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Perceptual Asymmetries Reflect Developmental Changes in the Neuropsychological Mechanisms of Emotion Recognition

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To study how perceptual asymmetries in the recognition of emotion reflect developmental changes in processing affective information, a fused rhyming dichotic word test with positive, negative, and neutral stimuli was administered to adults and children. Results suggested that the hemisphere in which affective information is initially processed affects the strength of perceptual asymmetry and that children's perceptual processing of emotional information is constrained by limited computational resources. Another experiment ruled out effects of volitional shifting of attention to emotional stimuli. These data further confirm that emotional processing involves integration of neural systems across brain regions, including distributed systems that support arousal and recognition. General developmental factors, such as processing capacity, contribute to the coordination of multiple systems responsible for processing emotional information.

Neuropsychological models of emotion information processing have emphasized four aspects of emotional functioning: expression (how individuals communicate what they are feeling to others), subjective experience (what it is that the individual feels), perception–recognition (how individuals recognize and encode emotional signals from others), and regulation (how individuals control and direct their behavior and feeling states while emotional signals are being communicated). Selective impairments in each of these aspects of emotional functioning have been associated with damage to different parts of the brain, suggesting that these functions may be supported by relative involvement of different neural systems. However, it is also apparent that adaptive social functioning requires these emotional functions to interact and cohere. Therefore, a challenge in understanding the neuropsychology of emotion is to avoid attributing specific emotional qualities to particular areas of the brain, but to try and understand emotional processes in terms of relative activation of various neural systems with reference to each other. Of continued interest are questions regarding how these different processes become integrated when an individual is presented with emotional material, how these emotional processes operate conjointly with other aspects of cognition, and the developmental mechanisms through which these systems organize. In the present article, we first introduce a theoretical model to help further understand one aspect of auditory emotion perception. Our particular interest is understanding the influence of developmental changes in cognitive structures on how emotional information is processed. Next, we present an initial set of studies to test some of the predictions that follow from this proposed integrative model.

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Parietal and Anterior Systems Associated With Emotion Recognition

The right-hemisphere parietotemporal system appears to be involved in the evaluation of emotional material. This function appears to be primarily oriented toward the arousal triggered by emotional stimuli (Borod, Andelman, Obler, Tweedy, & Welkowitz, 1992). Support for this system is drawn primarily from findings that patients with right-hemisphere posterior lesions display an impaired ability to comprehend emotional tone of voice (Tucker, 1981; Tucker, Watson, & Heilman, 1977), recognize facial expressions, and name emotional scenes (DeKosky, Heilman, Bowers, & Valenstein, 1980). Patients with damage to right parietotemporal regions also find it difficult to match emotional expressions or group emotional scenes with pictures of faces (Etcoff, 1984). Interestingly, although patients with damage to the right hemisphere are observed to have difficulty recognizing affective signals, they do not seem to show a loss of ability to verbally or facially express emotions (Borod, Koff, Lorch, & Nichols, 1986; Ross, 1981; Ross & Mesulam, 1979). It appears that recognition of emotion can also be distinguished from understanding of emotion. As an example, patients with right-hemisphere damage were unable to discern the emotional meaning of facial, vocal, and gestural expressions of emotion; however, these same patients were able to judge the appropriate affect when the emotional situations were described to them (Blonder, Bowers, & Heilman, 1991). One report indicated that patients with right-hemisphere damage were impaired in reading affective signals but viewed themselves as experiencing emotion as intensely as do both patients with left-hemisphere damage and normal controls (Cimino, Verfaellie, Bowers, & Heilman, 1991).

One hypothesis maintains that the right hemisphere not only monitors for the presence of arousing stimuli but also modulates arousal during emotion processing (Heller, 1993). Consistent with behavioral studies, patients with right- but not left-hemisphere damage fail to show heightened autonomic responsivity to affective scenes, even when they can rate the affective contents of those scenes (Schrandt, Tranel, & Damasio, 1989). This suggestion is consistent with the role of the right parietotemporal region in regulating elementary attentional-orienting processes. In Heller's (1993) view, it is not that arousal monitoring and arousal modulation are the same function, but that whatever mechanisms allow the right hemisphere to control elementary attentional processes may also be relevant to recruiting elementary affective responses to the appropriate stimuli (Heller, 1993). In short, it appears that emotional stimuli trigger the activation of this right-hemisphere system, which at the very least subserves functional integration of spatial attention and arousal modulation. Taken together, these reports suggest that the systems supporting the recognition of affect are distinct from those that support the expression, experience, and understanding of affective signals. More specifically, it appears that the parietotemporal region of the right, but not the left, hemisphere is implicated in the recognition of affective signals by means of arousal in response to affective stimuli.

Another hypothesis maintains that the right hemisphere is specialized for all emotion detection, regardless of valence (e.g., Borod et al., 1992, 1993; Bowers, Bauer, & Heilman, 1993; Buck, 1984; Heilman & Bowers, 1990). In this view, dissociation among emotional functions that are affected by brain lesions suggests a general-purpose affective system involved in the communication, comprehension, and expression of all emotions as represented within the right hemisphere (Borod, 1993). However, a variety of evidence has been amassed indicating that a valence-based system differentially involves the anterior portions of the right and left hemispheres in the *experience*, as opposed to the *recognition*, of affect (Davidson, 1984, 1992; Davidson, Mednick, Moss, & Saron, 1987; Kinsbourne, 1978; Silberman & Weingartner, 1986). For example, Gainotti (1972) described emotional differences between patients with right-hemisphere damage, who tended to display cheerful, euphoric emotions, versus patients with left-hemisphere damage, who were distressed and sad. Robinson et al. (Robinson, Kubos, Starr, Rao, & Price, 1984) have reported that clinical depression is more common after left-hemisphere damage than right-hemisphere damage—particularly when the lesion is in the anterior part of the frontal cortex. Further support for this position includes reports that higher relative electroencephalographic (EEG) activation over left frontal regions is associated with cheerful emotional states, whereas higher relative activation over right frontal regions is apparent during depressed emotional states (Davidson, 1992, 1995). In addition, EEG asymmetries in the frontal, but not the parietal, regions have been shown to predict individual affective responses to emotion elicitors (Tomarken, Davidson, & Henriques, 1990). Taken together, these reports suggest that the anterior systems supporting affective valence are distinct from the parietal systems that support the recognition and monitoring of affective signals.

Interhemispheric Processing

One approach to exploring processing between hemispheres has been through the dichotic listening

(DL) technique, wherein two different channels of information are presented simultaneously to each ear. In this procedure, auditory information is carried to both the right and left hemispheres via contralateral pathways, which are crossed connections between the right ear (RE) and the left hemisphere (LH) and between the left ear (LE) and the right hemisphere (RH). Ipsilateral pathways also carry some information from the RE to the RH and from the LE to the LH. Two constraints of the auditory perceptual system make this technique useful for highlighting neural pathways. First, the neural architecture of the sensory system prevents participants from analyzing simultaneously all of the information presented to them. Second, the contralateral neural connections are stronger and more efficient than the ipsilateral connections. Thus, differential activation of each hemisphere may be inferred on the basis of whether the participant reports hearing the message played to their left or right ear (Kimura, 1961). For example, normal right-handed adults and children are faster and more accurate in reporting linguistic information presented to their right ear because this information reaches the left-hemisphere language areas slightly more efficiently than a word presented simultaneously to the left ear (Bryden, 1988; Cohen & Merckelbach, 1987; Hellige, Bloch, & Taylor, 1988; Kimura, 1961; Wale & Carr, 1990). This effect is called a right-ear advantage (REA), and reflects a left-hemisphere perceptual asymmetry.

Although the DL technique was originally used to explore language processing, the methodology has also proved quite useful for the study of emotion-information processing. For example, when presented with word pairs made up of four different rhyming words (i.e., power, bower, dower, tower) spoken in a happy, sad, angry, and neutral tone of voice, normal right-handed participants tend to exhibit an REA when asked to recognize words, but a left-ear advantage (LEA) when asked to identify the emotional tone of the words, suggesting increased right-hemisphere activation (Bryden, Free, Gagne, & Groff, 1991). Another study required children to determine whether brief sentences presented to one ear matched a binaurally presented comparison sentence. When children were instructed to base their comparisons on the semantic content of the sentence, they displayed an REA, but when instructed to base their comparisons on the tone of voice in the sentence, the task yielded an LEA (Saxby & Bryden, 1984). These findings provide further evidence for a right-hemisphere advantage in the recognition of emotion and a left-hemisphere advantage for receptive language processing (Bryden et al., 1991).

In summary, a fundamental premise of the DL procedure is that asymmetric hemispheric activation is manifested by a contralateral-ear advantage (e.g., an activated left hemisphere results in a stronger right-ear advantage). The validity of the dichotic method was supported by a study of patients who also underwent intracarotid amytal evaluations. Patients with language localized in the left hemisphere identified verbal material better with the right ear than with the left ear, whereas the reverse was usually true for people with language localized in the right hemisphere (Zatorre, 1989). Of the 35 participants known to have left-hemisphere speech, 33 had an REA on the DL test (Zatorre, 1989). Importantly, although the ipsilateral pathways are viewed as weaker or less efficient—and are less well-understood—they, too, carry sensory information. Therefore, lack of a perceptual asymmetry may be interpreted as equivalent activation of both hemispheres.

The Present Studies

It is now commonly understood that the neural bases of nearly all human cognitive behavior depends on the conjoint functioning of neural systems, which are thought to differ at the level of the computations used to process many different types of information from the environment (Hellige, 1993; Jacobs, 1997). When a task favors the computational bias of one hemisphere or region within a hemisphere, performance asymmetries are likely to result; however, many seemingly anomalous findings have been reported. One principle that determines how information processing will be distributed across hemispheres concerns the computational complexity of the task. When computational complexity increases, there may be a profound advantage for recruiting the capabilities of both hemispheres (Banich, 1995; Banich & Belger, 1990). Hellige et al. (1988) and Banich (1995) have reported studies in which adult participants confronted with tasks that lead to processing overload in one hemisphere display an advantage for the hemisphere contralateral to the one being taxed. For example, in a consonant–vowel DL task, the left hemisphere perceptual asymmetry usually elicited was attenuated when adult participants were required to concurrently engage in a left-hemisphere-mediated verbal memory task, whereas right-hemisphere performance was unaffected by the manipulation (Hellige & Wong, 1983). Such findings suggest that because each cerebral hemisphere's information-processing capacity is limited, the activation of multiple specialized processes within one hemisphere may produce a processing advantage for the opposite hemisphere when processing loads are high or computationally complex (Banich, 1995; Hellige et al., 1988).

Similar computational limitations may also emerge in the processing of affective information. For example, Tucker, Stenslie, Roth, and Shearer (1981) noted a transient relationship between depressive affect and decreased processing capacity in the right hemisphere. In that report, Tucker et al. observed that right frontal alpha suppression (activation) in participants who were in a depressed mood was associated with poor attentional performance of the right hemisphere (Tucker et al., 1981). These data suggest that the frontal activity may have decreased right-hemisphere parietotemporal activity. Other reports have also suggested that depression is associated with both right-hemisphere anterior activation (increased negative affect) and right-hemisphere posterior suppression (impaired visuospatial functioning; Bruder et al., 1989; Henriques & Davidson, 1990). Across studies, there is compelling support for the view that computational load affects the processing workload between cerebral hemispheres.

The model presented in Figure 1 represents an attempt to synthesize the information reviewed previously. The figure schematically represents the distinction between the anterior-mediated processes of valence and the posterior-mediated process of arousal and valence monitoring in emotion recognition. This schematic reflects the assumption that the recognition of emotional stimuli will activate one's own emotional experience. We do not take the existence of these various systems as evidence that the left frontal region is specialized for positive emotion, or that the right frontal region is specialized for negative emotion. Rather, the suggestion is that certain emotional states are associated with the *relative* activation of these brain regions with reference to each other. Contralateral pathways through which auditory affective information may be communicated to and between these anterior and posterior systems are also shown in Figure 1, depending on the emotional valence of the dichotically presented stimulus and the ear–hemisphere to which the stimuli are presented. Because these pathways are predicted to be the most efficient, the hemisphere to which the arrow in Figure 1 is

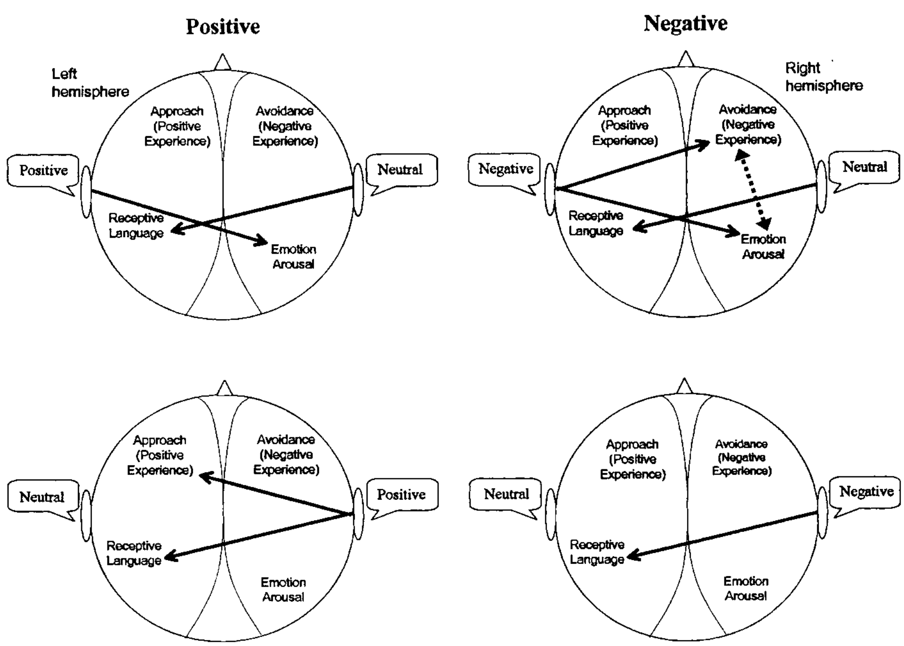

Figure 1. Schematic of contralateral pathways involved in the affective dichotic listening task by condition. Note that the condition in which negative stimuli are directed to the left ear is the only case in which two *affective* processes are initially activated within the same hemisphere. Solid arrows represent contralateral pathways. Dashed arrows represent the intrahemispheric pathway.

directed is expected to become more activated, resulting in a perceptual asymmetry (Table 1). A dashed arrow represents communication of information between two affective processing systems, activated within the same hemisphere; we did not predict similar effects when affective and nonaffective processes were activated in the same hemisphere. Arrows in Figure 1 are provided only as heuristics and are not meant to imply direct or exclusive neural connections.

Our interest is in how the right hemisphere parietotemporal and the right- and left-hemisphere anterior emotion systems may influence each other. And it is here that a developmental perspective on this problem may be particularly illuminating. Although modular approaches to cognition have been generally helpful in facilitating the identification and definition of mental operations, including emotion processing, the modularity heuristic may not be well-suited to putting these operations back together again. Relatively little is understood about how multiple cognitive, perceptual, and emotional systems or processes operate in relation to each other. The purpose of the present study is to examine this model first in mature, adult systems and then in the developing cognitive systems of younger children.

The predictions for Experiment 1 are summarized

Table 1
Predicted Perceptual Asymmetries for Children and Adults

Dichotic condition	Effect of contralateral pathway on LH	Effect of contralateral pathway on RH	Predicted resulting relative hemispheric activation
Neutral stimuli to LE/RH Neutral stimuli to RE/LH	Neutral RE stimulus word activates temporal receptive language processing system		Adults (Experiment 1): Increased relative activation of LH reflected in REA Children (Experiment 2): Increased relative activation of LH reflected in REA
Negative stimuli to LE/RH Neutral stimuli to RE/LH	Neutral RE stimulus word activates temporal receptive language processing system	Negative LE stimulus activates parietotemporal emotion arousal system Negative LE stimulus activates anterior affective experience system	Adults (Experiment 1): Activation of both hemispheres reflected in no perceptual asymmetry Children (Experiment 2): Simultaneous activation of multiple affective processes within RH confers processing advantage to LH, reflected in REA
Negative stimuli to RE/LH Neutral stimuli to LE/RH	Negative RE stimulus word activates temporal receptive language processing system		Adults (Experiment 1): Increased relative activation of LH reflected in REA Children (Experiment 2): Increased relative activation of LH reflected in REA
Positive stimuli to LE/RH Neutral stimuli to RE/LH	Neutral RE stimulus word activates temporal receptive language processing system	Positive LE stimulus activates parietotemporal emotion arousal system	Adults (Experiment 1): Activation of both hemispheres reflected in no perceptual asymmetry Children (Experiment 2): Activation of both hemispheres reflected in no perceptual asymmetry
Positive stimuli to RE/LH Neutral stimuli to LE/RH	Positive RE stimulus word activates temporal receptive language processing system Positive RE stimulus activates anterior affective experience system		Adults (Experiment 1): Increased relative activation of LH reflected in REA Children (Experiment 2): Increased relative activation of LH reflected in REA

Note. LH = left hemisphere; RH = right hemisphere; LE = left ear; RE = right ear; REA = right-ear advantage.

in Table 1. The basic premise for each of these predictions follows from what is known about perceptual asymmetries for receptive language and emotion recognition. Namely, the hemisphere in which affective information is initially processed is expected to affect the strength of the perceptual asymmetry, and the lack of a perceptual asymmetry is thought to reflect equivalent activation of both hemispheres. Because of the relative efficiency of the contralateral pathways, presentation of emotionally valent words to the left ear–right hemisphere is expected to activate the right-hemisphere arousal monitoring system, resulting in an REA. The concurrent activation of the emotion system in the right hemisphere and the receptive language system in the left hemisphere should result in equivalent activation of both hemispheres and no perceptual asymmetry should emerge. In contrast, when emotional stimuli are presented to the right ear–left hemisphere, the emotional information should be conveyed to the emotional arousal system via the ipsilateral pathways, which are less efficient than the contralateral pathways carrying the receptive language information, therefore, a right-ear perceptual asymmetry is expected. Because the task requires participants to listen to words, left-temporal receptive language activation is assumed to operate consistently across experimental conditions.

Experiment 1

Method

Participants. Participants were 18 (10 female) right-handed adults ranging in age from 18 to 54 (*M* = 23 years, 7 months, *SD* = 9 years, 4 months) years old. The Edinburgh Handedness Inventory (Oldfield, 1971) was used to determine handedness of the participants, all of whom also had two right-handed biological parents according to their report. All participants reported normal hearing and no history of neurological disorder or head trauma.

Stimuli. Fifty-eight undergraduates rated 171 words on a scale of 1 to 9 according to their emotional valence (1 = *positive/happy*, 5 = *neutral*, 9 = *negative/unhappy*). Words were chosen for use in the study based on mean emotional rating scores. The final set of positive words had ratings that ranged from 1.0 to 2.84 (*M* = 1.76, *SD* = 0.41); negative words had ratings between 6.74 and 9.0 (*M* = 7.86, *SD* = 0.98). Words retained in the neutral set had ratings ranging between 4.16 and 5.47 (*M* = 4.70, *SD* = 0.77). Fifty-six words (10 positive, 15 negative, 31 neutral) were used to form dichotic word pairs in the following categories: neutral–neutral, positive–neutral, and negative–neutral. The complete set of stimuli are listed in the Appendix.

Natural speech recordings of the words were spoken by an adult female and were digitized by using SoundEditPro software. Stimuli in each pair were matched on acoustic characteristics including intensity, amplitude variability, length of presentation, and speech contour. We used an important methodological improvement in the DL procedure by temporally aligning paired rhyming words and cross-splicing them so that they fused into a single auditory percept (Repp, 1977; Wexler & Hawles, 1983). These rhyming words are fused such that even when participants are explicitly informed of the nature of the stimuli, they are unable to reliably distinguish fused words from simple binaural presentations of a single stimulus. Words in each pair were also matched on emotionality ratings and frequency of occurrence in English (Kučera & Francis, 1967).

Procedure. The DL task consisted of three blocks of 15 trials each, resulting in 45 total trials. Each trial block consisted of three tokens each of five types of word pairs (presented as left ear–right ear input): positive–neutral, neutral–positive, negative–neutral, neutral–negative, and neutral–neutral. Positive, negative, and neutral words were equally presented to participants' left and right ears. Word pairs were randomized and not repeated within a trial block.

Participants listened to dichotic word pairs through high-resolution Optimus LV-20 headphones (Radio Shack, Forth Worth, TX) at a comfortable sound level of approximately 75 dB. Headphones were reversed after each trial block to minimize channel effects. An IBM PC computer equipped with an ELO Graphics (Touch Systems, Fremont, CA) touch-screen delivered stimuli and collected responses. Participants were not told about the dichotic nature of the stimuli and were instructed to indicate the word that they heard by touching with their dominant hand one of four words (representing the left-ear input, the right-ear input, and two rhyming foils) that appeared on the screen 50 ms after stimulus presentation. The placement of the response words on the computer screen was counterbalanced so that the left-ear input, right-ear input, and foils appeared equally at each quadrant of the computer screen. Participants were required to make a response for each trial. Each response was followed by a 2.5 s interstimulus interval.

Results and Discussion

The general prediction for this experiment is that the strength of perceptual hemispheric asymmetries will vary across the five experimental conditions as specified in Table 1. Raw performance data for the probability of participants' left- and right-ear responses are reported in Table 2. The difference in accuracy for the right and left ear (R – L) does not provide a good measure of perceptual asymmetry because this difference score is correlated with performance level (R + L). Therefore, the *f* index was calculated to provide a measure of perceptual asymmetry that is relatively free of psychometric artifact (Chapman & Chapman, 1988). This index is obtained as (R – L)/(R + L), where R = right-ear performance and L = left-ear performance. Positive or negative *f* values that significantly differ from zero reflect, respectively, right or left hemisphere perceptual asymmetries. An error score was calculated on the basis of the selection by participants of one of the two foil words rather than the left or right ear inputs.

To determine whether perceptual asymmetries varied as a function of stimulus condition, we computed a repeated measures analysis of variance (ANOVA) on *f* index scores. Emotion condition (left-ear input–right-ear input: neutral–neutral, negative–neutral, neutral–negative, positive–neutral, neutral–positive) was treated as a within-subject factor and participants' sex was used as a between-subject factor. For *F* tests involving repeated measures, the Greenhouse–Geiser correction was applied. This analysis revealed that the magnitude of perceptual asymmetries differed across emotion conditions, $F(4, 64) = 6.14$, $p < .001$.

The predictions presented in Table 1 were tested by examining whether the *f* index for each condition significantly differed from zero. In the neutral baseline condition, participants displayed an REA, $t(17) = 3.22$, $p < .05$. This increased left-hemisphere asymmetry is consistent with what would be expected of right-handed participants who performed a receptive language task. Left ear presentation of negative stimuli was expected to initially activate right-hemisphere anterior and parietotemporal processes as well as left-hemisphere receptive language processes, resulting in equivalent hemispheric activation. Consistent with this prediction, no perceptual asymmetry emerged when negative stimuli were presented to the left ear–right hemisphere, $t(17) < 1.00$, *ns*. In contrast, right ear–left hemisphere presentation of negative stimuli was expected to initially activate only receptive language processes. In this condition, receptive language areas would be served by more efficient contralateral pathways, whereas anterior affective areas would be served by slightly less efficient ipsilateral pathways. As expected, adults exhibited REAs when negative stimuli were presented to the right ear–left hemisphere, $t(17) = 2.56$, $p < .05$. We predicted that when participants were presented with positive stimuli to their left ear–right hemisphere, both left-hemisphere receptive language processes and right-hemisphere parietotemporal processes, which are both served by contralateral pathways, would become activated. The absence of a perceptual asymmetry in this condition, $t(17) < 1.00$, *ns*, is consistent with such symmetric arousal of both hemispheres. Finally, adults exhibited an REA when positive stimuli were presented to the right ear–left hemisphere, $t(17) = 4.87$, $p < .05$. This result is consistent with the expectation that right ear presentation of positive words would activate both left-hemisphere temporal receptive language and anterior affective experience processes.

Because the *f* index combines the probability of responses across both hemispheres, the probability of left- and right-ear responses across conditions allows for more specific examinations of the predictions advanced in Table 1. If the model presented in Figure 1 is correct, the probability of right ear responses should increase from baseline only when positive stimuli are

Table 2
Means (and Standard Deviations) for Dichotic Listening Performance by Condition for Experiment 1

Condition	POR	POL	Error	*f* index
Neutral baseline	.53 $(.10)_{a,b}$	.41 $(.08)_{a,b}$	.06 $(.08)_{a,b}$	.11 $(.15)_{a,b}$
Negative to LE/RH	.50 $(.12)_{c,d}$	.48 $(.12)_{c,d}$	.02 $(.04)_{a}$	.02 $(.24)_{c}$
Negative to RE/LH	.61 $(.13)_{a,c,e}$	.36 $(.13)_{c,e}$	.03 $(.05)_{c}$	.16 $(.27)_{d}$
Positive to LE/RH	.47 $(.13)_{e,f}$	.50 $(.15)_{a,e,f}$	.03 (.05)	−.03 $(.27)_{a,d,e}$
Positive to RE/LH	.67 $(.15)_{b,d,f}$	.32 $(.16)_{b,d,f}$	.01 $(.07)_{b,c}$	.36 $(.31)_{b,c,e}$

Note. POR = Percentage of right ear identifications; POL = Percentage of left ear identifications; LE = left ear; RE = right ear; LH = left hemisphere; RH = right hemisphere. Scores in the same column that share subscripts are significantly different according to planned protected contrasts ($df = 17$; $p < .05$, two-tailed).

presented to the right ear–left hemisphere. Similarly, the probability of participants' left-ear responses is expected to increase from baseline when both negative and positive stimulus words are presented to the left ear–right hemisphere. This pattern of results is shown in Table 2. There were no main effects or interactions involving sex of the participant.

An index of sensitivity to emotion was calculated to determine how often participants heard positive or negative stimuli by subtracting the number of neutral words heard from the number of positive (or negative) words heard and dividing the difference by the sum of the two. Across conditions, adult participants detected comparable proportions of negative (M = .14, SD = .15) and positive (M = .20, SD = .23) stimuli, $F(1, 16) = 1.09$, *ns*. This effect was not influenced by the sex of the participant, $F(1, 16) < 1.00$, *ns*.

These data suggest that changes in perceptual asymmetries are not only a function of the emotional content of the information being processed but also the hemispheric pathways used to process the information. As predicted by the model in Figure 1, adult participants displayed an REA in the neutral baseline condition and maintained this perceptual asymmetry when positive and negative stimuli were presented to their right ear–left hemisphere. However, when these same stimuli were directed to participants' left ear–right hemisphere, the REA was attenuated, suggesting comparable activation of both hemispheres.

Experiment 2

The results of Experiment 1 suggest that emotional valence affects patterns of information processing in adults. We were interested in possible changes that might occur in affective processing as a function of children's cognitive maturation. Because processing capacity is a prominent feature of cognitive development, one way to approach this issue is to draw on the capacity overload approach used by Banich (1995) and Hellige et al. (1988). One of the experimental conditions depicted in Figure 1 provided such an opportunity to compare adult and child DL performance. Specifically, presentation of negative stimuli to the left ear is expected to simultaneously activate both the anterior and posterior affective systems in the right hemisphere. If the model presented in Figure 1 is accurate, this is the only condition in which contralateral pathways activate both the anterior and posterior affective systems simultaneously within the same hemisphere. Although the demands of the present DL task are almost certainly insufficient to tax adult processing capacities, we reasoned that this presumed activation of multiple affective processes within one hemisphere may exceed the processing capacity of children. Adult performance in Experiment 1 suggested equivalent activation of the right and left hemispheres in this condition. However, we hypothesized that children would show a pattern of perceptual asymmetries opposite of adults in this same condition. In short, simultaneous activation of anterior and posterior affective processes within one hemisphere was predicted to produce a processing advantage for the opposite hemisphere, which would be reflected in decreased contralateral ear performance.

Method

Participants. Eighteen (11 female) right-handed 6–9-year-old (M = 8 years, 4 months, SD = 1 year, 3 months) children were recruited from a local elementary school. This represents the youngest age at which children could be expected to perform the experimental task with accuracy, comparable to that of adults. The Edinburgh Handedness Inventory (Oldfield, 1971) was used to determine handedness of the participants, all of whom also had two right-handed biological parents. Children were reported to have normal hearing and were free of head injury or neurological illness.

Procedure. Procedures were identical to those described in Experiment 1. An independent sample of 77 children ranging in age from 7.1 years to 9.3 years rated the 56 words used in Experiment 1 on a scale of 1 to 9 according to their emotional valence (1 = *positive/happy*, 5 = *neutral*, 9 = *negative/unhappy*). Children's ratings were very similar to those of adults: positive words ranged from 1.0 to 2.12 (M = 1.89, SD = 0.63), negative words had ratings between 7.12 and 9.0 (M = 7.29, SD = 0.77), neutral words had ratings ranging between 4.10 and 5.55 (M = 4.70, SD = 1.10).

Results and Discussion

To determine whether perceptual asymmetries varied as a function of stimulus condition, we computed a repeated measures ANOVA on f index scores. Emotion condition (left ear input–right ear input: neutral–neutral, negative–neutral, neutral–negative, positive–neutral, neutral–positive) was treated as a within-subject factor and participants' sex was used as a between-subject factor. For F tests involving repeated measures, the Greenhouse–Geiser correction was applied. This analysis revealed that the magnitude of perceptual asymmetries differed across emotion conditions, $F(4, 64) = 3.57$, $p < .05$.

The predictions presented in Table 1 were tested by examining whether the *f* index for each condition significantly differed from zero. In the neutral baseline condition, children displayed an REA, $t(17) = 3.69$, $p < .05$. This increased left-hemisphere asymmetry is consistent with what would be expected of right-handed participants who performed a receptive language task. Left ear presentation of negative stimuli was expected to initially activate right-hemisphere anterior and parietotemporal processes, as well as left-hemisphere receptive language processes. The activation of multiple affective processes within the right hemisphere was predicted to confer a processing advantage to the left hemisphere in children. Consistent with this prediction, and in contrast to adults, children showed an REA when negative stimuli were presented to the left ear–right hemisphere, $t(17) = 4.68$, $p < .05$. Right ear–left hemisphere presentation of negative stimuli was expected to initially activate only receptive language processes. Accordingly, children exhibited REAs when negative stimuli were presented to the right ear–left hemisphere, $t(17) = 1.99$, $p < .06$. Presenting positive stimuli to the left ear–right hemisphere, as predicted, resulted in the only condition in which children did not show a perceptual asymmetry, $t(17) = -1.35$, *ns*. However, children exhibited an REA when positive stimuli were presented to the right ear–left hemisphere, $t(17) = 2.20$, $p < .05$. This result is consistent with the expectation that right ear presentation of positive words would activate both left-hemisphere temporal receptive language and anterior affective experience processes. There were no main effects or interactions involving sex of the participant. Children's probabilities of left- and right-ear responses are shown in Table 3.

The sensitivity of children to positive and negative stimuli was calculated as described in Experiment 1. A score of zero suggests an equivalent probability of selecting a neutral or an emotionally valent word. This analysis revealed a marginal trend for children to detect fewer negative ($M = -.01$, $SD = .23$) as compared with positive ($M = .14$, $SD = .28$) stimuli, $F(1, 16) = 3.07$, $p < .09$. The tendency of children to miss negative stimuli may reflect limited processing capacity, which is consistent with the view that, for children, the presentation of negative stimuli to the left ear leads to processing overload in the right hemisphere. This effect was not influenced by the sex of the participant, $F(1, 16) = 3.43$, *ns*.

A 2 (adult, child) × 5 (condition) ANOVA revealed a significant interaction indicating that adult participants in Experiment 1 and child participants in Experiment 2 differed in their recognition of trials containing emotion words, $F(4, 128) = 4.483$, $p < .002$. Specifically, as predicted, the pattern of perceptual asymmetries for the groups of older and younger participants differed only when negative stimuli were presented to the left ear–right hemisphere, $F(1, 32) = 11.69$, $p < .05$. Groups did not differ in the other emotion conditions, all $Fs(1, 32) < 1.00$, *ns*. As shown in Figure 1, the experimental condition in which the two age groups differed was the one in which both anterior and posterior affective processes were initially activated within the same hemisphere. In children, increased activation of multiple affective processes in one hemisphere appears to have attenuated the left-hemisphere asymmetry. We hypothesized that the general developmental factor of processing capacity would influence the measurement of perceptual asymmetries for emotion in younger participants. Processing differences between adults and children are unlikely to be artifacts of general accuracy, as error rates and reaction times for both groups were equivalent across emotion conditions. If our hypothesis re-

Table 3
Means (and Standard Deviations) for Dichotic Listening Performance by Condition for Experiment 2

Condition	POR	POL	Error	*f* index
Neutral baseline	$.56\ (.14)_{a}$	$.33\ (.14)_{a}$	$.11\ (.08)_{a,b}$	$.25\ (.29)_{a}$
Negative to LE/RH	$.59\ (.12)_{b}$	$.35\ (.12)_{b}$	.06 (.09)	$.25\ (.23)_{b}$
Negative to RE/LH	$.56\ (.20)_{c}$	.42 (.18)	$.02\ (.04)_{a,c}$	$.12\ (.24)_{c}$
Positive to LE/RH	$.45\ (.14)_{a,b,c,d}$	$.47\ (.12)_{a,b}$	$.08\ (.07)_{c,d}$	$-.02\ (.12)_{a,b,c,d}$
Positive to RE/LH	$.59\ (.22)_{d}$	.39 (.21)	$.02\ (.05)_{b,d}$	$.20\ (.39)_{d}$

Note. POR = Percentage of right ear identifications; POL = Percentage of left ear identifications; LE = left ear; RE = right ear; LH = left hemisphere; RH = right hemisphere. Scores in the same column that share subscripts are significantly different according to planned protected contrasts ($df = 17$; $p < .05$, two-tailed).

garding processing capacity is correct, we would expect that the magnitude of the REA in response to negative stimuli presented to the left ear–right hemisphere should decrease with children's chronological age. Based on a median split of children's chronological age, younger children (M = .22) displayed a stronger REA in this condition than did older children (M = .17), $F(1, 17) = 7.59$, $p < .05$. This suggests that as children mature, their patterns of perceptual asymmetries begin to more closely approximate those of the adults.

Experiment 3

A potential confound to the perceptual asymmetry scores reported in Experiments 1 and 2 concerns the role of subject-initiated attentional factors. Right-handed individuals have a tendency to attend more to the right visual and auditory fields; therefore attentional strategies, rather than hemispheric activation, may contribute to the error variance associated with DL techniques (Hugdahl & Andersson, 1986; Mathieson, Sainsbury, & Fitzgerald, 1990). The use of fused rhyming stimuli was intended to attenuate the effects of volitional shifting of attention (cf. Asbjornsen & Bryden, 1996). However, the technique is not "attention-free" and it is unlikely that attentional effects are completely eliminated. Therefore, Experiment 3 was designed to examine whether the perceptual asymmetries elicited in Experiments 1 and 2 are artifacts of individual differences in attentional control. The present study adapted the DL procedure so that participants monitored and reported the information from only one ear at a time, allowing for experimental control of individual differences in selective attention (Obrzut, Boliek, & Bryden, 1997). If the patterns of perceptual asymmetries derived from these analyses differ from those obtained in Experiments 1 and 2, then we may conclude that the patterns elicited in the free-recall tasks are artifacts of attentional control. In contrast, similar patterns of results between these tasks would suggest either that attentional factors exert minimal influence on the measurement of perceptual asymmetries or that the perceptual characteristics of the fused stimuli sufficiently attenuated these influences.

Method

Participants. The sample consisted of 16 (8 female) right-handed adults, ranging in age from 18.0 to 23.0 years old (M = 19 years, 9 months, SD = 2 years, 0 months) and sixteen (10 female) right-handed children, ranging in age from 7.0 to 9.0 years old (M = 8 years, 6 months, SD = 7 months). None of these participants participated in either Experiments 1 or 2. The Edinburgh Handedness Inventory (Oldfield, 1971) was used to determine handedness of the participants, all of whom also had two right-handed biological parents.

Stimuli. Dichotic test stimuli were identical to those used in Experiment 1.

Procedure. Participants were tested individually in a quiet room. Each participant was seated in front of a computer monitor and fitted with Optimus LV-20 headphones. The DL task was similar to that described in Experiment 1, with the following exceptions. The task consisted of two blocks, with 20 trials in each block. Participants were instructed to listen to and report only the stimulus word presented to the left ear during the first trial block, and the right ear on the second trial block, or vice versa. A yellow cardboard circle was placed on the top left or top right corner of the computer monitor before each block to remind participants whether they were to monitor their left or right ear.

Results and Discussion

To adjust perceptual asymmetry scores for individual differences in attentional control, raw DL scores were used to calculate a parameter estimate, (λ) for each emotion condition. Lambda is the log-odds ratio of right-ear responses to left-ear responses and is not constrained by a participant's overall accuracy. Following Sprott and Bryden (1983) and Hellige, Block, and Taylor (1988), λ was adapted as:

$$\lambda = \log \{[DR_r(DI_r + DL_e)] + 1 / [DL_l(DR_l + DR_e)] + 1\}, \qquad (1)$$

where DR = direct–right condition, DL = direct–left condition, r = right-ear responses, and l = left-ear responses, and e = errors.

The results for the adult sample (presented in Table 4) mirrored those obtained in Experiment 1. The magnitude of perceptual asymmetries differed across emotion conditions, $F(4, 48) = 2.93$, $p < .05$. Specifically, adults displayed an REA in the neutral condition, $t(15) = 2.26$, $p < .05$, and when either positive, $t(15) = 2.38$, $p < .05$, or negative, $t(15) = 2.49$, $p < .05$, stimuli were presented to the right ear–left hemisphere. However, adults' asymmetry scores were attenuated when these same positive, $t(15) < 1.00$, *ns*, or negative, $t(15) < 1.00$, *ns*, stimuli were presented to the left ear–right hemisphere. There were no main

Table 4
Means (and Standard Deviations) of Performance Data by Directed Attention and Listening Conditions for Experiment 3

	POR		POL		Errors		
Listening condition	DR	DL	DR	DL	DR	DL	λ
Neutral baseline							
Children	.55 (.26)	.55 (.21)	.44 (.25)	.33 (.20)	.02 (.06)	.14 (.18)	.36 (.49)
Adults	.64 (.29)	.45 (.28)	.31 (.25)	.48 (.30)	.05 (.10)	.06 (.14)	.29 (.32)
Negative to LE/RH							
Children	.56 (.27)	.55 (.25)	.36 (.24)	.38 (.22)	.08 (.12)	.08 (.15)	.48 (.45)
Adults	.64 (.30)	.39 (.24)	.30 (.26)	.58 (.25)	.06 (.11)	.03 (.09)	.14 (.60)
Negative to RE/LH							
Children	.55 (.26)	.48 (.21)	.41 (.24)	.44 (.27)	.05 (.10)	.08 (.12)	.33 (.44)
Adults	.64 (.26)	.50 (.29)	.34 (.26)	.45 (.26)	.02 (.06)	.05 (.10)	.32 (.51)
Positive to LE/RH							
Children	.50 (.29)	.39 (.27)	.44 (.27)	.48 (.25)	.06 (.11)	.13 (.18)	.02 (.42)
Adults	.59 (.24)	.28 (.26)	.36 (.24)	.67 (.31)	.05 (.10)	.05 (.14)	−.11 (.54)
Positive to RE/LH							
Children	.45 (.34)	.38 (.29)	.45 (.33)	.50 (.33)	.09 (.15)	.13 (.16)	−.11 (.65)
Adults	.67 (.22)	.41 (.27)	.30 (.21)	.56 (.27)	.03 (.09)	.03 (.09)	.30 (.50)

Note. POR = Percentage of right ear identifications; POL = percentage of left ear identifications; DR = directed right condition; DL = directed left condition; LE = left ear; RH = right hemisphere; RE = right ear; LH = left hemisphere.

effects or interactions involving the participants' sex, or the order in which participants attended to either their right or left ear. Because directed-recall studies experimentally control for volitional shifting of attention (Hiscock & Decter, 1988; Obrzut et al., 1997), the present results suggest that selective attention alone does not appear to account for patterns of perceptual asymmetries observed in adults.

As expected, mean λ values for children (see Table 4) differed across emotion conditions, $F(4, 48) = 3.87$, $p < .05$. This interaction reflected that children displayed REAs in the neutral baseline condition, $t(15) = 2.87$, $p < .05$, and when negative stimuli were presented to either the left ear–right hemisphere, $t(15) = 4.16$, $p < .01$, or the right ear–left hemisphere, $t(15) = 2.96$, $p < .01$. Children's asymmetry scores were attenuated when positive stimuli were presented to either the left ear–right hemisphere, $t(15) < 1.00$, *ns*, or right ear–left hemisphere, $t(15) < 1.00$, *ns*. There were no main effects or interactions involving the participants' sex, or the order in which participants attended to either their right or left ear.

Two aspects of the results obtained from children in this selective attention task are noteworthy. The first pertains to our main hypothesis regarding the role of computational capacity in children's processing of emotional information. Even after we controlled for attentional factors, younger participants maintained the pattern of perceptual asymmetry observed in Experiment 2, supporting the prediction of an increased left-hemisphere perceptual asymmetry when negative stimuli were presented to the left ear–right hemisphere. This pattern is opposite that displayed by adults in Experiments 1 and 3, lending support to the hypothesis that activation of multiple affective processes within one hemisphere exceeds the computational capacity of that hemisphere in less mature participants.

A second, unexpected finding among the child sample involved the presentation of positive stimuli to the right ear–left hemisphere. The free-recall task used in Experiment 2 resulted in a left-hemisphere perceptual advantage for children. However, results from the selective listening task used in Experiment 3 did not reveal an ear advantage for the same stimuli, which likely indicates symmetric activation of both hemispheres. This shift represents the only change observed in either the adult or child samples between the free-recall and the selective-listening tasks. The role of attention in children's recognition of emotion certainly requires further experimental examination. The finding of increased left-hemisphere activation in response to positive stimuli is consistent with the tendency of children to detect more positive as compared with negative stimulus words in Experiment 2. It seems likely that the functions of attention and emotion are tightly linked because one purported function of emotion is to help the individual respond to changing environmental demands. As noted by Heller (1990) and others, one aspect of right-hemisphere functioning may include a system that directs attention to salient environmental events. Although not specifically linked to emotion processing, the role of the right hemisphere in distributing spatial attention to both sides of space has been well-documented (Heilman & Van den Abell, 1979; Pardo, Fox, & Raichle, 1991).

Conclusions

The theoretical formulation presented in this article is an attempt to combine what is known about interhemispheric processing of auditory information to better understand developmental changes in the processing of affective information. In this manner, the schematic presented in Figure 1 is meant to be taken only as a summary of research findings by using different hypotheses, methods, and populations. The motivation for the present set of studies was to begin to explore some of the developmental changes that occur in emotional functioning between less and more mature individuals. Our hypothesis was guided by the view that general cognitive limitations, such as processing capacity, may help explain developmental changes between adults and children in emotion processing.

We first tested the premise that the hemisphere in which affective information is initially processed, via more efficient contralateral pathways, will be reflected in the strength of an individual's perceptual asymmetry. Experiment 1 confirmed this prediction. Next, we hypothesized that children's perceptual processing of emotional information would be constrained by a general limitation in developing cognitive systems, namely, the capacity of computational resources. To begin to examine this idea, we tested young children in a task identical to that used with adults. This approach was based on the well-replicated finding with adults, that taxing the processing capacity of one hemisphere results in a contralateral hemispheric advantage. We reasoned that if each cerebral hemisphere's affective information-processing capacity is limited by developmental constraints, the activation of multiple affective processes within one hemisphere would produce a processing advantage for the opposite hemisphere in less mature participants. Experiment 2 yielded data consistent with this interpretation. During the experimental condition presumed to concurrently activate both anterior and parietotemporal affective processes within the same hemisphere, children displayed a decrease, rather than an increase, in that hemisphere's computational advantage.

One methodological concern with the technique used in Experiments 1 and 2 is the extent to which the fused perceptual characteristics of the stimuli sufficiently controlled for subject-initiated attentional factors, a source of error variance associated with DL techniques (Asbjornsen & Bryden, 1996; Hugdahl & Andersson, 1986; Mathieson et al., 1990). A third experiment used the same stimuli as those in Experiments 1 and 2, but required both adult and child participants to monitor and report the information from only one ear at a time. These data support the conclusion that the patterns of perceptual asymmetries obtained in Experiments 1 and 2 are not artifacts of individual differences in attentional control. However, an unexpected finding emerged from Experiment 3 that warrants further investigation. Children, like adults, displayed an REA when positive words were presented to their right ear–left hemisphere in the free-recall task. Yet, this perceptual asymmetry was attenuated for children when controlling for selective attention. This volitional aspect of attention may affect the measurement of emotion processing in children.

The present findings are both consistent with extant neuropsychological data and suggestive of the role of general developmental changes in children's processing capacity on affect processing. We view these results as compelling, but certainly open to and in need of further refinement. For example, in future work it will be important to measure processing capacity in children and adults directly, perhaps through resource allocation paradigms (e.g., Navon & Gopher, 1979). If our hypothesis is correct, even within samples of children, processing capacity would be expected to covary with the magnitude of contra-hemispheric activation. Moreover, although attempts to understand cortical activation based on behavioral data provide empirically tractable formulations, they are both inferential and underspecified. The hypothesis-driven exploration of developmental changes in affective processing through both direct measures of brain physiology and computational modeling approaches would certainly lead to greater specificity in understanding the processes suggested in this article.

We have advanced a model suggesting that parietal systems involved in processes related to the recognition of emotional cues, anterior systems initiated by the recognition of emotional information, and the distribution of attention to salient affective information in the environment are constrained by children's developing cognitive resource capacity. These developmental changes in cognitive resources appear to influence the processing and measurement of emotion recognition in children. Further research will be required to ascertain whether these perceptual asymmetry differences between adults and children emerged because recognition of affective stimuli elicited more or less emotional experiences in younger participants, whether the development of general processing capacities in adults alters the nature in which emotional information is handled by the brain, or both. Rather than making inferences about neuroanatomic functional specialization for processes such as language or emotion, our formulation is intended to support the view that multiple interacting processes underlie the recognition of emotional information. As the neurophysiological mechanisms involved in emotional processes become clarified, we may better understand how both maturational and experience-dependent factors are involved in the emergence and maintenance of emotional systems.

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Appendix

Dichotic Word Pairs

Neutral–Neutral	*Positive–Neutral*	*Negative–Neutral*
nest–vest	laugh–calf	sad–pad
rug–mug	smile–pile	kill–hill
bell–sell	best–nest	hate–gate
calf–half	love–glove	yell–sell
skirt–shirt	hug–rug	cry–tie
mug–jug	flower–tower	hurt–shirt
feet–sheet	fun–bun	shove–glove
crate–gate	hug–mug	hate–crate
cane–rain	sweet–feet	cut–nut
	hug–jug	gun–bun
	fun–run	fight–light
	cake–rake	pain–rain
	laugh–half	yell–bell
	sun–bun	dead–head
	best–vest	sick–brick
	smile–dial	die–tie
	sun–run	hurt–skirt
	sweet–sheet	frown–town

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