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Ancient Architectural Acoustic Resonance Patterns and Regional Brain Activity

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Abstract

Previous archeoacoustic investigations of prehistoric, megalithic structures have identified acoustic resonances at frequencies of 95–120 Hz, particularly near 110–12 Hz, all representing pitches in the human vocal range. These chambers may have served as centers for social or spiritual events, and the resonances of the chamber cavities might have been intended to support human ritual chanting. We evaluated the possibility that tones at these frequencies might specifically affect regional brain activity. In a pilot project, 30 healthy adults listened to

tones at 90, 100, 110, 120, and 130 Hz while brain activity was monitored with electroencephalography (EEG). Activity in the left temporal region was found to be significantly lower at 110 Hz than at other frequencies. Additionally, the pattern of asymmetric activity over the prefrontal cortex shifted from one of higher activity on the left at most frequencies to right-sided dominance at 110 Hz. These findings are compatible with relative deactivation of language centers and a shift in prefrontal activity that may be related to emotional processing. These intriguing pilot findings suggest that the acoustic properties of ancient structures may influence human brain function, and suggest that a wider study of these interactions should be undertaken.

Keywords: Acoustic resonance; prefrontal cortex; left temporal region; quantitative electroencephalography; cordance measure; 110 Hz.

Introduction

Previous archeoacoustic investigations have examined the acoustic properties of a sample of chambered prehistoric (primarily Neolithic) megalithic structures in England and Ireland, including the major passage-grave site of Newgrange, Ireland (constructed c.3200 BC). These structures were found to exhibit a common acoustic property: all were characterized by primary resonance frequencies in the 95–120 Hz range, with most at 110–112 Hz (Jahn et al. 1996; Devereux and Jahn 1996; cf. Devereux 2006). Notably, the central chamber of Newgrange, the largest and most architecturally sophisticated of the sites tested in that work, displayed a primary resonance frequency of 110 Hz. In some cases, fairly massive stones had been placed at particular locations within the chambers apparently to adjust their physical properties and yield these resonant properties (cf Watson, 2006).

The exact purposes of these archeological sites are incompletely understood, but it has been suggested that they served as more than simple tombs, and may have been centers for social or spiritual rituals (cf Scarre 2006). The motivation for the apparent "tuning" of the chamber cavities to particular resonance patterns is likewise unclear, but it has been suggested that cavity resonance may have been designed to support human ritual chanting, because the resonance frequency lies within the human vocal range. Certainly, considerable efforts were expended to position these massive stones in specific locations, and it seems probable that not merely was the positioning performed to create a decorative feature but that it had some more functional role. The present pilot project was conducted to evaluate the possibility that patterns of regional brain activity might be altered by listening to sounds at these specific resonance frequencies. By monitoring brain activity with the electroencephalogram (EEG) while individuals listened to tones in this frequency range, it was possible to test whether patterns of brain activity changed during brief exposure to these sounds.

Methods

Subjects

Data were collected from 30 healthy adult volunteers (16 females:14 males) who were participants in a project studying healthy aging (Cook et al. 2002a). All were in good health at the time of enrollment and had a normal neurological and psychiatric examination. Twenty-eight were right-handed; one male and one female reported being left-handed. Exclusion criteria included any active or past history of any major psychiatric disorder (an "Axis I" diagnosis, such as schizophrenia, manic depression, or Alzheimer's dementia, per American Psychiatric Association's DSM-IV manual [1994]); any poorly controlled medical illness that could affect brain function (e.g. untreated hypothyroidism); concurrent use of medications that could interfere with EEG activity (e.g. benzodiazepines); current or past drug or alcohol abuse; or any history of head trauma, brain surgery, skull defect, stroke or transient ischemic attacks, or presence of stroke on previous brain-imaging study. The mean age for all 30 subjects was 78.6 years (s.d. 6.3 yrs). The paradigm of listening to these tones was included as a task in a larger set of activations and rest periods during EEG recording in a project studying brain function and structure in healthy aging, and was reviewed and approved by the UCLA Institutional Review Board. Informed consent was obtained from all subjects, in accordance with the Declaration of Helsinki.

Acoustic Stimuli

Subjects were instructed to listen to tones at each of five frequencies (90, 100, 110, 120, and 130 Hz) as they rested with eyes closed; data recorded during each stimulus could be compared to resting baseline data (no tone). The duration of each tone was approximately 1 minute and the pure sine wave stimuli were presented in a random order through speakers positioned near the subjects' ears. Subjects were instructed to adjust the sound intensity level to a "loud but comfortable level" for that individual, and once set, was kept constant for all stimuli for that subject. They were not given any specific instructions about what to think about while listening to the tones other than to rest with closed eyes and listen; no information about the context of the hypotheses was provided to the subjects, so that their internal experiences might not be subject to contamination by statements of the investigators' expectations.

Neurophysiologic Recordings

Quantitative electroencephalography (QEEG) recordings of brain electrical activity were performed using the QND digital EEG system (Neurodata, Inc., Pasadena CA). Surface EEG activity was recording with 35 scalp electrodes, positioned with a lycra cap (ElectroCap, Inc., Eaton OH) in accordance with the standard International 10–20 system of electrode placement. Signals were recorded at 256 samples per channel per second (filter passband 0.3–70 Hz). Technical details of the recording procedure have been described elsewhere (Cook et al. 2002a).

Cordance Measure

In order to assess regional brain activity, we employed QEEG cordance, a measure which is more highly correlated with regional brain bloodflow than other QEEG spectral power measures (Leuchter et al. 1999) (see also SIDEBAR). Cordance values were calculated using 20–30 seconds of artifact free data for each tone frequency. Cordance values in the theta band (4–8Hz) have been used to detect differences in regional brain activity during treatment for depression (Cook et

Functional neuroimaging techniques provide several ways to study regional brain activity. Indirect measures of neuronal activity include PET scanning (positron emission tomography) and fMRI (functional magnetic resonance imaging): depending on the radioactive tracer injected, PET studies can yield a measure the metabolic demands of brain tissue or of regional blood flow, while fMRI data are generally interpreted as a blood-flow measure. The electrical signals recorded noninvasively at the scalp by electroencephalography (EEG) arise directly from the primary electrical events of the working brain's neuronal activity. *Quantitative* electroencephalography (QEEG) allows for the numerical measurement of this cerebral electrical activity. The classic QEEG measures of absolute and relative power yield complementary perspectives on regional brain activity (Leuchter et al. 1993): absolute power in a frequency range (e.g. alpha 8–12 Hz, theta 4–8 Hz) addresses the question "how much energy is measurable at a particular brain region" and is expressed in power units, while relative power (also in frequency bands) reflects "what percentage of the total power measured at a particular brain region is contained within that frequency band."

Cordance is derived by a linear transformation that combines absolute and relative power (Leuchter et al. 1999). By using QEEG data recorded simultaneously with ^{15}O-PET perfusion scans, cordance has been shown to be more strongly correlated with regional cerebral blood flow than either of its component parts (Leuchter et al. 1999); this relationship allows cordance findings to be interpreted in the same conceptual framework as other functional neuroimaging measures (e.g., PET and fMRI scans). The magnitude and sign of the correlation between cordance and blood-flow was found to depend upon the frequency band (Cook et al. 1998; Leuchter et al. 1998); in the theta band, the correlation is positive and significant, so larger values of theta cordance are associated with regions of higher blood flow.

Activity in the theta range is of interest in this project because the theta band has been associated with abnormalities in depression, implicating it in the processing of emotional information (Knott and Lapierre 1987; Ulrich et al. 1988a, 1988b, 1994; Knott et al. 1996, 2000, 2001, 2002; Anderer et al. 2000; Davidson et al. 2002; Davidson 2004; Pizzagalli et al. 2001; Cook et al. 2001, 2002, 2005; Bareš et al. 2007).

Theta activity in the prefrontal region is believed to reflect locally generated activity and also the influence of activity in limbic regions such as the anterior cingulate cortex (ACC) which are interconnected anatomically and functionally (Asada et al. 1999; Ishii et al. 1999; Desiraju 1976; Vogt and Pandya 1987; Koski and Paus 2000).

al. 2002b, 2005, Bareš et al. 2007) and may reflect cortically projected rhythms from the activity in deeper limbic structures that are related to emotional experience.

Statistical Analyses

For each subject, we compared average cordance values over left (T3, T5 electrodes) and right (T4, T6) temporal regions between the different stimuli using a series of paired t-tests (SPSS 13.0, SPSS, Inc., Chicago IL), because the temporal regions of the brain play important roles in processing of language and speech. We also used an asymmetry index (L-R) to assess dominance of one hemisphere or the other in the prefrontal region, using a difference between the averages of AF1 and FP1 electrodes on the left and AF2 and FP2 on the right (i.e., negative values indicate higher right-sided activity, while positive values indicate higher activity on the left). The prefrontal regions have been implicated in the balance between approach and withdrawal behaviors (cf. Davidson 2004) and ancient ritual activities could have been intended to establish a merging or affiliative bond among participants.

Results

Cordance values at 110 Hz differed from values at other frequencies in the left temporal region and over the prefrontal cortex (Table 1, Figures 1 and 2). In the left temporal region, cordance values were significantly lower at 110 Hz compared with 90 Hz ($p=0.04$), and 130 Hz ($p=0.01$), with a statistical trend value at 100 Hz ($p=0.07$). In the prefrontal region, hemispheric dominance shifted at 110 Hz. The average cordance values in channels over the left hemisphere were higher than the right at 90, 100, 120, and 130 Hz, but this prefrontal asymmetry reversed at 110Hz ($p \leq 0.05$ for 90, 100, and 130 Hz).

Comment

The central finding in this pilot study was that listening to tones at 110 Hz was associated with patterns of regional brain activity that differed from those observed when listening to tones at neighboring frequencies. These differences were statistically significant in left temporal activity and in prefrontal asymmetries. The meaning of these changes in brain function is open to speculation. The left temporal region has been implicated in

Table 1 EEG Measures at each Stimulus Frequency. Cordance in the temporal region (left side) and the frontal asymmetry index values (L-R) are shown for each frequency (mean (s.d.)).

EEG Measure	Stimulus Frequency				
	90 Hz	100 Hz	110 Hz	120 Hz	130 Hz
Temporal Cordance	1.71 (1.37)	1.69 (1.45)	1.36 (1.27)	1.45 (1.65)	1.78 (1.34)
p value (vs 110 Hz)	0.04	0.07	- -	0.31	0.01
Asymmetry Index	0.10 (1.05)	0.02 (0.88)	-0.18 (1.06)	0.12 (0.85)	0.15 (0.99)
p value (vs 110 Hz)	0.02	0.04	- -	0.05	0.03

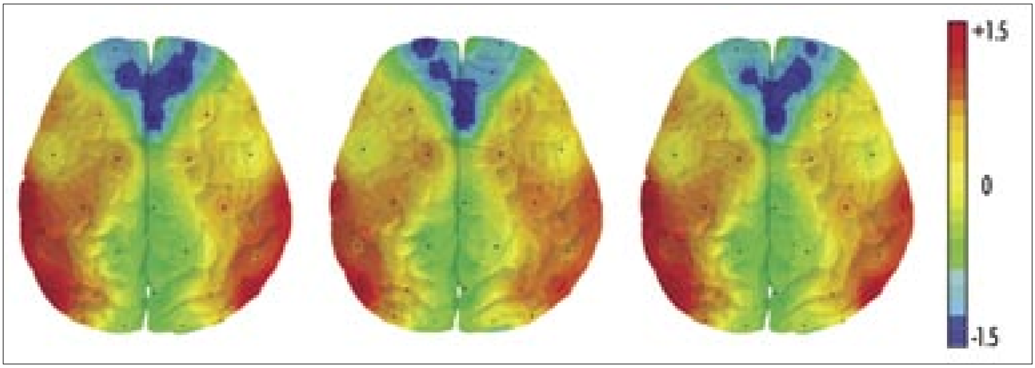
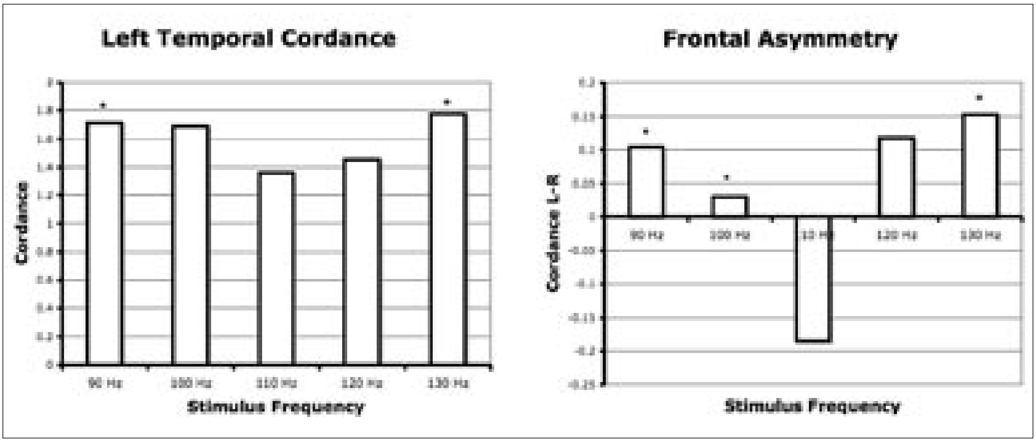


Fig 1 Changes in Regional Brain Activity at 90, 110, and 130 Hz Tones. Changes from baseline condition (no tone) are shown at three frequencies of stimulation. Red-orange colors denote increases in activity, while blue-green colors are shown over regions with decreased activity, and yellow indicates no change (mapped in cordance z-score units). Brains are shown from above.



* p<0.05 vs 110 Hz.

Fig 2 Activity at Each Frequency. Activity in the left temporal area is plotted in Panel A (upper), while asymmetries in frontal activity are shown in Panel B (lower). Values show changes from baseline condition (no tone).

the cognitive processing of spoken language; lower cordance values during the 110 Hz stimuli would be consistent with reduced activity under that condition. This might be interpreted as a relative deactivation of language centers in the brain to allow other mental processes to become more prominent. The localization to the temporal lobe is also consistent with prior studies implicating this region in the processing of musical pitch information (reviewed by Peretz and Zatorre 2005). Studies of prefrontal asymmetry have suggested that patterns of shifting asymmetry are related to emotional states (cf. Davidson et al. 2002), so the inversion of the asymmetric pattern we observed may reflect some differences in activation in cortical or cortico-subcortical networks in response to that specific tone (cf. Jackson et al. 2003).

The primary limitations of this study are the ages of the subjects, technical aspects of the stimulus exposure, reliance on self-report for assessing handedness, and concerns with the interpretive framework. The high average age of our subjects is a potential concern because it may limit generalizability of our findings, but an advantage of using this age group is that men and women can be included without concern about phase of menstrual cycle as a confound. While aging is associated with reduced ability to hear sounds at high frequencies (cf. Gates and Mills 2005), the low-pitch frequencies of 90–130 Hz in our investigation were far from that range. It is unknown whether aging may impact on the processing or the apprehension of acoustic information, though Bertoli and Probst (2005) and others have reported older subjects exhibited greater variability in an auditory evoked potential measure than did younger subjects. Future work might extend the present pilot observations by studying subjects across a wider age range. Similarly, we let subjects adjust the volume of the tones and did not record the individual sound level at the external meatus; future studies might consider either measuring this explicitly or using a fixed sound level for all subjects. As to handedness, future studies may benefit from formal testing of subject handedness, rather than relying on self-report of being right- or left-handed.

With regard to the interpretive framework, our preliminary observations arose from the simple question of whether there might be anything "special" for the brain about sounds in the resonant range of the ancient structures, which led to formal hypotheses that frontal and temporal regions would exhibit a frequency-dependent activity pattern. We did not collect information about the subjects' internal, subjective state as they listened to these sounds, and future experiments might assess whether any of the sounds lead to shifts in emotional state, in the content of the listener's thoughts, or in a sense of "disorientation" (cf. Cross and Watson 2006). Along with this, it may be useful to examine the activity in deeper limbic structures which may also participate in emotional processing of auditory information (cf. Peretz and Sloboda 2005), as these areas (e.g., amygdala, hippocampus) are also part of the "social brain" (cf. Frith 2007) and might show altered patterns of activity that could enhance ritual-based experiences. Recent analysis of resting state fMRI data has suggested that a network of brain regions may be linked in what has been termed a "default network" of areas that coordinate their activity when processing internal (as opposed to external) stimuli, such as "day dreaming" (reviewed by Raichle and Snyder, in press); it is possible that the default network may also play a role in altered-state ritual-driven experiences. This possibility could be examined explicitly in future work.

While we examined specific resonant frequencies based on the observations of Jahn, Devereux, and colleagues, other archeoacoustic work suggests a broader approach may also have merit. The study by Watson and Keating (1999) of prehistoric sites in northeast Scotland found intriguing echo patterns at the Easter Aquorthies recumbent stone circle near Aberdeen, and at Camster Round, a passage-grave in Caithness. Distortions in timbre and in speech were also noted in the Camster Round site, along with possible infrasonic resonances. These primary archeoacoustic findings merit efforts for replication, to better determine the scope and characteristics of the acoustic properties of ancient structures. Future work which incorporates measures of brain activity may examine the effects of these other sorts of acoustic phenomena. Additional quantitative analyses of the acoustic properties of ancient sites (Campos and Howard 2001; Murphy, 2006) may suggest yet other stimuli that merit investigation with brain activity measures.

Finally, it should be noted that 110 Hz is the frequency of the musical note "A" played two octaves below the 440 Hz "tuning A" used by orchestras since the adoption of the tempered musical scale in the 1700s. While this may be simply a curious coincidence, it is also possible that the development of the Western musical scale could reflect some intrinsic properties of the human brain and mind, and the acoustic properties of the neolithic structures which began this inquiry may have been selected to couple into these brain mechanisms, even if the designers of these structures had only an empirical understanding of the phenomenon. This experiment clearly cannot address this possibility, but may serve as a useful step in studying the neurophysiology of these particular frequencies.

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