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The dynamic nature of language lateralization: effects of lexical and prosodic factors

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Abstract

In dichotic listening, a right ear advantage for linguistic tasks reflects left hemisphere specialization, and a left ear advantage for prosodic tasks reflects right hemisphere specialization. Three experiments used a response hand manipulation with a dichotic listening task to distinguish between direct access (relative specialization) and callosal relay (absolute specialization) explanations of perceptual asymmetries for linguistic and prosodic processing. Experiment 1 found evidence for direct access in linguistic processing and callosal relay in prosodic processing. Direct access for linguistic processing was found to depend on lexical status (Experiment 2) and affective prosody (Experiment 3). Results are interpreted in terms of a dynamic model of hemispheric specialization in which right hemisphere contributions to linguistic processing emerge when stimuli are words, and when they are spoken with affective prosody.

Keywords: Hemispheric specialization; Prosody; Language; Emotion; Dichotic listening

1. Introduction

It has been well-established that the dichotic listening paradigm provides an estimate of hemispheric specialization [21,38,45]. Typically, a right ear advantage (REA) is observed for linguistic processing, reflecting left hemisphere specialization, and a left ear advantage (LEA) is observed for some forms of nonlinguistic processing, reflecting right hemisphere specialization. The direction of the ear advantage depends on the task, and not on the nature of the stimulus itself. For example, when messages are presented in different emotional tones of voice, an REA is observed when attending to linguistic content, but an LEA is observed when attending to the tone of voice, or emotional prosody [6,24].

The ear advantage on a dichotic listening task can arise through one of two possible mechanisms, which Zaidel et al. have termed "direct access" and "callosal relay" ([43], see also Moscovitch [26,27] who uses the terms "efficiency model" and "strict localization", respectively). In both models dichotic stimuli are projected from each ear to the opposite hemispheres via the contralateral auditory pathways. Under dichotic competition, the ipsilateral pathways are thought to be suppressed [20]. In the callosal relay model, hemispheric specialization is absolute, and the stimuli from both ears are ultimately processed in the dominant hemisphere. An REA for linguistic processing thus arises because the stimulus from the left ear must be relayed across the callosum from the right hemisphere to the left hemisphere, resulting in a delay and possible degradation of the signal. Similarly, the LEA observed on a prosodic task arises because the right ear signal must be relayed from the left hemisphere to the right hemisphere. In the direct access model, each hemisphere is capable of performing the task, but one is superior to the other. Stimuli are processed in the hemisphere to which they are projected. The REA for linguistic processing now results because the left hemisphere is better (faster and/or more accurate) than the right at performing the task.

If one's goal is to determine which hemisphere is better at a task, it does not matter which mechanism leads to the ear advantage. However, if one wishes to make inferences about locus of processing, or to evaluate relative versus absolute specialization, this distinction is very important. For example, the left ear score on a linguistic dichotic task might reflect right hemisphere processing of the stimulus (direct access), but it might also reflect the efficiency of callosal transfer. The present experiments empirically determine the mechanisms through which the ear advantages arise in

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dichotic listening as a function of both task and stimulus parameters. Experiment 1 examines a dichotic listening task that has previously been demonstrated to produce an REA for linguistic processing and an LEA for prosodic processing [6,7]. Experiments 2 and 3 examine the effect of semantic and prosodic factors on the mechanism underlying the REA.

Many verbal dichotic effects are considered to arise through callosal relay [43]. This conclusion is based primarily on the finding that split-brain patients demonstrate extinction of the left ear signal under dichotic conditions [25,28,35,36], suggesting that the left ear signal cannot be processed in the right hemisphere. However, claims of left ear extinction may be somewhat exaggerated. A careful literature review of dichotic listening in the split-brain patients described above reveals that only 2 of 16 patients demonstrate complete extinction of the left ear. Furthermore, it is possible that left ear attenuation reflects an attentional neglect of the left ear that arises under conditions of bilateral competition, and not right hemisphere incompetence. A similar phenomenon has been demonstrated in the visual modality, in which split-brain patients may be able to respond to words presented in the left visual field on unilateral trials, but not on bilateral trials [39]. Lassonde et al. [23] have suggested that left ear suppression in split-brain patients reflects trauma to the right hemisphere during surgery and not callosal disconnection. They report a split-brain patient (SL) who demonstrated extinction of the left ear immediately after surgery, but demonstrated normal dichotic performance after 5 years. An alternative explanation for left ear performance in split-brain patients is a failure of ipsilateral suppression that may occur as a result of cortical reorganization, so that the left ear stimulus was actually projected to the left hemisphere. We conclude that the data from these patients is equivocal on this issue.

The callosal relay model is based on the strong assumption of absolute hemispheric specialization. However, considerable evidence indicates that the right hemisphere has some competence in speech comprehension [15,16,44]. It has been proposed that callosal relay may be necessary for consonant–vowel syllables that have no semantic association, but that direct access might be observed when the stimuli are words [10,36]. Thus the lexical status of the stimuli may play a key role in the mechanisms that underlie the ear advantage.

Almost nothing is known about the mechanism leading to the LEA for prosodic processing, except that it reflects right hemisphere specialization. Patients with right hemisphere damage may have deficits in both the production and comprehension of affective prosody [4,18,33], patients undergoing the Wada procedure lose the ability to express affective prosody during right-side injection [31], and dichotic listening studies in normals consistently report LEAs for comprehension of affective prosody [14,34,37]. There is very little data as to the competence of the left hemisphere in prosodic processing, although there is some evidence that linguistic prosody may not be as strongly lateralized as affective prosody, or may even be lateralized to the left hemisphere [2,18].

Fortunately, it is possible to distinguish between direct access and callosal relay interpretations of the ear advantage in normal subjects. A number of criteria that identify a direct access pattern of processing have been described by Moscovitch [26,27] and by Zaidel et al. [43]. A simple method relies on the use of a response hand manipulation: callosal relay predicts an ear advantage that does not interact with response hand, direct access predicts the ear advantage will be attenuated when the response is made with the hand contralateral to the dominant ear. The logic for assessing an REA follows: under conditions of callosal relay, stimuli from both ears are processed by the left hemisphere, which then generates the motor response when responding with the right hand, or relays the response to the right hemisphere when responding with the left hand. The REA arises solely from the time required for the left ear signal to cross the callosum from the right hemisphere to the left hemisphere. One therefore expects a main effect of ear (arising from interhemispheric transmission time), possibly a main effect of response hand, reflecting the additional time required to relay the response to the right hemisphere when responding with the left hand (although this effect depends on an equivalence of right and left hands, and is therefore questionable), but importantly, no interaction between ear and hand. The magnitude of the ear advantage should be the same whether the participant is responding with the left hand or the right hand. Under conditions of direct access, however, different predictions arise. Here the basic ear advantage arises because of a difference in processing efficiency between the left and right hemispheres, but the magnitude of that ear advantage is modified by the responding hand. When responding with the right hand, the REA is enhanced, because the left hemisphere has more immediate access than the right hemisphere to the responding right hand. However, when responding with the left hand, the REA is attenuated, because now the right hemisphere has more immediate access than the left hemisphere to the responding left hand. Thus an interaction between ear and response hand should be observed such that the REA is attenuated when responding with the left hand. A similar logic holds for right hemisphere processes such as prosody. Callosal relay should result in an LEA that does not interact with response hand. However, direct access should produce an LEA that is attenuated when responding with the right hand. The three experiments presented here used a response hand manipulation to examine the mechanisms producing the ear advantages for linguistic and prosodic processing.

2. Experiment 1

The dichotic task in Experiment 1 was developed by Bryden and MacRae [6] and consists of dichotically-paired words, spoken in different emotional tones of voice. Using this task, a number of studies have reported an REA when subjects are instructed to listen for a target word, and an LEA when instructed to listen for a target tone of voice (e.g. [7,17]). Direct access can be inferred if there is an interaction between ear and response hand such that the ear advantage is attenuated when responding with the hand contralateral to the dominant ear.

2.1. Method

2.1.1. Participants

Thirty-two right-handed undergraduate students (16 men and 16 women) participated in the study in exchange for course credit. All were native English speakers or learned English before the age of 5. None had any hearing deficits. Handedness was assessed by the Waterloo Handedness Questionnaire—Revised [13].

2.1.2. Apparatus and stimuli

The experiment was controlled by the Superlab Pro software package [9] on a Power Macintosh 8600 computer with a 17 in., 256-color display monitor and an Apple extended keyboard. The stimuli were obtained from B. Bulman-Fleming at the University of Waterloo and were presented through Sony MDR-V600 headphones with circumaural cushions. The stimuli consisted of the words "bower", "dower", "power", and "tower", spoken in angry, happy, neutral, and sad tones of voice [6]. The words were spoken in a male voice and digitized in 16 bits at a sampling rate of 44.1 kHz. The SoundEdit 16 software package was used to edit the stimuli such that each token included 30 ms of silence preceding the initial burst and were truncated at 500 ms. All possible pairings of words and emotions were produced with the constraint that a different word and a different tone of voice were presented to each ear on each trial, yielding a total of 144 stimulus pairs.

2.1.3. Procedure

Participants were individually seated at the computer with headphones on. Participants were given a target word or a target tone of voice at the beginning of the block of 144 trials, and monitored for that target for the entire block. They were required to respond as to whether or not they heard their target in either ear, using their index and middle fingers on the "1" (present) and "2" (absent) keys of the computer's number keypad. Each word or tone of voice was present on 50% of the trials, 25% in the left ear and 25% in the right ear. Participants responded to both their word target and their tone of voice target for one complete block of trials with their left hand and to another block with their right hand. There were thus four blocks of 144 trials for a total of 576 trials. Target and block order were counterbalanced across subjects. Each possible target combination (word target and voice target) was assigned to two participants (one man and one woman). In order to control for any mechanical differences between channels, headphone placement was also counterbalanced across subjects—no effects of headphone placement were observed. Participants were instructed to respond as quickly and accurately as possible. Experimental trials were preceded by practice trials in which they heard each of the four words spoken once in each of the four tones of voice (16 trials) binaurally in order to familiarize themselves with their target. Response times (RT) and accuracy were recorded by the computer's internal timer. The experiment took approximately 50 min to complete.

2.2. Results and discussion

Mean number of correct responses (hits), false alarms, and mean response times (RT) for hits were calculated for each of the conditions. Note that false alarms cannot be attributed to either ear. However, in order to control for individual subject variability in response bias, d' was calculated for each condition on the assumption that false alarms were split evenly between the ears. d' is a signal detection measure that considers both hit rate and false alarm rate, and varies from negative infinity to positive infinity, with 0 representing chance performance. Positive values reflect increasingly accurate discrimination. Mean hit rates, false alarm rates, and d' values for each linguistic and prosodic target are presented in Table 1. In the RT analyses, outliers were identified as RTs more than three standard deviations from the mean, on an individual subject basis. Mean RTs for each target are presented in Table 2. Data collapsed across all linguistic and prosodic targets are presented in Fig. 1 (d' values) and Fig. 2 (RT).

2.2.1. Accuracy analyses

Accuracy analyses were conducted using both hit rate and d' values as dependent measures. Hit rates for each condition were analyzed in a 2 (Task) × 2 (Ear) × 2 (Hand) × 2

Table 1
Mean hit rate for each ear, ear advantages (EA), and false alarm rate (FA) for each target and response hand for Experiment 1

	Left hand				Right hand			
	LE	RE	EA	FA	LE	RE	EA	FA
Linguistic								
Bower	0.32	0.57	0.25*	0.15	0.33	0.51	0.18*	0.10
Dower	0.59	0.69	0.10*	0.14	0.53	0.70	0.17*	0.12
Power	0.55	0.57	0.02	0.15	0.60	0.58	−0.02	0.15
Tower	0.70	0.79	0.09*	0.08	0.73	0.78	0.05*	0.09
Mean	0.54	0.66	0.12*	0.13	0.55	0.64	0.09*	0.12
Prosodic								
Angry	0.71	0.66	−0.05	0.06	0.71	0.64	−0.07	0.09
Happy	0.67	0.59	−0.08	0.04	0.74	0.66	−0.08	0.05
Neutral	0.69	0.71	0.02	0.18	0.71	0.63	−0.08	0.20
Sad	0.78	0.70	−0.08	0.04	0.78	0.68	−0.10	0.02
Mean	0.71	0.66	−0.05*	0.08	0.74	0.65	−0.09*	0.09

Note: LE: left ear; RE: right ear. A negative EA indicates a left ear advantage (LEA) and a positive EA indicates a right ear advantage (REA).

* Indicates a significant ear advantage, $P < 0.05$.

Table 2
Mean response times (in ms) for each ear and ear advantages (EA) for each target and response hand for Experiment 1

	Left hand			Right hand		
	LE	RE	EA	LE	RE	EA
Linguistic						
Bower	976	940	36*	1253	1079	175*
Dower	990	961	29	901	886	15
Power	906	967	−61	879	883	−4
Tower	852	843	9	1082	1006	76
Mean	931	928	3	1029	963	66*
Prosodic						
Angry	1063	1122	−59	975	1005	−30
Happy	996	1048	−52	1027	1173	−146*
Sad	1164	1099	65	1188	1186	2
Neutral	1162	1274	−112	1131	1225	−94
Mean	1096	1136	−40*	1080	1147	−67*

Note: LE: left ear; RE: right ear. A negative EA indicates a left ear advantage (LEA) and a positive EA indicates a right ear advantage (REA).
* Indicates a significant ear advantage, $P < 0.05$.

(Sex) × 2 (Order) mixed analysis of variance (ANOVA) with Task, Ear, and Hand as within-subject variables and Sex and Order as between-subject variables (see Fig. 1). There were no main effects or interactions involving order, and so they were removed from the analysis. A sex difference was observed such that women had higher hit rates than men on both tasks, $F(1, 30) = 5.39$, $P = 0.027$, however sex did not interact with other variables. A main effect of Task was also observed, $F(1, 30) = 6.43$, $P = 0.017$, reflecting higher hit rates for the prosodic task than for the linguistic task. Most importantly, a Task × Ear interaction was observed, $F(1, 30) = 26.05$, $P < 0.001$. As expected, a significant right ear advantage (REA) was observed for the linguistic task, $F(1, 30) = 16.54$, $P < 0.001$ and a significant left ear advantage (LEA) was observed for the prosodic task, $F(1, 30) = 6.01$, $P = 0.020$. There were no main effects or interactions involving response hand.

Effects of individual targets were analyzed in separate analyses for the linguistic and prosodic task in 4 (Target) × 2 (Ear) × 2 (Hand) repeated-measures ANOVAs. On the

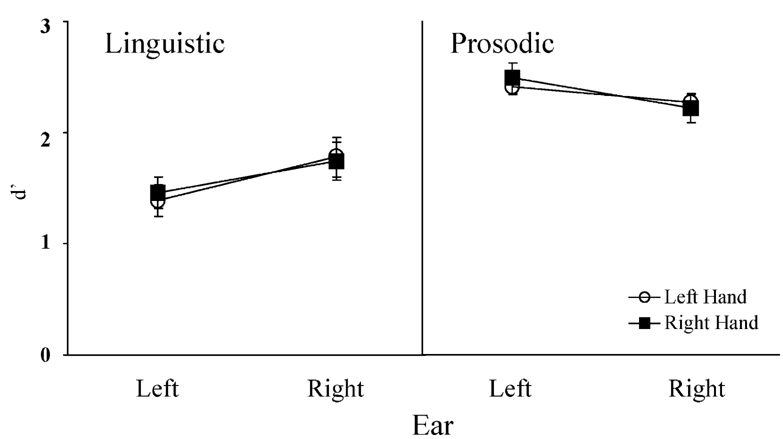

Fig. 1. d' values for detection of linguistic and prosodic targets as a function of ear and response hand.

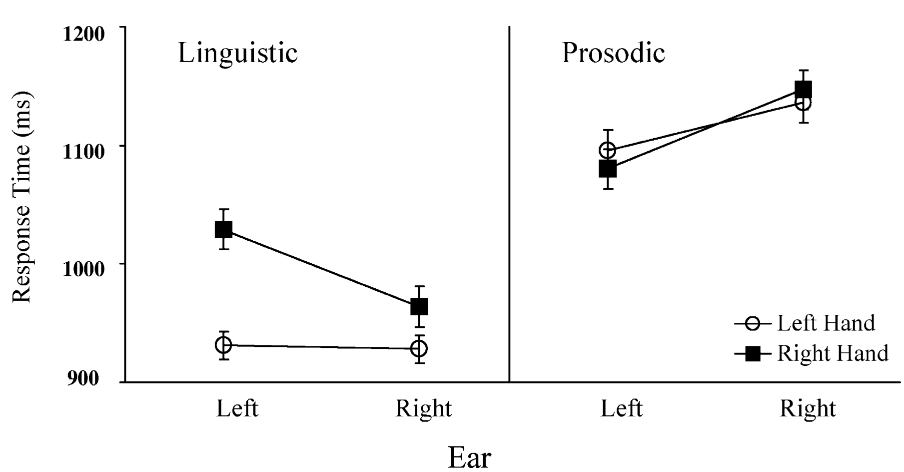

Fig. 2. RTs for detection of linguistic and prosodic targets as a function of ear and response hand.

linguistic task, main effects of Target, $F(1, 3) = 7.24$, $P = 0.001$ and Ear, $F(1, 28) = 22.44$, $P < 0.001$ were qualified by a Target × Ear interaction, $F(3, 28) = 4.24$, $P = 0.014$, such that the ear advantage was greatest for the target "bower". On the prosodic task, no main effects or interactions involving target were observed.

A similar analysis of d' values found parallel effects, except that the sex difference was not observed, $F < 1$. Therefore the sex difference in hit rate reflected a more liberal criterion in women, and not a sex difference in discrimination. Analysis of d' by target found results parallel to those in the hit rates on the linguistic task. On the prosodic task, there was a main effect of target, such that discriminability was best for the sad tone of voice, and worst for the neutral tone of voice, $F(3, 28) = 3.57$, $P = 0.026$.

2.2.2. RT analyses

Mean RTs for each condition were analyzed in a 2 (Task) × 2 (Ear) × 2 (Hand) × 2 (Sex) × 2 (Order) mixed ANOVA with Task, Ear, and Hand as within-subject variables and Sex and Order as between-subject variables (see Fig. 2). As there were no main effects or interactions involving order, it was eliminated from the analyses. Participants responded faster during the linguistic task than during the prosodic task, $F(1, 30) = 26.76$, $P < 0.001$. Although accuracy was higher on the prosodic task, this discrepancy likely does not reflect a speed-accuracy trade-off, as the linguistic judgment can be made on the basis of the first phoneme, but the prosodic judgment necessarily requires more information, and thus more time. Therefore response times on the two tasks are not necessarily comparable. Importantly, a Task × Ear interaction was observed, $F(1, 30) = 9.40$, $P = 0.005$, that mirrors the interaction in the accuracy data. An REA was obtained for the linguistic task, $F(1, 30) = 4.42$, $P = 0.044$ and an LEA for the prosodic task, $F(1, 30) = 5.76$, $P = 0.023$. Additionally, a trend toward an Ear × Task × Hand interaction was observed, $F(1, 30) = 3.82$, $P = 0.060$. Given the purpose of the study, the nature of this interaction was further explored. An Ear × Hand interaction was observed for the linguistic task, $F(1, 30) = 4.32$, $P = 0.046$, reflecting an REA that was attenuated when participants responded with their left hand (see Fig. 2), indicating direct access. No interaction between ear and hand was observed for the prosodic task, $F(1, 30) = 0.69$, $P = 0.413$, reflecting a callosal relay pattern.

Effects of individual linguistic and prosodic targets were analyzed for the linguistic and prosodic tasks separately in 4 (Target) × 2 (Hand) × 2 (Ear) repeated-measures ANOVAs. On the linguistic task, a Target × Ear interaction, $F(3, 28) = 3.69$, $P = 0.023$, reflected a greater REA for "bower" than for other targets. Notably, this effect did not interact with response hand, indicating that the direct access pattern observed in RT on the linguistic task is consistent across targets. On the prosodic task, no main effects or interactions involving target were observed.

In summary, the present study replicated the primary finding of an REA for linguistic processing and an LEA for the prosodic analysis. Although the analysis of accuracy data support a callosal relay explanation of both the REA and the LEA, the RT data indicate direct access for the linguistic task and callosal relay for the prosodic task. Because the inference of callosal relay relies on the lack of a statistically significant interaction, greater power is necessary to detect direct access than callosal relay. Zaidel et al. [43] have argued therefore that the presence of a hand by ear interaction in either the accuracy or the RT data is sufficient to infer direct access. Interestingly, Zaidel et al. report that the interaction is more often observed in the accuracy than in the RT data [43], although the opposite pattern was observed in the present study. From a mechanistic point of view, interactions in response time data are directly derived from the direct access model, but an interaction in accuracy requires the assumption of a degradation in accuracy with the relay of the motor command, and thus, a priori, interactions in RT should be more diagnostic of a direct access pattern.

The finding of a direct access pattern of processing on the linguistic task indicates that the right hemisphere is capable of and involved in linguistic comprehension, and raises some interesting questions. Evidence from split-brain patients has suggested that the REA in dichotic listening to nonsense CV syllables arises through callosal relay mechanisms (e.g. [25]). Two possible explanations for the discrepancy are proposed. First, it is possible that the right hemisphere has some competence in processing these stimuli because they are words, and not CVs. Clinical evidence supports the supposition that the right hemisphere may be better at semantic than phonological processing, and better at processing words than nonsense syllables. Specifically, it is possible that the right hemisphere has auditory word-form representations that can be used in speech perception. By this hypothesis, non-words (e.g. CVs) should not have similar right hemisphere representations. Therefore, direct access might be observed for these words, but should not be observed for linguistic (phonological) processing of non-words.

An alternative hypothesis is that the presence of affective prosody in these stimuli activated right hemisphere linguistic processing systems, leading to the direct access pattern observed. Thus right hemisphere arousal may activate right hemisphere linguistic processes, so that direct access would be observed in the presence of affective prosody, but not for words spoken in emotionally neutral tones of voice. Experiments 2 and 3 further explore these hypotheses.

3. Experiment 2

Experiment 2 was designed to test the hypothesis that the direct access pattern observed for linguistic processing in Experiment 1 was a result of the lexical/semantic nature of the stimuli. This experiment was a replication of Experiment 1, except that the stimuli were the nonsense words "baka", "paka", "taka", and "daka", spoken in tones of voice that were happy, angry, sad, and neutral. If the right hemisphere demonstrates competence for words, but not non-words, then a callosal relay pattern should be observed for linguistic processing. However, if the right hemisphere contribution does not depend on semantic or lexical factors, a direct access pattern like that of Experiment 1 should be observed. Because the goal of this study was to further explore the mechanism leading to the REA for linguistic processing, participants did only the linguistic task, and not the prosodic task.

3.1. Method

3.1.1. Participants

Sixty-four right-handed undergraduate students (38 women and 26 men) participated in exchange for course credit. All were native English speakers or reported learning English before the age of 5 years. None reported any hearing deficits. Handedness was assessed via the Waterloo Handedness questionnaire—Revised [13].

3.1.2. Apparatus and stimuli

The experiment was controlled by the PsyScope software package [11] on a Power Macintosh 8600/300 computer with a 17 in., 256-color display monitor and an Apple extended keyboard. All stimuli were presented auditorily through MDR-V600 Dynamic Stereo headphones with circumaural cushions. The experiment consisted of stimuli (non-words) locally produced using the SoundEdit 16 software package. These stimuli were spoken in a female voice and consisted of the non-words "baka", "paka", "taka", and "daka", each spoken in neutral, angry, happy, and sad tones of voice. The stimuli were edited such that each token included 30 ms of silence before the initial burst. Pilot testing confirmed that stimuli were equally discriminable and could be identified with 100% accuracy under untimed binaural conditions. These stimuli were presented using every possible pairing of non-words and tone of voice with the constraint that a different non-word and different tone of voice were presented to each ear on each trial. This method yielded a total of 144 stimulus pairs. These stimuli were divided into two blocks of 72 trials in which each non-word and each tone of voice were presented 18 times (nine times in the left ear and nine times in the right ear).

3.1.3. Procedure

Participants were individually seated at the computer with headphones on. They were given the target non-word at the beginning of each session, and were told to monitor that target for the entire experiment. Because "bower" had produced the most robust ear advantage in Experiment 1, "baka" was chosen as the target for all participants. This reduced the error variance associated with using different targets, and increased the power of the experiment to detect response hand interactions. The stimuli were presented dichotically. The target was pseudo-randomly presented to ensure that 25% of the time it was present in the left ear, 25% of the time it was present in the right ear and 50% of the time it was absent. Participants were required to indicate whether or not they had heard the target in either ear over four blocks of 72 trials, for a total of 288 trials. Response hand was alternated across blocks, with the index fingers indicating "present" with the *m* or *c* key, and the middle fingers indicating "absent" with the *k* or *d* key. Participants were instructed to respond as quickly and accurately as possible.

Experimental trials were preceded by 16 practice trials, during which the stimuli were presented binaurally. Headphone placement was counterbalanced across participants in order to control for mechanical effects. The experiment took approximately 15 min to complete.

3.2. Results and discussion

Hit rates, false alarm rates, d' values and RTs to correct trials were tabulated. Response time data were trimmed by eliminating outliers that exceeded three standard deviations from the participant's mean RT. Accuracy data were converted into d' values, based on the assumption of an equivalent false alarm rate for each ear. Data are presented in Fig. 3 (d') and Fig. 4 (RT).

3.2.1. Accuracy analyses

Hit rates were analyzed in a 2 (Ear) × 2 (Hand) × 2 (Sex) mixed ANOVA, with ear and hand as within-subject variables. Results indicated only a significant REA, $F(1, 62) = 41.58$, $P < 0.001$. Similarly, only an REA was observed in the d' analysis, $F(1, 62) = 37.97$, $P < 0.001$.

3.2.2. RT analyses

Five subjects were excluded from the RT analyses because they showed complete extinction of the left ear, and therefore had no left ear RT to be included in the analyses. For the remaining 59 subjects, results paralleled those in the accuracy analyses, revealing only a significant REA, $F(1, 57) = 62.12$, $P < 0.001$. Notably, the Hand × Ear interaction did not approach significance, $F(1, 57) = 0.13$, $P = 0.772$.

In summary, the non-word stimuli revealed a typical right ear advantage that was not modulated by response hand. This

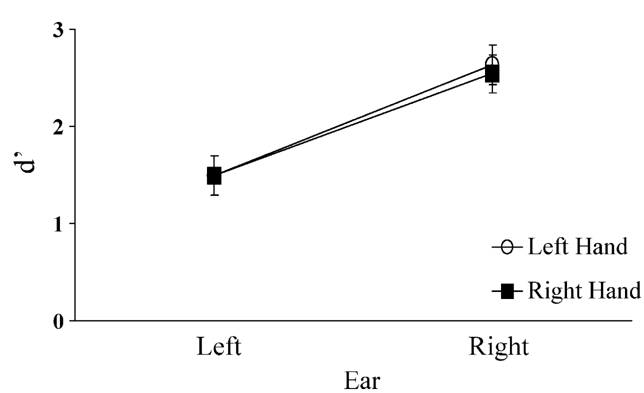

Fig. 3. d' values for detection of the non-word target "baka" as a function of ear and response hand.

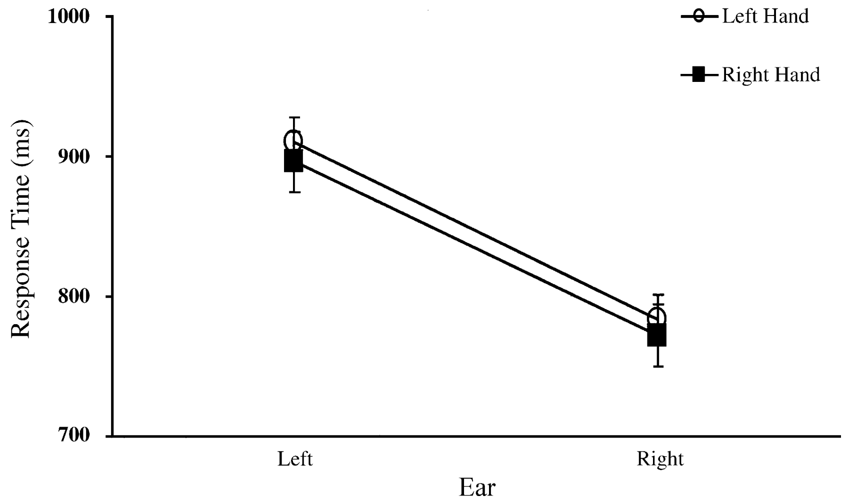

Fig. 4. RTs for detection of the non-word target “baka” as a function of ear and response hand.

finding supports the conclusion that linguistic processing in this condition was carried out through a callosal relay mechanism, and suggests that the presence of affective prosody itself cannot activate right hemisphere linguistic systems, at least for the nonsense words used in the present experiment. It is unlikely that the lack of an interaction reflects low power, as this experiment has greater power than Experiment 1, in which the interaction was observed. This finding is consistent with the hypothesis that one factor that led to the direct access pattern observed in Experiment 1 was the semantic nature of the stimuli.

4. Experiment 3

Experiment 2 suggests that the pattern of direct access for linguistic processing that was observed in Experiment 1 was the result of the semantic/lexical nature of the stimuli. However, the stimuli were also exceptional in that they were spoken in emotional tones of voice. Thus it is possible that the presence of affective prosody interacted with the semantic/lexical nature of the stimuli to facilitate right hemisphere processing. Experiment 3 tested the hypothesis that the affective prosody of the word stimuli activated the right hemisphere, leading to the direct access pattern. In the neutral prosody condition of this experiment, stimuli were the words from Experiment 1, spoken only in a neutral tone of voice. If the direct access pattern from Experiment 1 required the presence of affective prosody, then a callosal relay pattern should be observed in this condition. In the affective prosody condition, stimuli were spoken only in a sad tone of voice. If the right hemisphere is activated by the presence of affective prosody, then a direct access pattern should be observed in this condition. Specifically, a three-way (Hand $\times$ Ear $\times$ Condition) interaction was predicted, with the affective prosody condition producing a direct access pattern, and the neutral prosody condition producing a callosal relay pattern. If direct access results only because of the semantic/lexical nature of the stimuli, then direct access should be observed in both conditions.

4.1. Method

4.1.1. Participants

Sixty-four right-handed undergraduate students (38 women and 26 men) participated in exchange for course credit. These were the same participants from Experiment 2, and all participants completed Experiment 3 before Experiment 2. Half participated in the neutral prosody condition and half in the affective prosody condition. All were native English speakers or reported learning English before the age of 5 years. None reported any hearing deficits. Handedness was assessed with the Waterloo Handedness Questionnaire—Revised [13].

4.1.2. Apparatus and stimuli

The computer apparatus was the same as that used in Experiment 2. The stimuli were the words “bower”, “tower”, “dower” and “power” taken from Experiment 1, but consisted of only those tokens spoken in neutral and sad tones of voice. Two scripts were developed, one consisting only of neutral words and the other consisting only of sad words. Words were paired dichotically so that a different word was presented in each ear, yielding six possible pairings. These pairs were randomly repeated eight times each to produce blocks of 48 trials. Across trials, each stimulus was presented 25% of the time to the left ear, 25% of the time to the right ear, and was absent 50% of the time.

4.1.3. Procedures

Participants were seated at the computer with headphones on and given the target word at the beginning of the experiment. The target was always “bower”, which was chosen because it produced the most robust REA in Experiment 1.

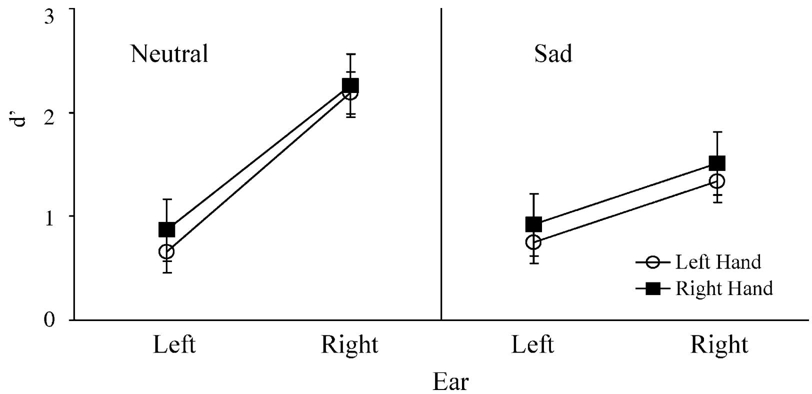

Fig. 5. d' values for detection of word "bower" spoken in neutral (left panel) or sad (right panel) tone of voice, as a function of ear and response hand.

The use of a single target should reduce the error variance associated with different targets and increase the power of the experiment to detect a response hand interaction. Participants were instructed to monitor for this target throughout the experiment, and indicate on each trial whether the target was present or absent. Participants completed two blocks with the left hand and two blocks with the right hand, for a total of 196 trials. Block order was counterbalanced across participants. They indicated that a target was present with the index fingers on the *m* or *c* key, and absent with the middle fingers on either the *k* or *d* key. Participants were required to respond as quickly and accurately as possible, and response times were recorded by the computer's internal timer. Headphone placement was counterbalanced across subjects in order to control for mechanical effects. Experimental trials were preceded by two blocks of 12 practice trials, one performed with each hand. Practice trials were repeated if necessary. The experiment took approximately 10 min to complete.

4.2. Results and discussion

Hit rates, false alarm rates, and mean RTs were calculated for each condition. d' values were calculated for each ear, based on the assumption of equivalent false alarm rates. RT data were trimmed by excluding all RTs greater than three standard deviations from the mean on an individual participant basis. Results are presented in Fig. 5 (d') and Fig. 6 (RT).

4.2.1. Accuracy analyses

Hit rates were analyzed in a 2 (Ear) × 2 (Hand) × 2 (Condition) × 2 (Sex) mixed ANOVA with Ear and Hand as within-subject variables, and Condition and Sex as between-subject variables. The omnibus ANOVA revealed an overall REA, $F(1, 60) = 43.57$, $P < 0.001$ and a main effect of condition, $F(1, 60) = 12.90$, $P = 0.001$, such that subjects were more accurate in the neutral than in the sad condition. However, these effects interacted, $F(1, 60) = 8.91$, $P = 0.004$. A robust REA was observed for the neutral condition, $F(1, 31) = 44.32$, $P < 0.001$, but this advantage was attenuated in the affective condition $F(1, 31) = 10.28$, $P = 0.003$. The attenuated REA in the affective condition is the result of both a decrease in right ear accuracy and an increase in left ear accuracy. This pattern is consistent with the hypothesis that the presence of affective prosody activated the right hemisphere.

All of the accuracy effects were also found in the d' analyses, indicating that they do not reflect differences in response bias. Again, there was an overall REA $F(1, 60) = 43.01$,

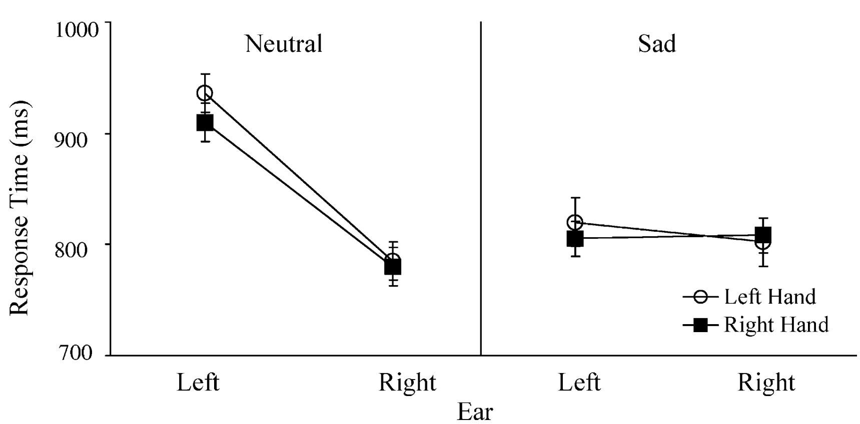

Fig. 6. RTs for detection of word "bower" spoken in neutral (left panel) or sad (right panel) tone of voice, as a function of ear and response hand.

$P < 0.001$ that was smaller in the affective prosody condition than in the neutral prosody condition.

4.2.2. RT analyses

Mean RTs were similarly analyzed in a 2 (Ear) × 2 (Hand) × 2 (Condition) × 2 (Sex) mixed ANOVA, with Ear and Hand as within-subject variables, and Condition and Sex as between-subject variables. Eight participants were eliminated from this analysis, as they demonstrated left ear extinction and thus had no left ear RT. Notably, these participants were all in the neutral prosody condition. Overall results were similar to those in the accuracy analyses. An REA was observed in the neutral prosody condition, $F(1, 22) = 13.47$, $P = 0.001$, but it was eliminated in the affective prosody condition, $F(1, 30) = 0.05$ (ns). This change in the REA reflected mainly a decrease in RT for left ear stimuli spoken in a sad tone of voice. This finding is consistent with the hypothesis that the presence of affective prosody activated the right hemisphere. An overall Hand × Ear interaction was observed that did not interact with Condition, $F(1, 52) = 4.81$, $P = 0.033$. The REA was slightly attenuated when responding with the right hand.

In summary, the most important finding from Experiment 3 is that the magnitude of the REA is affected by the affective prosody of the speaker's voice, even though the words themselves have no semantically affective dimension. In accuracy, the REA is attenuated when the words are spoken in a sad voice; in RT, the REA is eliminated. The implication of this finding is that the right hemisphere is capable of processing words as quickly as the left (but not quite as accurately) when those words are spoken in a sad tone voice. Hemispheric equivalence in the affective prosody condition points directly to a direct access pattern of processing.

A second finding is the Hand × Ear interaction that did not interact with Condition. The direction of the interaction in this experiment was opposite that found in Experiment 1, that is, the REA was attenuated with the right hand. Note that the prediction of a straight-forward direct access model is an REA that is attenuated with the left hand. Thus, although it is clear that the results do not indicate callosal relay, the interaction is difficult to interpret. One possibility is that the interactions are influenced by task difficulty. The predicted attenuation of the REA with the left hand is based on the assumption that within-hemisphere connections are shorter/faster than between hemisphere connections, and thus the right hemisphere has better access to the left hand than does the left hemisphere. However, when tasks become difficult, an advantage may arise for cross-hemisphere processing [3,42], thus there may be an advantage for housing linguistic processing and response preparation in opposite hemispheres, leading to an REA that is attenuated when responding with the right hand. Indeed, Zaidel et al. [43] have argued that a Hand × Ear interaction is diagnostic of direct access if the ear advantage is attenuated with either the ipsilateral or contralateral hand. Accuracy rates are indeed lower for Experiment 3 than for Experiment 1, as might be expected as the dichotic stimuli in Experiment 1 were presented in different tones of voice, but in Experiment 3 they were presented in the same tone of voice. However, responses were also faster for Experiment 3 than for Experiment 1, and so any interpretation based on task difficulty is made cautiously. As these experiments were run with different subjects by different experimenters in different semesters, it is not clear whether this pattern reflects a true speed-accuracy trade-off. A future experiment in which the same subjects participate in the conditions of Experiments 1 and 3, perhaps with a deadline procedure, will be necessary to fully elucidate the role of task difficulty in producing specific Hand × Ear interactions.

This interaction does not negate the primary finding, the attenuated (in accuracy) or eliminated (in RT) ear advantage in the affective prosody condition, in clear support of the direct access model. If one interprets the Hand × Ear interaction as support for the direct access model, Experiment 3 leads to the conclusion that dichotic word stimuli are processed by both hemispheres. When the words are spoken in a neutral tone of voice, the left hemisphere is superior to the right. However, when the words are spoken in a sad tone of voice, the two hemispheres are equivalent.

4.3. General discussion

Experiment 1 replicated the well-established finding of an REA for linguistic processing and an LEA for prosodic processing. However, the inclusion of a response hand manipulation allowed us to extend those findings and conclude that, for this particular task, linguistic processing occurred through a mechanism of direct access, and prosodic processing occurred through a mechanism of callosal relay. The finding of direct access on the linguistic task was unexpected, and reflects some right hemisphere competence for the task. Experiments 2 and 3 explored the factors that contributed to right hemisphere competence, and it appears that both the semantic nature of the stimuli and the presence of affect in the speech signal are important factors. Callosal relay was observed for non-words spoken in different emotional tones of voice (Experiment 2), indicating that the presence of affect alone is not enough to enable the right hemisphere to engage in linguistic processing. A direct access pattern was observed for words spoken in a sad tone of voice—in fact the hemispheres were equivalent in this condition (Experiment 3). The mechanism for processing words spoken in a neutral tone of voice is still equivocal on the basis of this data, given the unexpected nature of the response hand interaction. However, it is clear that hemispheric contributions to word processing are modulated by affective prosody.

It appears then that the specific mechanism leading to the ear advantage in a dichotic listening task depends on a number of factors. Although there is a tendency in the literature to speak of direct access and callosal relay "tasks", it seems unlikely (although of course possible) that a gatekeeping mechanism opens and closes the corpus callosum depending on the nature of the stimuli or the task. A more parsimonious explanation is a horse race model, first proposed by Umilta et al. [40] to explain visual field effects in face perception. Let us first consider a process for which the left hemisphere is superior to the right, although both hemispheres have some level of competence. The left ear stimulus is first projected to the right hemisphere, and then relayed to the left. Both hemispheres process the stimulus. The right hemisphere is handicapped because it is less efficient than the left. The left hemisphere is handicapped because it received the stimulus after the delay of interhemispheric transfer time. When the right hemisphere wins, a direct access pattern will be observed. When the left hemisphere wins, a callosal relay pattern will be observed. The actual winner may vary on a trial by trial basis, with a particular pattern emerging over the course of an experiment only if one is the predominant winner.

In the present study it appears that two factors that facilitate the right hemisphere are lexicality and the presence of affective prosody. It is of course impossible to say that the right hemisphere *cannot* process non-words. However in the present experiments evidence was observed for right hemisphere processing of words, but not non-words. Furthermore, words were only processed by the right hemisphere when they were spoken in emotional tones of voice, suggesting that the presence of affective prosody activated right hemisphere language areas, possibly activating auditory word-form representations. When the stimuli were non-words, the presence of affective prosody alone was not sufficient, because the right hemisphere has no representations for non-words.

Support for the horse race model also comes from imaging studies. Although patient data suggest strong lateralization of a number of cognitive functions, imaging studies of normal subjects indicate that bilateral activation is the norm. For example, O'Leary et al. [30] used PET to examine regional cerebral bloodflow (rCBF) during auditory tasks involving detection of binaurally presented words and environmental sounds. They found equivalent bilateral activation of superior temporal gyrus (STG) for both tasks. On a dichotic CV task, an attentional manipulation produced asymmetric activation, with attend-right instructions producing greater left than right hemisphere activation, and attend-left instructions producing greater right than left hemisphere activation. Unfortunately, O'Leary et al. did not include a dichotic CV task without attentional instructions, so it is not possible to know if dichotic CVs produce asymmetric activation on their own. However, Hugdahl et al. [19] did examine brain activation in response to dichotic stimuli in a PET study, and found bilateral activation in superior temporal gyrus, with greater right than left activation for dichotic CVs and greater left than right activation for dichotic musical passages. Thus the neuroimaging data supports the position that hemispheric specialization for linguistic processing is relative and not absolute.

More relevant to the current study, Buchanan et al. [8] recently used the same stimuli we used here in an fMRI study. They found significant bilateral activity in superior temporal gyrus and inferior and middle frontal gyrus, for both linguistic and prosodic tasks. When auditory cortex was specifically examined, the prosodic task produced greater right than left activation of anterior auditory cortex, and both the linguistic and prosodic tasks produced greater right than left activation of posterior auditory cortex. Thus, even with the linguistic task, significant right temporal activity was produced with these stimuli. Task specific hemispheric effects were observed mainly in frontal cortex, with left inferior frontal cortex activation for the linguistic task and right inferior frontal cortex activation for the prosodic task. These activations may have been associated with directing attention to a particular dimension, or with response selection.

From the design of the present study, it is not possible to conclude whether it is prosody per se or affect itself that activated the right hemisphere, as both hypotheses could be supported. For example, Ivry and Roberston [20] have argued that the right hemisphere is specialized for prosody because the prosodic dimension of speech relies more heavily on low spectral frequencies. This hypothesis is a variation of Sergent's [32] spatial frequency hypothesis, which posits that the left hemisphere is specialized for high spatial frequencies and the right hemisphere is specialized for low spatial frequencies. Along similar lines, prosodic identification requires the summation of information over a long time window, whereas linguistic identification requires analysis of rapid transitions; thus the hemispheric differences may reflect processing differences in low versus high temporal frequencies (e.g. [5,29]). Of course, all speech stimuli, even those spoken in neutral tones of voice, have prosody, and should engage prosodic processing. It is possible, however, that the continually changing patterns of prosody in Experiment 1 or the atypically sad prosody of Experiment 3 may have enhanced the activation of prosodic processing areas. If right hemispheric activation results from prosodic activity, then similar results should be observed for stimuli that vary in non-affective prosody, for example, in linguistic prosody or in regional accent.

Alternatively, it may be the affective component of the prosody that is activating the right hemisphere. Although data on hemispheric specialization for linguistic prosody are equivocal, right hemisphere specialization for affective prosody seems to be robust, suggesting that the emotional component of the prosodic dimension may be important. Recent findings support the hypothesis that affective stimuli or manipulations activate the right hemisphere. Asbjornsen et al. [1] manipulated participants' arousal levels while performing a dichotic listening task with CV stimuli, and found that negative arousal (threat of electric shock) abolished the REA. In the visual modality, evidence comes from Van Strien and Boon [41] who found that listening to effectively negative music abolished the right visual field advantage (RVFA) observed in lexical decision. Similarly Compton et al. [12], using an interference paradigm, found that threatening words were read as effectively by the left and right hemispheres (that is, they interfered equally with color-naming) when they were present in high proportion. The authors interpret this effect as a reflection of right hemisphere priming that built up through continuing exposure to threatening information. In an fMRI study, Lane et al. [22] found that pictures of both positively and negatively arousing stimuli produced activation in right anterior temporal cortex. In the context of the present study, the presence of affective prosody may have activated right hemisphere language processing areas sufficiently to produce the direct access pattern in Experiment 1; the presence of only sad prosody in Experiment 3 may have produced enough right hemisphere activation to abolish the REA entirely. Affective prosody might activate the right hemisphere directly, or it may induce a mood state in the participant, that then produces right hemisphere activation. Unfortunately, we do not have mood scale ratings on participants in this set of studies, and so this question awaits further study.

Increasing evidence suggests that affective factors, both as properties of stimuli and properties of individuals, may have meaningful influences on hemispheric specialization and on many aspects of cognitive processing. Although affect and cognition have traditionally been seen as independent factors, and have been studied by different scientists with different methods, it is clear that any real understanding of the mechanisms of cognition will come from an integration of cognitive and affective science.

In the 30 years that psychologists have been examining perceptual asymmetries, they have often been found to be unreliable and subject to variability due to a host of parameters, including stimulus size, stimulus duration, imageability, luminance, lexicality, spatial frequency, emotionality, task demands, menstrual stage, mood state, and time of day, to name just a few. Laterality effects are thus seen as “temperamental”, and perhaps not reflective of some underlying basic difference in hemispheric processing. The advantage of the dynamic model of hemispheric specialization is that it predicts that laterality effects will indeed be influenced by stimulus, task, and subject variables, to the extent that those variables affect the left and right hemispheres differently. With the model, it is possible to make specific predictions about how procedural and subject variables should influence asymmetries, and variability becomes not a nuisance, but a clue to the dynamic nature of hemispheric specialization itself.

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