Title: Specific Brain Regions Involved in Decoding of the Anger Acoustic Parameters

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Abstract

***Background*.** The purpose of the present study was to identify brain regions sensitive to emotion-specific acoustic parameters in healthy individuals.

Method. Three pseudo-words consecutively in the form of one stimulus were spoken with neutral and angry prosody. Then, we changed the acoustic parameters (mean fundamental frequency, intensity, and speech tempo) in angry prosody. The stimuli were presented in a functional magnetic resonance imaging (fMRI) experiment to detect anger or neutrality.

***Results*.** Stronger activation in the left superior temporal gyrus (STG) and Heschl's gyrus (HG) when the mean f0 converted from 300 Hz to 250 Hz was observed. Increased activity in the right posterior STG and posterior middle temporal gyrus (MTG) was revealed in more intensity anger prosody. Moreover, we found stronger activity in the right mid-STG, MTG, and the left STG in a faster speech tempo.

***Conclusion*.** According to the increased activity in the STG and MTG of both hemispheres following the more intense anger (lower fundamental frequency, more intensity, and faster speech tempo), it can probably be concluded that a more intense comprehension of anger is resulted from the sending different information from these regions to the inferior frontal gyrus (IFG) and orbital frontal cortex (OFC).

Keywords: Acoustic parameters; Emotional prosody; Functional MRI; Intensity; Mean F0; Speech tempo

Introduction

Speech prosody refers to fluctuations in pitch (fundamental frequency), variations in loudness (intensity), durational features (e.g., phone, syllable, word, and phrase length; pausing, rhythm, and speech tempo), and voice quality [1-4]. Prosody can serve a range of functions such as linguistic, pragmatic, and emotional functions [5]. These parameters can be influenced by affective states and play an important role in emotion perception [6]. An incorrect interpretation of emotional prosody can cause failure in social interactions and increased risk of social isolation [7-9]. Finding the neural mechanism underlying the emotion-specific acoustic parameters can improve our knowledge of prosodic impairments (dysprosodia).

A large number of neurological studies have found that the right cerebral cortex is responsible for emotional prosody processing [10-38]. Although most lesions and neurological studies have suggested the right hemisphere (RH) dominance for emotional prosody, others have found no difference between the left hemisphere (LH) and RH lesion effects [27, 32, 39-42].

Functional MRI studies showed that widespread brain networks are involved in decoding emotional prosody [43-45]. In detail, auditory temporal regions such as the primary/secondary auditory cortex (AC), superior temporal cortex (STC) [11, 43, 45-61], and other temporal areas such as supramarginal gyrus, right parahippocampal (BA 28) gyrus and subcallosal (BA 34) gyrus [62], frontal areas such as the inferior frontal cortex (IFC) and orbital frontal cortex (OFC) [43, 51-55, 63, 64], insula [56], cerebellum [62] and subcortical structures such as thalamus, basal ganglia and amygdala [53, 54, 56, 59, 63-65] have been found to be involved in the perception of emotional prosody.

Furthermore, according to a hierarchical model that has been proposed for emotional prosody processing [43, 49, 66], voice-sensitive structures of the AC and mid-STC contribute to the extraction of acoustic parameters; the posterior part of the right STC contributes to the identification of emotional prosody, and eventually, the semantic comprehension of affective prosody is concerned with the bilateral IFG and OFC [45, 58].

As discussed above, most studies have focused on emotional prosody processing, and there are few reports on how emotion-specific acoustic parameters are processed. In the following, we refer to studies related to the processing of acoustic parameters including pitch, intensity and duration separately.

1. *pitch*

The lesion studies addressed the role of the hemispheres in pitch processing. It has been demonstrated that the RH is related to pitch processing in speech [67]. Patients with the RH lesions use duration cues rather than F0-variability to assess affective prosody. In other words, right temporoparietal lesions could disrupt the discrimination of tones [67].

Several structural and functional neuroimaging studies have shown that inferior frontal regions in RH [68, 69], left STG, left Heschl's gyrus (HG), and the right temporal pole [59], pars triangularis of Broca's area [70], the right posterior STG and left STG subregions [44], and Heschl's gyrus (HG) and adjacent cortical areas in STG [71] were the main structures for pitch processing. In addition, it has been suggested that the lateral HG functions as a general "pitch center" [72], and the processing of pitch patterns such as melodies, involves much more distributed processing in the superior temporal lobes and frontal lobes [73]. However, another study demonstrated that parts of the planum temporal are more relevant for pitch processing than lateral HG [74]. In addition, the anterior temporal cortex is more sensitive to female voices with high F0 than to male voices with low F0 [75].

2. Intensity and duration

Previous reports found widespread activation clusters in the bilateral AC to stimuli that are deviant in intensity or duration [76-78], in the STG and MTG of both hemispheres to intensity and duration, in the right IFG and superior frontal gyrus (SFG) to duration [59], and in the right posterior STG and the left STG to intensity variations in emotional prosody [44, 79].

In sum, it seems that different brain regions may be involved in emotion- specific acoustic parameters processing. Finding the neural representation of each emotion-specific acoustic parameter may improve our knowledge about the neural mechanism of emotional prosody processing. Difficulties in emotional prosody comprehension, including anger in neurological disorders such as Alzheimer's, Parkinson's, Traumatic brain injury (TBI), or psychological disorders such as depression, autism, and alexithymia cause failure in social relationships and increase the risk of isolation [7-9]. Recent studies have demonstrated the improvement of some neurological, psychological, and motor disorders using non-invasive protocols such as tDCS and rTMS. Previous studies showed that the stimulation of a region such as the dorsal and lateral part of the prefrontal cortex leads to the strengthening of the functional connectivity of the brain networks [80, 81]. Rare studies have been conducted in the treatment of emotional prosody disorders. Findings the brain regions and functional connectivity sensitive to changing the acoustic parameters of the emotional prosody of anger can probably help in providing therapeutic solutions.

The emotional prosody used in the present study was anger. It was demonstrated in the previous reports [82] that lower mean f0, louder voice, and faster speech tempo constitute acoustic parameters of anger. However, it was revealed in one study [83] that ''hot'' anger seemed to be characterized by an increased in mean F0 and decreased in mean F0 was probably due to ''cold'' anger. Thus, it is expected that with increasing intensity and speech tempo and changing the mean f0, the anger becomes more intense and the brain regions sensitive to these parameters show different activity. In this study, we tried to use a novel experimental fMRI design in which a range of different anger stimuli with difference in only one acoustic parameter every time were presented to participants. The goals of the present study were two-fold. In the first place, our aim was to identify brain regions sensitive to emotion-specific acoustic parameters. In the second place, we wanted to investigate the difference in brain activity related to emotion-specific acoustic parameters variations. We hypothesized that increasing anger intensity following to lower frequency, louder (more intensity) and faster speech tempo leads to stronger activity in the brain regions sensitive to emotion-specific acoustic parameters. To ensure the relevance of the results with the difference in only one emotion-specific acoustic parameter, we changed one of the acoustic parameters each time while keeping the other two constant, and the stimuli were spoken only by one speech and language pathologist.

Materials and methods

Participants

Twenty healthy young male adults participated in the study (ages ranging from 18 to 35, mean age: 23.51 years, standard deviation [SD] = 5.08 years). All participants were native Persian speakers, right-handed, and had normal or corrected-to-normal vision. No participant had a history of neurological or psychiatric problems, substance abuse, or impaired hearing. Furthermore, the Toronto alexithymia scale was used to identify individuals who have trouble understanding emotions. All participants provided informed and written consent for participation in the fMRI study. MRI data had to be excluded from four participants because of incorrect responses. Thus, the results reported are based on the analysis of the remaining 16 participants. This study was approved by the ethical committee of the Iran University of Medical Sciences. The ethical code was IR.IUMS.REC.1399.1284

Stimuli

Three pseudo-words (‘’čârs”, “mâruk”, and “nirâpat”) were selected from a Persian language study [84] that was administrated a Persian non-word repetition (NWR) test. These pseudo-words were spoken in either a neutral or an angry tone by a male speech and language pathologist. After that, the three pseudo-words were used consecutively in a form of one stimulus. Then, the acoustic parameters (mean f0, intensity, and speech tempo) of the anger stimulus was changed using Audacity software. Every time, one of the parameters was changed while keeping the other two constant. In detail, the mean f0 was changed between 200 and 400 Hz while keeping the other two parameters constant. Once again, by keeping the mean f0 and tempo constant, the mean intensity was changed between 50 and 90 dB. Finally, the speech tempo was changed between 1 to 5 seconds without changing the mean f0 and intensity. After applying the changes, to judge if they were anger or not, they were piloted on a group of healthy adults (N = 10) before the fMRI study. These healthy individuals were selected among the students of the Iran University of Medical Sciences. Finally, two changes were selected in the highest and lowest range of anger in each acoustic parameter. The highest and lowest mean f0 detectable as anger prosody was about 350 and 250 Hz, respectively. The highest and lowest rate of change in speech tempo that could be recognized as anger prosody was about 4.2 and 2.1

seconds, respectively. The highest and lowest audible intensity in the fMRI were about 90 and 70 dBs, respectively. Therefore, six new changes (two changes in each parameter) were administrated (see Table 1).

Experimental design

During the fMRI-scan, auditory stimuli were presented binaurally using magnetic resonance imaging compatible headphones. Participants were lying in the scanner with their eyes open staring at the screen. Auditory stimuli were preceded by a visual fixation cross (1 × 1°) for 2s. The participants were asked to pay attention to the emotion of the auditory stimuli in fMRI experiment to detect anger or neutral stimulus and distinguish the correct option by pressing the button (right index, left index) after displaying the options on the screen for 2s. Auditory stimuli were presented during three blocks of prosody discrimination on the stimuli (angry or neutral; right index and left index) in two runs. Each anger/neutral discrimination block contained 12 conditions with 3 parameters (anger_neutral, stimulus_time, jitter), including 2 silent events with no auditory stimulation, 3 neutral events, and 7 anger events (see Figure 1). Every block of prosody discrimination on the stimuli lasted 132 seconds.

Image Acquisition

Structural and functional imaging data were obtained using a 3T PRISMA scanner in the National Brain Mapping Laboratory (NBML). A magnetization prepared rapid acquisition gradient echo (MPRAGE) m3 sequence was employed to acquire high-resolution (1×1×1 mm3) T1-weighted structural images (TR=1600 ms, TE=3.47 ms, TI=800 ms). Functional images were obtained using a multislice echo planar imaging (EPI) sequence (36 axial slices, slice thickness: 3.0 mm, TR=2000 ms, TE=30 ms, field of view (FOV)=195 mm, flip angle=90°).

Image analysis

The fMRI data analysis was performed using Statistical Parametric Mapping SPM (version 12; Welcome Department of Cognitive Neurology, London, UK). Preprocessing was performed using default settings in SPM 12. Functional images were realigned and coregistered to the anatomical image. A segmentation of the anatomical image revealed warping parameters that were used to normalize the functional images to the Montreal Neurological Institute (MNI) stereotactic template brain. Normalized images were spatially smoothed with a nonisotropic Gaussian kernel of full-width at half-maximum 3 × 3 × 4 mm.

A general linear model [85] was used for the first-level statistical analysis, in which separate regressors were defined for each trial using a stick function convolved with the hemodynamic response function. Events were time-locked to stimulus onset. Separate regressors were created for each experimental condition. Linear contrasts for the conditions for each participant were taken to a second-level random effects group analysis of variance.

Factorial subtraction analysis was employed to evaluate which brain regions respond more strongly to changes in emotion-specific acoustic parameters of anger prosody. To examine whether hemodynamic responses in the temporal lobe, especially STG, are subject to repetition suppression effects, parameter estimates of the most significantly activated voxel in this area were submitted to a two-factorial analysis of variance (ANOVA) with emotion-specific acoustic parameters variations and repetition (first fMRI session, second fMRI session) as within-subject factors. Activations are reported at a height threshold of $p < 0.001$ uncorrected and an extent threshold of 0 voxels. Significance was examined at the cluster level with an extent threshold of $p < 0.05$ (corresponding to a minimal cluster size of 50 voxels) corrected for multiple comparisons across the whole brain.

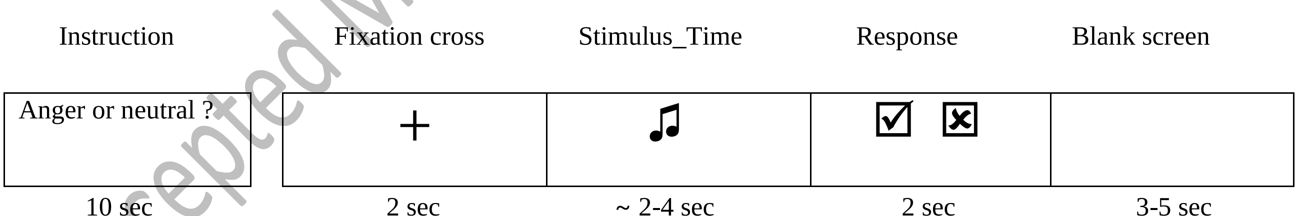


Figure 1: illustration of an example trial of the fMRI task. The instruction was displayed for 10 s before every block. A fixation cross was displayed after a blank screen for a total of 5-7 s. After that, audio stimulus was played for anger/neutral discrimination. The duration of each stimulus was between about 2 and 4 seconds. The time required to respond was 2 seconds.

Table 1: Acoustic parameters description of all stimuli

	Mf0 (Hz)	Intensity (dB)	Speech tempo (s)
Main stimulus (anger)	~ 300	~ 80	~ 3
Mean f0 variations	~ 250	~ 80	~ 3
	~350	~80	~ 3
Intensity variations	~ 300	~ 70	~ 3
	~ 300	~ 90	~ 3
Speech tempo variations	~300	~ 80	~ 2
	~300	~80	~ 4

Results

The hemodynamic responses of the various acoustic parameters of anger prosody will be described in detail.

1.Mean F0

To examine brain activation in response to mean F0 variations in anger prosody, a one-sample t-test was run for the contrasts: anger (300 Hz) > anger (250 Hz) prosody, anger (250 Hz) > anger (300 Hz) prosody, anger (350 Hz) > anger (300 Hz) prosody, and anger (300 Hz) > anger (350 Hz) prosody. Comparison of these contrasts with each other showed increased activity in the left STG (MNI Coordinates: x= -60, y= -20, z= 8; T= 5.33; cluster size= 17 voxels) and in HG (MNI Coordinates: x= -55, y= -22, z= 9; T= 5.33; cluster size= 17 voxels) in response to anger (250 Hz) prosody compared with anger (300 Hz) at $p < 0.001$ (uncorrected). (Figure 2). No significant clusters were found in other contrast comparisons.

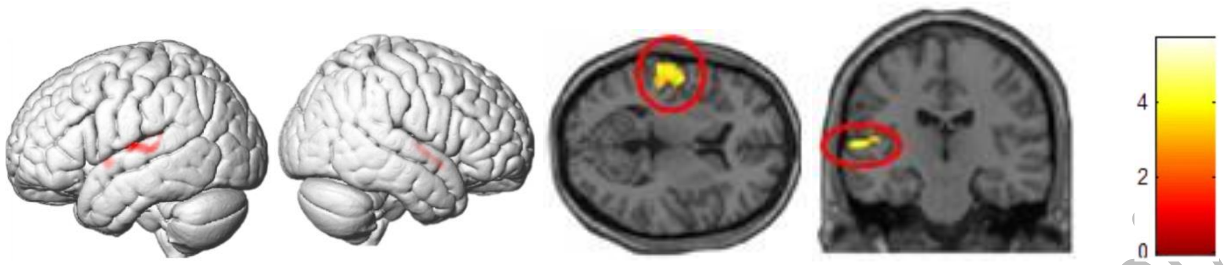
2. Mean Intensity

When we compared brain activity among intensity variations (70, 80, and 90 dBs) while keeping the other two acoustic parameters constant, the STG and MTG in the RH showed greater activation to anger prosody with more intensity. This increased activation was greater for anger (90 dB) compared with anger (70 dB) [90 dB > 70 dB] than for anger (90 dB) compared with anger (80db) [90 dB > 80 dB] (Figure). In detail, when we compared brain activation between anger (90 dB) and anger (70dB) (90 dB > 70 dB), our analysis revealed stronger activity in the right posterior STG (MNI coordinates: x = 42, y = -38, z = 6; T = 7.4; cluster size = 22 voxels) and a significant cluster in the right posterior MTG (MNI Coordinates: x = 49, y = -38, z = 4; T = 7.4; cluster size = 22 voxels) at the threshold of $p < 0.001$ uncorrected. In addition, when we compared brain activation between anger (90 dB) and anger (80 dB) (90 dB > 80 dB), we found increased activity in the right posterior STG (MNI Coordinates: x = 38, y = -38, z = 8; T = 6.52; cluster size = 21 voxels). Furthermore, the difference in activity extent in anger 90 dB compared with anger 70 dB is greater than anger 90 dB compared with anger 80 dB (Figure 2).

3. Duration (speech tempo)

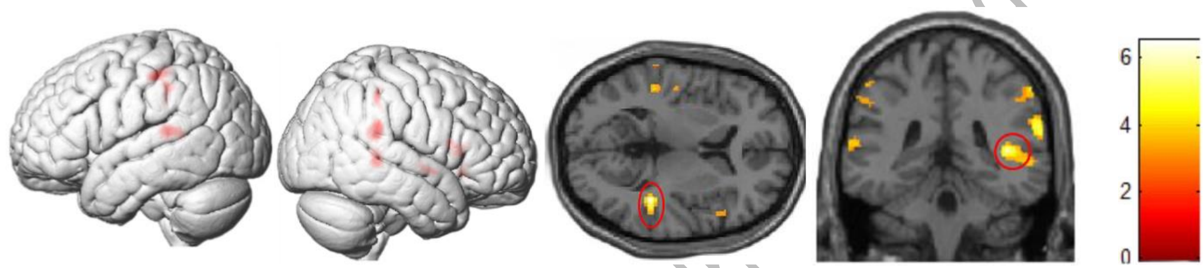
Comparison of hemodynamic responses to anger (2s) compared with anger (3s) (anger (2s) > anger (3s)) revealed two significant clusters in the temporal lobe of both hemispheres, which were located within the mid-STG in the RH (MNI coordinates: x=54; y=-20; z=0; BA:22; T = 9.3; cluster size = 27 voxels), and the posterior STG in the LH (MNI coordinates: x=-64; y=-36; z=16; BA:22; T = 6.6; cluster size = 27 voxels) at the threshold of $P < 0.001$ (uncorrected) with a minimum cluster extent of k = 0 voxels. This activation was stronger in the RH (Figure). On the other hand, when we compared brain activity between anger (4s) and anger (3s) (anger (4s) > anger (3s)), we found increased activity in the right MTG (MNI coordinates: x=50; y=-26; z=-8; T = 8.2; cluster size = 21 voxels), and in the posterior STG in LH (MNI coordinates: x=-66; y=-40; z=6; T = 7.8; cluster size = 21 voxels) at the level of $P < 0.001$(uncorrected) with a minimum cluster extent of k = 0 voxels. This activation was stronger in LH (Figure). Eventually, the comparison between anger (2s) and anger (4s) (anger (2s) > anger (4s)) revealed stronger activity in the right mid-STG (MNI coordinates: x=54; y=-18; z=0; T = 11.8; cluster size = 27 voxels) and in the left STG (MNI coordinates: x=-54; y=-2; z=0; T = 5.9; cluster size = 27 voxels) at the level of $P < 0.001$ (uncorrected) (Figure 2).

A 250 Hz > 300 Hz



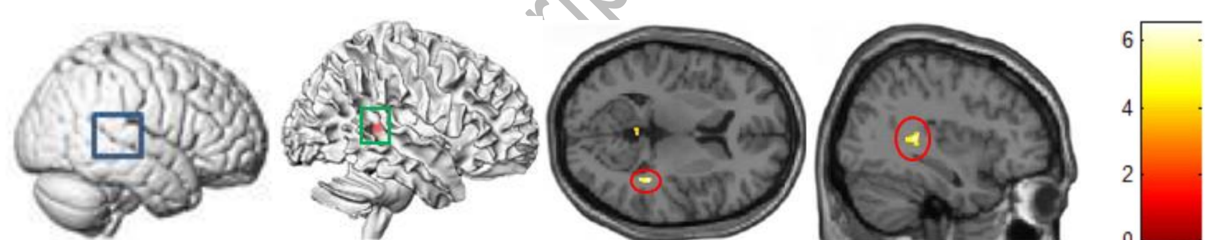
Left STG / HG

B1 90 dB > 70 dB



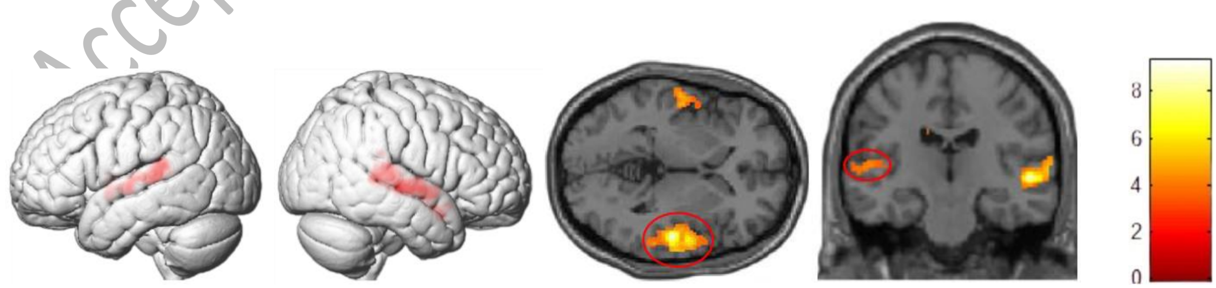
Right pSTG / pMTG

B2 90 dB > 80 dB



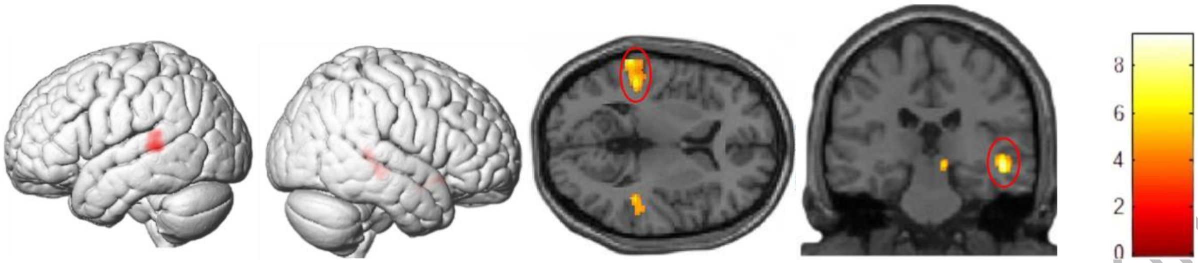
Right pSTG

C1 2 sec > 3 sec



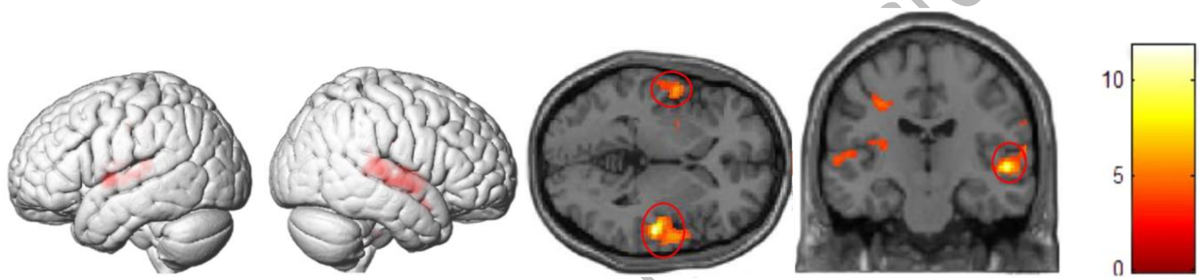
Right mid-STG **Left pSTG**

C2 4 sec > 3 sec



Left pSTG **Right MTG**

C3 2 sec > 4 sec



Left STG **Right mid-STG**

Figure 2. **(A)** Increased activity in the left STG and the left HG across all individuals for anger (250 Hz) compared with anger (300 Hz) prosody. **(B1)** Increased activity in the posterior STG and posterior MTG in the RH for anger at 90dB in comparison with anger at 70dB. **(B2)** Increased activity in the right posterior STG for anger at 90 dB compared with anger at 80 dB. **(C1)** Stronger activity in the right mid-STG and the left posterior STG for anger (2s) compared with anger (3s). **(C2)** Stronger activity in the right MTG and the left posterior STG for anger (4s) compared with anger (3s). **(C3)** Stronger activity in the mid-STG in the RH and the left STG for anger (2s) compared with anger (4s). All contrasts were thresholded at $p < 0.001$ (uncorrected) with a minimum cluster extent of $k = 0$ voxels. The data images were extracted using xjview.

Table 2. Main effects of anger with different acoustic parameters, P < 0.001 uncorr.

	MNI coordinates				
Anatomical definitions	X	Y	Z	K	T
Anger (250Hz) > anger (300Hz):					
L-STG	-60	-20	8	328	5.33
L-HG	-55	-22	9	328	5.33
Anger (90dB) > anger (70dB):					
R-posterior STG	42	-38	6	192	7.4
R-posterior MTG	49	-38	4	192	7.4
Anger (90dB) > anger (80dB):					
R-posterior STG	38	-38	8	32	6.52
Anger (2s) > anger (3s):					
R-mid STG	54	-20	0	1771	9.33
L-posterior STG	-64	-36	16	955	6.64
Anger (4s) > anger (3s):					
R-MTG	50	-26	-8	271	8.21
L-posterior STG	-66	-40	6	378	7.84
Anger (2s) > anger (4s):					
R-mid STG	54	-18	0	1330	11.8
L-STG	-54	-2	0	931	5.92

Peak coordinates from significant clusters. (FWE p< 0.05, extent threshold= 0 voxels). K = cluster size

Discussion

The present study was conducted to investigate the brain activity underlying the decoding of emotion-specific acoustic parameters in anger prosody. In fact, we wanted to identify brain regions that are sensitive to changing acoustic parameters. According to our assumption, changing any of the emotion-specific acoustic parameters can result in different hemodynamic responses within the STG and MTG of both hemispheres. Our findings showed stronger activation in the STG, HG, and MTG of both hemispheres when the acoustic parameters of anger were changed. Our results confirm previous reports on regions showing increased responsiveness to acoustic parameters [46, 57, 59]. In previous studies, it has been suggested that the decoding of acoustic parameters occurs in the temporal lobe, especially in STG subregions, and there is no study related to how brain activity differs in the temporal lobe following changes in any of these acoustic parameters. Therefore, we tried to change any of the acoustic parameters separately, keep the other two parameters constant, and examine how the brain activity differs.

When we changed the mean f0 from 300 Hz to 250 Hz and kept the intensity and duration constant, our analysis revealed stronger activity in HG and adjacent areas in STG in LH. The activity in the left STG in our findings is consistent with the results of previous studies [44, 59].

We also showed the role of HG in pitch processing, which is in agreement with the studies suggesting HG as ‘’pitch center’’ [72]. Previous studies [83] demonstrated that one of the characteristics of ‘’hot’’ anger was increased in mean F0. Studies in which this feature was not found may have been measuring ‘’cold’’ anger. Our finding about mean F0 variations was probably due to the use of ‘’cold’’ anger. In fact, according to the previous study [82], low fundamental frequency is one of the characteristics of anger. With a further decrease in the fundamental frequency, anger is perceived more intense. Therefore, we expected to see increased activity in the regions related to fundamental frequency decoding by reducing the mean F0. Thus, according to the use of ‘’cold’’ anger in the present study, the increase in the mean F0 did not lead to an increase in the intensity of anger, and as expected, the brain regions related to mean F0 decoding should not show increased activity.

In the present study, no activity was observed in the anterior temporal cortex. In fact, due to the use of male voices for the stimuli, we did not expect that the anterior temporal cortex would be active because according to previous studies [75], the anterior temporal cortex is more sensitive to female voices with high F0 than to male voices with low F0. Thus, the inactivity of the anterior temporal cortex was predictable.

Our findings on the speech tempo revealed stronger activity in different parts of the STG and MTG of both hemispheres when we only changed the speech tempo. These findings are pretty in line with the results of previous studies [59, 76, 77] demonstrating activation clusters in the bilateral auditory cortex, including STG, to stimuli that are deviant in duration. Because the temporal lobe, especially STG, is mentioned in all studies on duration processing, we can address the importance of these regions in the decoding of duration. The slight difference in our results with those of other previous studies probably goes back to the difference in the method and the type of acoustic parameter investigation. We examined the speech tempo as a type of durational feature, whereas others used duration-deviant tone in noise or stimuli duration in emotional prosody.

The results of our study about the effect of mean intensity variety on brain activity showed that increasing the mean intensity of anger prosody leads to increased activity in the posterior part of STG and MTG in the right hemisphere. The activity of right posterior part of STG in our study is in agreement with previous findings [44, 79]. Inspection of responses in the right posterior MTG revealed a fairly linear relationship within the investigated intensity range. These findings converge with previous findings demonstrating a linear relationship of BOLD response and sound intensity for a range of intensity [59, 78]. The type of stimulus used in our study and previous studies led to different results. In our study, only one type of emotional prosody (anger) was used while keeping other parameters (mean F0, duration, voice gender) constant to investigate the effect of mean intensity variations on brain regions activity. Other studies used frequency-modulated tones [78] or types of emotional prosody [59]. In the latter study, they found widespread activity in different brain regions including STG and MTG of both hemispheres due to the use of different types of emotional prosody without considering the fundamental frequency and duration of stimuli, while our results were limited to posterior part of STG and MTG in the right hemisphere which probably was due to the use of only anger prosody and keeping other parameters constant.

In total, the STG and MTG subregions were significantly correlated with changes in mean intensity, mean fundamental frequency, and duration (speech tempo). This sensitivity to a variety of acoustic parameters is probably due to the role of STG subregions in the detailed analysis of voice information [79, 86].

Limitation and strength

The current study aimed at investigating automatic processing of anger acoustic parameters. Thus, the experimental design did not include any behavioral task. Therefore, our study limitation is the lack of behavioral control indicating that subjects comprehended the auditory information in the presence of scanner noise. However none of the subjects reported difficulties in comprehending the presented stimuli and all subjects reported after scanning that all of the stimuli were spoken in an emotional tone of voice. On the other hand, in order to avoid the influence of various factors on the results of the study, including the use of various emotional prosody, different length of stimuli, presenting stimuli with the voices of different individuals, and the long duration of the task, we decided to use only one emotional prosody (anger) stimulus, change its acoustic parameters, and be spoken by only one male speech and language pathologist. Considering the different acoustic characteristics of emotional prosody and the different role of each acoustic parameter in the semantic comprehension of emotional prosody, we suggest that other emotional prosody should be investigated to improve our knowledge about the decoding of emotion-specific acoustic parameters.

Conclusion

As discussed in the introduction, according to the role of the AC and mid-STC [43, 49, 66] in the extraction of acoustic parameters, and different parts of STG and MTG of both hemispheres in our findings in decoding of the anger acoustic parameters, we can conclude that more intense anger following the lower fundamental frequency, increased intensity, and faster speech tempo leads to increased activity in the specific brain regions related to the decoding of the anger acoustic parameters, and eventually different information is sent to IFG and OFC [45, 58] for more intense comprehension of anger.

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