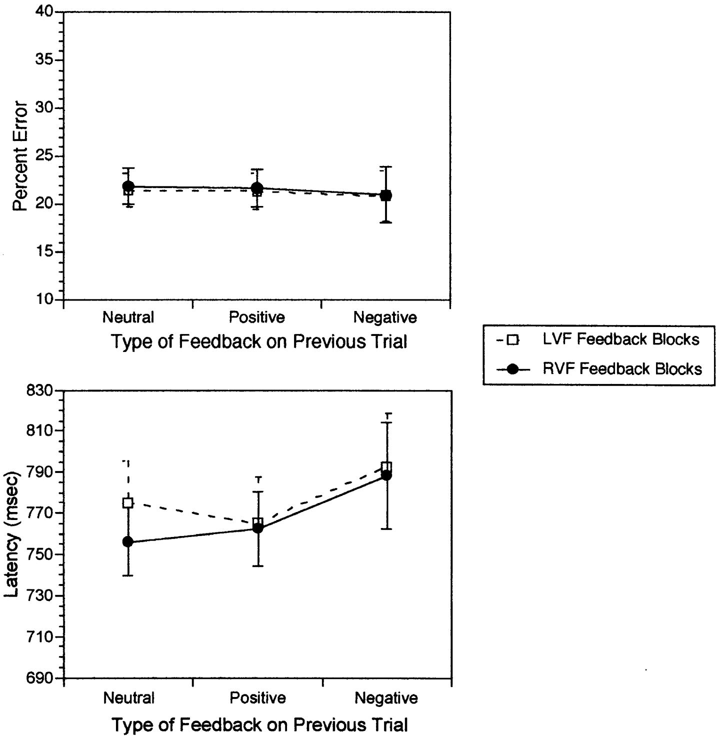

Fig. 4. Experiment 3: interaction between type of feedback on previous trial and feedback block.

however, a significant main effect of previous trial feedback type ($F(2, 62) = 3.18$, $P < 0.05$). This was due to slower responses following negative feedback (790 ms) as opposed to positive (766 ms) or neutral (764 ms) feedback.

We then analyzed the "both" blocks with a 2 (visual field of previous trial: left, right) × 2 (type of feedback on previous trial: positive, negative) repeated measure ANOVA for both percent error and latency. There were no significant main effects or interactions found in these data.

4.2.3. Implicit monitoring

Data from the control blocks was analyzed with a 2 (correctness of previous trial: correct, incorrect) × 2 (visual field of previous trial: left, right) repeated measures ANOVA for accuracy and latency. The latency data showed no significant slowing after errors (794 ms) compared to after correct trials (781 ms). Nor was there an interaction between previous trial visual field and previous trial correctness. The accuracy data also showed no main effect of previous trial correctness. The interaction between previous trial visual field and previous trial correctness did not reach significance ($F(1, 31) = 2.99$, $P < 0.10$). Participants tended to commit fewer errors after an RVF error trial (17.6%) than after an LVF error trial (21.8%), but this result did not reach significance in a planned comparison ($F(1, 31) = 3.43$, $P < 0.08$).

4.3. Discussion

Experiments 2 and 3 were identical except for the nature of the feedback stimulus, yet they bore out very different results. The verbal feedback seems to have eliminated the interaction found in the first two experiments. This underscores the importance of the type of feedback; some modes of feedback are more effective than others, and each hemisphere may be sensitive to different modes of feedback.

It is possible that the verbal stimulus was more difficult to perceive and therefore was ineffective. This explanation is not satisfying, since participants in this task are making decisions about words that appear very briefly in both visual fields. Another interpretation is that the RH is specialized for error monitoring, and is unable to use verbal stimuli effectively as feedback.

5. General discussion

The general pattern observed here is a RH advantage in error processing that became progressively less pronounced when we changed the feedback stimulus from faces to colored squares to words. One of the goals of these experiments was to test whether the hemispheres differ in their sensitivity to different types of feedback stimuli. Comparing error rates across experiments, we find that trials following negative feedback when presented to the RVF have the greatest error rates in Experiment 1 with faces as feedback (32.6%), slightly lower error rates in Experiment 2 with squares as feedback (28.1%), and the lowest error rates in Experiment 3 with verbal feedback (21.0%). Error rates following negative feedback presented to the LVF, however, seem less affected by the type of feedback, with

20.2% in Experiment 1, 22.3% in Experiment 2, and 20.9% in Experiment 3. It may be argued that the LH is more sensitive to the type of feedback presented, or more specifically that the LH can only benefit from feedback presented in its preferred verbal format. According to this interpretation, the RH seems to be able to benefit from feedback information regardless of its format, and thus may be regarded as a more generalized monitor. However, a post-hoc ANOVA of trials following negative feedback using Experiment as a between-subjects variable failed to support an interaction between feedback stimulus and visual field of feedback presentation.

While we used three different types of feedback in these experiments, the feedback stimuli were all similar in that one symbol represented correctness while another symbol indicated errors. Feedback about performance could, however, be more informative than this. For example, feedback that summarizes the last few trials in a graphical format might be used more effectively, and might distinguish better between hemispheric monitoring styles. Summary feedback has been shown to be more effective than trial-by-trial feedback in some motor learning paradigms (Schmidt, 1991).

We did not find strong evidence for implicit monitoring in these experiments. As described above, the lack of evidence for implicit monitoring in these experiments may be due to the neutral stimulus intervening between the response and the subsequent trial. Iacoboni et al. (1997) did find evidence for implicit monitoring in a lexical decision task with no intervening feedback stimuli. Recall that in that experiment, accuracy improved after LVF error trials, but did not change following RVF error trials. Those data are consistent with the present findings of RH error sensitivity.

An important consideration in this experiment is the nature of the lateralized lexical decision task. The LH is consistently better at performing lexical decisions. The RH's status as an error monitor in this task may depend on its position as the inferior lexical processor. There may be a dynamic shifting of responsibility that depends on the demands of the task, such that when we provide a task that the RH performs better the monitoring functions will be taken over by the LH.

Since our results are largely based on responses to explicit feedback, the processes we are describing relate to the ability of each hemisphere to use this feedback to guide behavior. That is, our results do not bear on the issue of the neural mechanisms of detecting errors, rather they describe the hemispheric processes of compensating for erroneous responses. It is possible that a generalized error processing mechanism (perhaps in the anterior cingulate) detects the commission of an error and sends that information to each hemisphere. Konow and Pribram (1970) pointed out this distinction between the detection of errors and the utilization of error information. They described a patient with frontal lobe damage who was aware of her errors, but was unable to use this information to change her behavior. This is a pattern typical of frontal lobe patients (see for example, Milner & Petrides, 1984), suggesting that error compensation mechanisms may reside in the frontal lobes. Recent neuroimaging data have also supported the distinction between monitoring and control processes, implicating the dorsolateral prefrontal cortex in control functions and the anterior cingulate in monitoring functions (MacDonald, Cohen, Stenger, & Carter, 2000).

Furthermore, based on these data we cannot rule out a central component of the feedback processing mechanism. There may be, for example, a central mechanism that extracts error information from the feedback stimuli and sends this information to each hemisphere where it affects behavior differently. It is also possible that each hemisphere performs initial processing of the feedback stimulus, and sends it along to a central behavior adjustment system. This central system might then have differential effects on behavior because it received different information from each hemisphere, or because it has a better communication with one hemisphere. Further research will be required to distinguish among these alternatives. These data do, however, demonstrate that at least part of the feedback processing system is lateralized.

The relationship of error processing to emotion is still unresolved. As discussed above, Derryberry (1989, 1990) interpreted his feedback results as reflecting activity in arousal and emotion systems. We have interpreted our results in purely information processing terms. It makes sense that if there are specific error-related mechanisms in the brain they would be closely related to success and failure-linked emotions. Support for the relationship between error monitoring and emotion comes from an ERP study by Phan, Collins, and Tucker (2000) showing that the amplitude of the ERN is larger in individuals with higher ratings of negative affect. However, Derryberry's model in which the right frontal lobe inhibits sensory to motor pathways does not seem sufficient to explain the present data. In Experiments 1 and 2 the RH appeared to improve its performance in the lexical decision task in response to negative feedback. Additionally, the LH slowed down more than the RH when presented with negative feedback. An alternative explanation might be that negative feedback activates the right frontal lobe, and that this activity leads both to negative emotion and error compensation mechanisms. The RH's strong response to errors, then, may be related to its selective sensitivity to negative emotion in general. The idea that the RH is specifically concerned with the processing of negative emotions has much support in the literature (Davidson, 1995).

In fact, there are at least two other studies that address the issue of feedback-related emotional states and hemispheric asymmetry using electrophysiological methods. Aftanas, Koshkarov, Pokrovskaja, Lotova, and Mordvintsev (1996) recorded event-related desynchronization (ERD) patterns from participants in a choice reaction time task with feedback. As in the Derryberry (1989) task, negative feedback followed trials that were either slow or incorrect. The results showed an increased ERD response following negative feedback that was greater over the RH than the LH. A similar result was obtained by Sobótka, Grabowska, Grodzicka, Wasilewski, and Budohoska (1992). Participants in this experiment fired a photoelectric gun at a target while ERPs were recorded. In some blocks, participants were told that they had hit or missed, while in other blocks no feedback was given. Amplitudes of the P180 and N400 potentials were higher in the RH than the LH, but this difference was only present in the feedback blocks. These results are consistent with our finding of a greater response to negative feedback when it is presented to the RH.

The experiments described here demonstrate that initial processing of the stimulus and error detection can be computationally autonomous. This means that one can fail independently of the other. We have shown that the LH is specialized for word recognition whereas the RH is specialized for monitoring this process. It remains to be discovered whether this is an example of more general RH specialization for monitoring or whether this is an example of complementary hemispheric specialization for processing and monitoring. It also remains to be discovered where in the RH monitoring is controlled, and how this process works. Candidates for localization are the right prefrontal cortex, the anterior cingulate, and the limbic-frontal circuit. A plausible preliminary hypothesis about the "how" of RH monitoring is that it proceeds top-down, whereas initial processing proceeds bottom-up.

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