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RESEARCH NOTE

Interhemispheric interaction expands attentional capacity in an auditory selective attention task

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Abstract Previous work from our laboratory indicates that interhemispheric interaction (IHI) functionally increases the attentional capacity available to support performance on visual tasks (Banich in The asymmetrical brain, pp 261–302, 2003). Because manipulations of both computational complexity and selection demand alter the benefits of IHI to task performance, we argue that IHI may be a general strategy for meeting increases in attentional demand. Other researchers, however, have suggested that the apparent benefits of IHI to attentional capacity are an epiphenomenon of the organization of the visual system (Fecteau and Enns in Neuropsychologia 43:1412–1428, 2005; Marsolek et al. in Neuropsychologia 40:1983–1999, 2002). In the current experiment, we investigate whether IHI increases attentional capacity outside the visual system by manipulating the selection demands of an auditory temporal pattern-matching task. We find that IHI expands attentional capacity in the auditory system. This suggests that the benefits of requiring IHI derive from a functional increase in attentional capacity rather than the organization of a specific sensory modality.

Introduction

A robust body of work demonstrates that attentional capacity may be most efficiently exploited if items relevant to a demanding task are divided between the cerebral hemispheres (see Banich 2003). This advantage may derive from the connected hemispheres' ability to process some information in parallel (Scalf et al. 2007; Alvarez and Cavanagh 2005). Banich and colleagues propose that interhemispheric interaction (IHI) is a mechanism by which the independent attentional resources of the two hemispheres are brought to bear on task performance (e.g. Banich 2003). As such, IHI may be a mechanism of attentional control.

Previous investigations of the impact of IHI on attentional capacity have modulated attentional demand by varying either the computational complexity or the selection demands of participants' tasks. Initial investigations (e.g. Banich and Belger 1990) manipulated computational complexity, defined as the number of operations required during task performance. Although more complex tasks tend to benefit from IHI, less complex tasks do not. For example, Banich and Belger (1990) asked participants to determine whether a target letter matched one of two probe letters. If the matching letters were printed in the same case, perceptual analysis was sufficient to support the match judgment. If the matching letters were printed in different cases, however, both perceptual analysis and either name extraction or case conversion were required to support the match judgment. Although performance of the less complex physical-identity (PI) task was best if the target and the matching probe appeared in the same visual field (allowing a single hemisphere to perform the task), performance of the name-identity (NI) task was best if the target and the matching probe item appeared in different visual fields (requiring the hemispheres to interact to perform the task). Variations in

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selection demand produce similar results. Weissman and Banich (1998) asked participants to determine whether one of two probe items matched a target item along a task-relevant dimension (i.e. global). If the matching items also contained identical information in the task-irrelevant dimension (i.e. local), within hemisphere presentation produced better performance. If the items conflicted in the task-irrelevant dimension, task performance was best when IHI was required. Furthermore, the benefits of IHI were greatest if the more difficult local dimension was task-relevant. Because increases in both computational complexity and selection demand produce this direct relationship between the benefits of IHI and attentional demand, Banich (1998) propose that IHI is a general strategy through which the brain can allocate its attentional resources with maximal efficiency.

Two alternative explanations for these results argue that the relationship between the across-field advantage and attentional demand is an artifact of visual system organization. One hypothesis is that the across-field advantage results from the different visual search strategies used when changing task conditions make perceptual features differentially salient (Fecteau and Enns 2005). This shift from highly salient (PI task) to less salient (NI task) perceptual features actually forces participants to switch from a parallel to a serial search strategy, Indeed, both explicit and implicit manipulation of participants' search strategies affected the degree to which across-field presentation benefited performance in the NI task (Fecteau and Enns 2005). Another explanation is that different visual subsystems are used during the performance of the PI and NI tasks; these subsystems are differentially robust to the costs of interhemispheric transfer (Marsolek et al. 2002), The specific visual form subsystem that supports the PI task is relatively vulnerable to the transfer-related information loss; the abstract visual form subsystem that supports the NI task, in contrast, is relatively robust to transfer-related information loss. According to this logic, IHI does bring additional computation power to bear on the task at hand, but it is the task-specific visual subsystem's tolerance for callosally degraded material, rather than the attentional demand of the task per se, that determines whether these additional resources will benefit task performance. Marsolek et al. (2002) report that a highly challenging PI task actually benefits more from within hemisphere processing than does an easier PI task. Both of these alternative hypotheses suggest that the benefits of dividing information between the visual fields are epiphenomena of visual system organization rather than the result of increased attentional capacity afforded by IHI.

The finding that individual factors such as scanning bias and specific task characteristics can alter the costs and benefits of within- and across-field stimulus placement to task performance does not mean that these factors exclusively underlie the pattern of results reported by Banich and colleagues. For example, although Fecteau and Enns (2005) demonstrate that attentional scanning strategies can influence the pattern of results observed on NI and PI tasks, this need not imply that scanning patterns generate the IHI advantage reported by Banich and colleagues. Certainly we would expect the relative cost and benefits of IHI to interact with factors such as attentional biases and stimulus vulnerability to callosal transfer. On the other hand, specific features of the visual system could indeed be the source of the observed shifts from a within- to an across-field advantage.

A demonstration of the relationship between IHI and attentional demand in a non-visual task would be more convincing evidence that such benefits reflect the contribution of IHI to attentional capacity rather than the organization of the visual system. Data partially supporting this claim does exist; increasing computational complexity decreases the within-hemisphere advantage in the auditory modality (Passarotti et al. 2002). Passarotti et al. (2002) presented participants with a monaural target digit (paired with a dichotic foil) followed by two different monaural probe items. They varied computational complexity by manipulating task condition (physical identity or ordinal value judgments) and temporal processing requirements [interstimulus intervals (ISIs) were either 250 or 100 ms]. Both ISI conditions produced a robust within-hemisphere advantage for the physical-identity task; for the ordinal decision task, this advantage decreased for the 250 ms condition and disappeared for the 100 ms condition. Increases in computational and perceptual complexity, then, interacted to increase the relative advantage of requiring IHI for successful task performance. Yet because an across-hemisphere advantage was not observed in any condition, it is difficult to use these data to demonstrate that IHI provides functional expansion of attentional capacity in a non-visual sensory system.

The most unequivocal support for the claim that IHI expands attentional capacity in a modality-general manner would be an increase in attentional demand in an auditory task that shifts performance to a significant IHI-required advantage. We hypothesized that Passarotti et al. (2002) failed to increase attentional demands to a level at which IHI would be beneficial to performance (see Banich and Brown 2002 for a longer discussion of these issues). Consequently, in the present experiment we look for evidence that IHI can expand the attentional capacity available to auditory selective attention tasks just as it can to visual selective attention. We would consider a shift from a significant IHI-not required advantage under easy task conditions to a significant IHI-required advantage for difficult task conditions to constitute such evidence.

We presented participants with an auditory temporal pattern-matching task. Participants heard two lateralized sequences of three tones and determined whether the rhythm (i.e. pattern of short and long tones) of the two sequences matched. We manipulated selection demand by varying stimulus consistency along two dimensions; absolute timing of the sequences (tempo), or the frequencies used to carry the rhythm information (pitch). We crossed these manipulations of tempo and pitch to produce multiple levels of attentional demand. We anticipated that these variations in selection demand would produce variations in benefit of IHI to task performance. Specifically, we expected that IHI would significantly benefit the most demanding condition. Such findings would provide strong support for the idea that levels of task demand, rather than modality specific processing strategies, primarily determine the benefits of IHI. This, in turn, would support the idea that IHI is a means by which attentional capacity may be functionally increased.

Methods

Participants

28 right-handed University of Illinois students (21 women and 7 men, ages 18 to 30) received either class credit or cash in return for their participation in this experiment. Participants were considered right handed if they wrote with their right hand and performed simple tasks with their right hand more than 85% of the time (assessed via questionnaire). All participants were screened for normal hearing between 256 and 2,048 Hz.

Stimuli

We used Sound Edit 16 software to create “low” (440 Hz) and “high” (512 Hz) 70 dB sawtooth waveforms. For each frequency, we constructed “short” tones of 600 ms and 750 ms, and “long” tones of 1,200 and 1,500 ms. Each tone began and ended with a 100 ms envelope. Short and long tones of 600 and 1,200 ms were combined to create six patterns. We duplicated these patterns using the 750 and 1,500 ms tones. This produced fast and slow sets of rhythms. These 12 patterns could be played using any of six combinations of “high” and “low” frequencies, leading to a total of 72 perceptually different sound patterns.

We paired these patterns as target and probe sequences, separated by a silent 300 ms ISI. The rhythms of the two patterns were either the same (match trials) or different (mismatch trials). We created four types of match trials; these could include perceptually identical target and probe sequences, target and probe sequences that contained different pitches but identical tempos, target and probe sequences that contained the same pitches but different tempos or target and probe sequences that contained both different pitches and tempos (see Fig. 1a). We also created four analogous types of mismatch trials (see Fig. 1b).

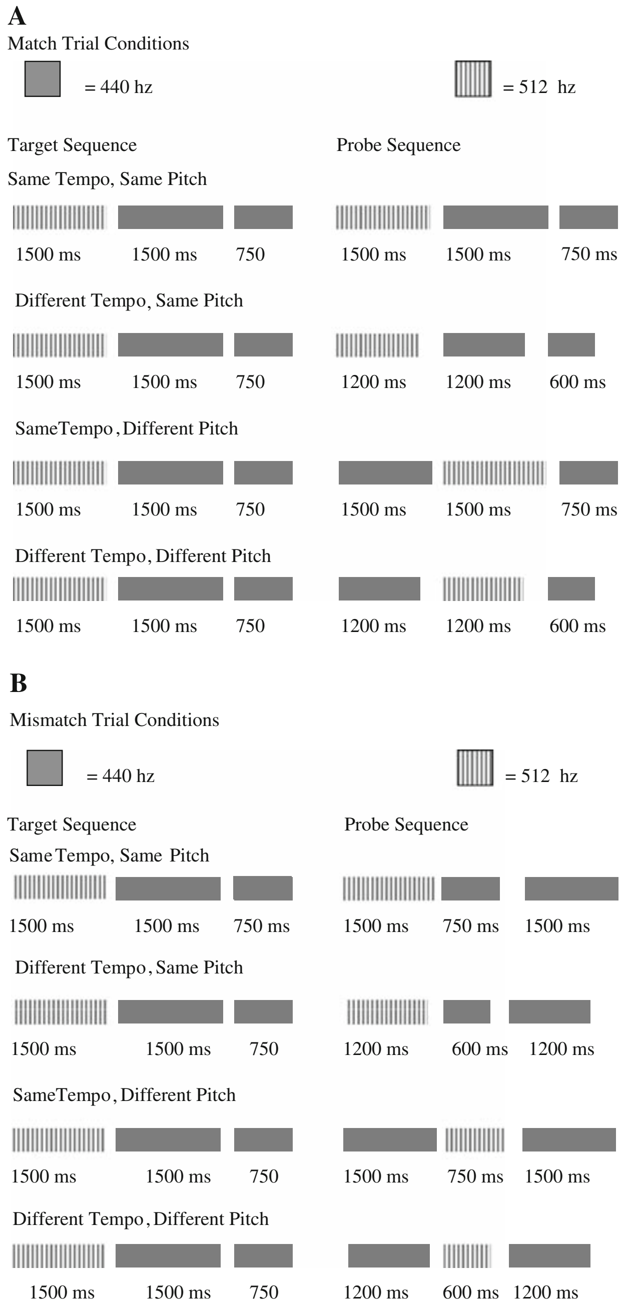

Fig. 1 **a** Match trial conditions. **b** Mismatch trial conditions

Trials were counterbalanced such that all rhythmic sequences occurred in all pitch patterns and were distributed as evenly as possible through each of the match conditions. (Full counterbalancing was not possible, as this would have made the experiment prohibitively long.) In the mismatch trials, all sequences served an equal number of times as the target and probe. For half of the mismatch trials, however, we paired sequences such that the target and probe sequences were of the same duration in order to prevent their comparative lengths from predicting whether the sequences contained matching rhythms. This counterbalancing required that only sequences with the same number of short and long elements be paired together for conditions in which the target and probe sequences were of the same tempo. The conditions of having the same number of short and long elements and of being of the same absolute duration were mutually exclusive for sequences of different tempi, however. Consequently, mismatch trials whose sequences were of different tempi but of the same absolute duration never contained the same number of short and long elements.

We used dichotic presentation to determine which hemisphere initially received stimulus information. Although each hemisphere receives information from both ears, each is considerably more sensitive to information presented to the contralateral ear than to information presented to the ipsilateral ear (Milner et al. 1968; Woldorff et al. 1999). We paired each task-relevant stimulus with a white noise mask to maintain the contralateral attentional biases of each hemisphere (for a review, see Bradshaw and Nettleton 1988). Ear of sequence presentation was counterbalanced so that each ear received the target and probe an equal number of times, and the target and probe were presented to a single hemisphere as often as they were presented to opposite hemispheres. IHI was required only on trials in which the target and probe information were presented to opposite ears.

Procedure

After prescreening, participants were introduced to the experimental task via a visual and auditory representation of the task material. Participants performed seventeen auditory practice trials that were monitored by the experimenter. On these trials, the participants verbally indicated the match/mismatch status of the trial and received visual and verbal feedback regarding their answer.

Participants performed one block of practice trials and four blocks of experimental trials. The practice block contained 32 trials, and was included to familiarize participants with the computer interface. Each experimental block contained 64 unique combinations of target and probe stimuli, equally divided among the 16 conditions described above. Participants responded to and received visual feedback during a 2,300 ms intertrial interval.

Participants responded using the “g” and “h” keys on the computer keypad. Letters’ response mappings were counterbalanced across subjects. Participants alternated response hand for each block of experimental trials. The order of response hand (right hand first or left hand first) was counterbalanced across subjects.

Equipment

Stimuli were presented using SuperLab 1.68 on a Macintosh Power PC 6600/66. Realistic Pro-60 Headphones were used to present the sound stimuli. Headphone position was reversed between experimental blocks two and three; start position was counterbalanced across subjects.

Results

For each participant, we subtracted the normalized hit rate from the normalized false alarm rate from corresponding match and mismatch trials to create a d-prime score for each condition. Because of the difficulty of interpreting negative d-prime scores, we eliminated any participant who showed a negative d-prime score in any cell. Using these criteria, we analyzed the results of 23 participants. The factors target ear (left, right), IHI (required, not required), tempo (same, different) and pitch (same, different) were combined to create 16 conditions.

We observed a main effect of tempo [$F = 43.65$; $df = 1.22$, $P < 0.0001$]. Sensitivity was higher on same tempo trials (d-prime = 2.61) than on different tempo trials (d-prime = 1.81). We found a similar main effect of pitch [$F = 6.438$; $df = 1.22$, $P < 0.05$]. Sensitivity was higher on same pitch trials (d-prime = 2.38) than on different pitch trials (d-prime = 2.07). We found a significant interaction between the factors ear and tempo [$F(1,22) = 5.8$; $P < 0.05$]. Although sensitivity was best on same tempo trials if targets were directed to the left ear rather than the right (d-primes = 2.79 and 2.49, respectively), it was best on different tempo trials if targets were directed to the right ear rather than the left ear (d-primes = 1.86 and 1.77, respectively).

We found an interaction between the factors IHI and tempo [$F(1,22) = 6.61$; $P < 0.05$]. Sensitivity on same tempo trials was higher when IHI was not required (d-prime = 2.75) than when IHI was required (d-prime = 2.53) ($P < 0.10$). Sensitivity on different tempo trials, however, was higher when when IHI was required (d-prime = 1.89) than when it was not required (d-prime = 1.73) ($P < 0.15$). Because we found an interaction between the factors ear and tempo, we note here that the three-way interaction among the factors ear, IHI, and tempo did not approach significance [$F(1,22) = 0.024$; $P > 0.87$]. This indicates that the left ear and right ear trials did not have differential roles in driving the interaction between IHI and tempo. We also found an interaction between the factors IHI and pitch [$F(1,22) = 30.18$; $P < 0.01$]. Planned comparisons revealed

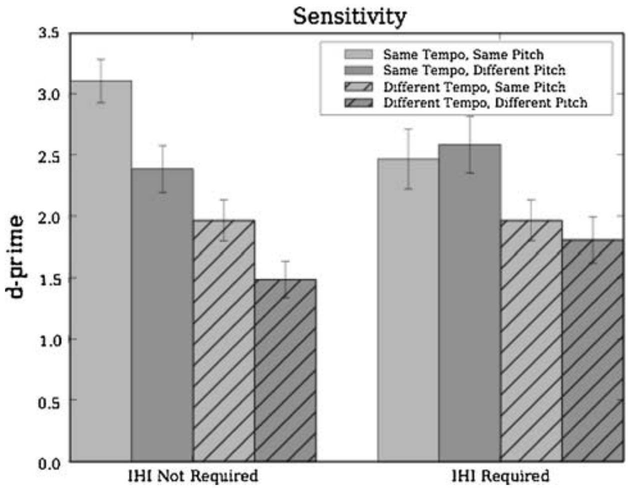

Fig. 2 Sensitivity to rhythm matches. Increasing selection demand produces an increased interhemispheric interaction (IHI) advantage

that sensitivity on same pitch trials was higher when IHI was not required (d-prime = 2.54) than when IHI was required (d-prime = 2.23) ($P < 0.01$). Sensitivity on different pitch trials, however, was higher when IHI was required (d-prime = 2.2) than when IHI was not required (d-prime = 1.94) ($P < 0.05$).

Finally, we found a marginally significant three-way interaction among the factors IHI, tempo and pitch [$F(1,22) = 2.46$; $P < 0.14$]. We used planned comparisons to interrogate our specific hypothesis that the stepwise increases in difficulty produced by combining tempo and pitch interference would produce a similar increase in the benefits of IHI to task performance (see Fig. 2). We found that sensitivity on same pitch, same tempo trials was higher when IHI was not required (d-prime = 3.11) than when IHI was required (d-prime = 2.477) ($P < 0.05$). Sensitivity on same tempo, different pitch trials did not differ between when IHI was not required (d-prime = 2.39) and when IHI was required (d-prime = 2.59) ($P > 0.20$). Sensitivity on different tempo, same pitch trials also did not differ between when IHI was not required (d-prime = 1.97) and when IHI was required (d-prime = 1.98) ($P > 0.95$). Finally, sensitivity on different tempo, different pitch trials was higher when IHI was required (d-prime = 1.81) than when IHI was not required (d-prime = 1.49) ($P < 0.05$).

Discussion

Our data show that benefits of IHI to task performance can be observed in auditory tasks as they can in visual tasks. Although previous work has demonstrated that within-hemisphere processing becomes less beneficial for auditory tasks as they become more demanding (Passarotti et al. 2002), those data did not confirm that IHI benefited more demanding conditions. This left unresolved the question of whether IHI actually improves the performance of tasks that do not rely on the visual system. In the current experiment, we found that IHI compromised performance for trials that matched on both task-irrelevant dimensions, that IHI neither aided nor compromised performance for trials that matched on one dimension and mismatched on the other, and that IHI improved performance on trials that mismatched on both dimensions. Our data consequently indicate that increasing the selection demands in an auditory task can reveal the benefits of IHI to attentional capacity as it can in the visual modality.

Demonstrating that IHI functionally increases the attentional resources available to non-visual tasks adds evidence to the claim that IHI benefits task performance by expanding the resources available to perform a task. Neither the proposal that the across-field advantage reflects the tendency of attention to shift between objects maximally displaced in the visual field (Fecteau and Enns 2005) nor the idea that the across-field advantage results from the efficiency of callosal transfer for different types of visual information (Marsolek et al. 2002) can explain the current findings. Instead, the more parsimonious explanation is that IHI must play a role in modulating attentional capacity regardless of sensory modality. The ability of IHI to functionally expand attentional capacity seems to generalize across computational complexity and selection demand in both the visual and auditory modalities.

Our data may help to explain the somewhat inconsistent findings regarding the lateralization of rhythm processing. A left hemisphere advantage (e.g. Gordon and Bogen 1974; Robin et al. 1990; Zatorre and Belin 2001), a right hemisphere advantage (Penhune et al. 1999) or no advantage (Peretz and Morais 1980; Peretz 1990) in rhythm processing have all been reported. Our tempo manipulation produced a laterality effect such that items with identical tempo were best processed if the target was directed to the left ear/right hemisphere and items with different tempos were best processed if the target was directed to the right ear/left hemisphere. One possible explanation for our findings is that each hemisphere may use a different type of processing to represent the target item; these processes may be differentially efficient for processing stimuli with matching or mismatching tempos. For example, the right hemisphere is associated with a more "holistic" style of processing while the left hemisphere is associated with a more "piecemeal" style of processing (e.g. Robertson and Lamb 1991; Levy and Trevarthen 1976). Whereas a bias towards a holistic, perceptual representation of the target item would likely benefit sensitivity to same tempo trials, which contain elements of the same duration, a bias towards a piecemeal, conceptual representation of the target item would likely benefit sensitivity to different tempo trials, which contain elements of different duration. Laterality effects in rhythm processing, then, may be in part driven by the processing strategies that are best suited to the specific characteristics of the task at hand.

The laterality effects we observed prevented neither IHI from benefiting performance when selection demands were high nor within-hemisphere processing from benefiting performance when selection demands were low. These data suggest that the costs and benefits of IHI were higher than any performance advantage of either hemisphere under different conditions of tempo similarity. Specifically, on same tempo trials, the costs of transferring information between the hemispheres outweighed any benefit of right hemisphere participation, and on different tempo trials, the benefits of engaging the computational power of both hemispheres outweighed any benefit of restricting processing to the more efficient left hemisphere. As long as each hemisphere in isolation can perform the task reasonably well across all task conditions, the costs and benefit of IHI will continue to emerge on trials with low and high attentional demands, respectively. Although these results may seem surprising, they are not unique. In fact, Belger and Banich (1992) report a right hemisphere advantage for both the NI and PI tasks that initially established the relationship between IHI and computational complexity. Weissman and Banich (1998) also replicate the well-established right and left hemisphere asymmetries for global and local processing; they continue to find a direct relationship between the benefits of IHI and the selection demand of matching both global and local stimulus levels. Only when the task at hand absolutely relies on the processes of a single hemisphere (e.g. visual rhyming) have we found hemispheric asymmetries to influence the costs and benefits of IHI to task performance (Belger and Banich 1998).

In sum, our data indicate that IHI can functionally increase the attentional resources available to auditory tasks. Consequently, the benefits of IHI to attentional capacity are artifacts of neither the attentional biases nor the organization of the visual system. Our data add support to the idea that IHI is a mechanism by which the brain can make the most efficient use of its limited attentional capacity.

References

Alvarez GA, Cavanagh P (2005) Independent resources for attentional tracking in the left and right visual field. Psychol Sci 16:637–643

Banich MT (1998) The missing link: the role of interhemispheric interaction in attentional processing. Brain Cogn 36:128–157

Banich MT (2003) Interactions between the hemispheres and its implications for the processing capacity of the brain. In: Hugdahl K, Davidson RJ (eds) The asymmetrical brain. MIT Press, Cambridge, pp 261–302

Banich MT, Belger A (1990) Interhemispheric interaction: how do the hemispheres divide and conquer a task? Cortex 26(1):77–94

Banich MT, Brown WS (2002) A life-span perspective on interaction between the hemispheres. Dev Neuropsychol 18:1–10

Belger A, Banich MT (1992) Interhemispheric interaction affected by computational complexity. Neuropsychologia 30(10):923–929

Belger A, Banich MT (1998) Costs and benefits of integrating information between the cerebral hemispheres: a computational perspective. Neuropyschology 12(3):380–398

Bradshaw JL, Nettleton NC (1998) Monaural asymmetries. In: Hugdahl K et al (eds) Handbook of dichotic listening: theory, methods and research. Wiley, Chichester, pp 45–69

Fecteau JH, Enns JT (2005) Visual letter matching: Hemispheric functioning or scanning biases. Neuropsychologia 43:1412–1428

Gordon HW, Bogen JE (1974) Hemispheric lateralization of singing after intracarotid sodium amylobarbitone. J Neurol Neurosurg Psychiatry 37:727–738

Levy J, Trevarthen C (1976) Metacontrol of hemispheric function in human split-brain patients. J Exp Psychol Hum Percept Perform 3:299–312

Marsolek CJ, Nicholas CD, Andresen DR (2002) Interhemispheric communication of abstract and specific visual-form information. Neuropsychologia 40:1983–1999

Milner B, Taylor L, Sperry RW (1968) Lateralized suppression of dichotically presented digits after commissural section in man. Science 161(837):184–186

Passarotti AM, Banich MT, Sood RK, Wong JM (2002) A generalized role of interhemispheric interaction under attentionally demanding conditions: evidence from the auditory and tactile modalities. Neuropsychologia 40:1082–1096

Penhune VB, Zatorre RJ, Feindel WH (1999) The role of auditory cortex in retention of rhythmic patterns as studied in patients with temporal lobe removals including Heschl's gyrus. Neuropsychologia 37:315–331

Peretz I (1990) Processing of local and global musical information by unilateral brain-damaged patients. Brain 113:1185–1205

Peretz I, Morais J (1980) Modes of processing melodee and ear asymmetries in non-musicians. Neuropsychologia 18:477–489

Robertson LC, Lamb MR (1991) Neuropsychological contributions to theories of part/whole organization. Cogn Psychol 23:299–330

Robin D, Tranel D, Damasio H (1990) Auditory perception of temporal and spectral events in patients with focal left and right cerebral lesions. Brain Lang 39:539–555

Scalf PE, Banich MT, Kramer AF, Narechania K, Simon CL (2007) Double take: parallel processing by the cerebral hemispheres reduces the attentional blink. J Exp Psychol Hum Percept Perform 33:298–329

Weissman DH, Banich MT (1998) A role for interhemispheric interaction in reducing the effects of global-local interference. J Exp Psychol Gen 128(3):283–308

Woldorff MG, Tempelmann C, Fell J, Tegeler C, Gaschler-Markefski B, Hinrichs H, Heinz HJ, Scheich H (1999) Lateralized auditory spatial perception and the contralaterality of cortical processing as studied with functional magnetic resonance imaging and magnetoencephalography. Hum Brain Mapp 7:49–66

Zatorre RJ, Belin P (2001) Spectral and temporal processing in human auditory cortex. Cerebral Corex 11:946–953