

Some Investigations into Non Passive Listening.

A.R. Palmer, D.A. Hall, C. Sumner, D.J.K. Barrett, S. Jones, K. Nakamoto, D.R. Moore

*MRC Institute of Hearing Research,
University Park, Nottingham, NG7 2RD*

Abstract

Our knowledge of the function of the auditory nervous system is based upon a wealth of data obtained, for the most part, in anaesthetised animals. More recently, it has been generally acknowledged that factors such as attention profoundly modulate the activity of sensory systems and this can take place at many levels of processing. Imaging studies, in particular, have revealed the greater activation of auditory areas and areas outside of sensory processing areas when attending to a stimulus. We present here a brief review of the consequences of such non-passive listening and go on to describe some of the experiments we are conducting to investigate them. In imaging studies, using fMRI, we can demonstrate the activation of attention networks that are non-specific to the sensory modality as well as greater and different activation of the areas of the supra-temporal plane that includes primary and secondary auditory areas. The profuse descending connections of the auditory system seem likely to be part of the mechanisms subserving attention to sound. These are generally thought to be largely inactivated by anaesthesia. However, we have been able to demonstrate that even in an anaesthetised preparation, removing the descending control from the cortex leads to quite profound changes in the temporal patterns of activation by sounds in thalamus and inferior colliculus. Some of these effects seem to be specific to the ear of stimulation and affect interaural processing. To bridge these observations we are developing an awake behaving preparation involving freely moving animals in which it will be possible to investigate the effects of consciousness (by contrasting awake and anaesthetized), passive and active listening.

Selective attention to sensory input

Perception is much more than a passive interpretation of the information derived from our senses. A variety of factors determine what we perceive, some under conscious control while others are more automatic. One of the main factors that influences auditory perception is attention. Selective attention is a top-down function that facilitates the selection of a target object when other objects are present in the scene. There is some evidence that attention is necessary for using schema-driven constraints for the sequential grouping of sounds into separate auditory streams (Carlyon et al., 2001; 2003), although this interpretation has been challenged (Macken et al., 2003). Attention also seems to be required for making perceptual comparisons between sounds since patients with attentional deficits due to cortical lesions are impaired at 2-interval 2-alternative forced-choice frequency discrimination (Cusack et al., 2000) and also at temporal order judgements task (Karnath et al., 2002). In both visual and auditory systems, there have been many studies using ERPs (see Anllo-Vento et al., 2004; Naatanen and Alho, 2004 for reviews) that have demonstrated effects of attention on sensory processing, but more recently the advent of other imaging technologies has enabled cogent answers to some of the questions about where and how attention modulates activity in sensory systems. These have revealed, for example, that attending to an area of visual space increases both the baseline and the gain in appropriate retinotopic regions at very early stages of processing (V1) and this effect is stronger in most subsequent regions of visual processing (e.g. Tootell et al., 1998). Researchers make the distinction between ‘sources’ and ‘sites’ of attention modulation (Anllo-Vento et al., 2004.). The fronto-parietal network seems to function as an attention control ‘source’, mediating the modulation of activity in sensory areas of the brain via descending input to appropriate sensory ‘sites’ (see Kanwisher and Wojciulik, 2000 for review). Attention-demanding tasks therefore typically engage a distributed set of cortical areas regions reflecting the interplay between bottom-up stimulus-driven and top-down modulatory processes.

Compared to research on aspects of visual attention, there have been many fewer studies conducted on auditory attention. However, the evidence so far provides support for the fronto-parietal control network being a general purpose system that is engaged during many different types of perceptual tasks. A number of different listening tasks have been shown to engage these higher brain centres irrespective of the class of sound stimulus and whether selective attention is directed towards the spatial or the non-spatial features of that target sound (e.g. Zatorre et al., 1999; Maeder et al., 2001). Auditory sites of attention also show enhancement of activation as a function of the listening instructions. For example in a recent study a group of ten listeners were instructed to detect shorter duration targets in the one of two pitch streams (attend pitch), in the left or right ears (attend location) or in one of two sequences of attended coloured circles (attend vision) (Degerman et al., 2006). Both attention to location and attention to pitch produced enhanced activity in widespread areas of the superior temporal cortex when compared with activation caused by the same sounds when attention was directed to the pictures. The precise spatial topography of the modulatory effects of attention and its relationship to the underlying feature-based specificity of neural coding has yet to be fully explored.

In this short account we review three different lines of work that address intentional modulation of auditory processing with different techniques and at different levels. In the first, we describe some recent fMRI data that again confirm

that activity in the auditory cortex is much enhanced, occurs over a wider extent and engages additional brain centres when attending rather than passively listening. In the second, we describe current acute physiological experiments in which we are investigating the nature of the modulation of auditory processing in thalamus and midbrain by corticofugal activity. Finally, we provide a glimpse of where we are currently putting our efforts into developing an awake behaving preparation that should allow us to directly examine the relationships between neural coding, auditory perception and behaviour.

Some effects of selective attention shown by fMRI of the auditory cortex

Very early on in our program of fMRI imaging it became abundantly clear from both our own data (e.g. Hall et al., 2000; Hart et al., 2004) and from elsewhere, that the attentive state of the listener had a radical effect on the activation that we could detect. In its simplest form, this involved using oddball (target detection) paradigms to ensure that the listener remained attentive (e.g. Hall et al., 2000). More sophisticated paradigms use well-controlled signals that allow discrimination of two different dimensions depending on the instructions to the listener: e.g. signals where the listener is instructed to attend to frequency changes *or* its spatial position changes (Degerman et al., 2006; Hart et al., 2004). Hart et al. (2004) reported that detection of motion produced stronger activation in the medial part of planum temporale while detection of frequency modulation produced stronger activation in the lateral part of planum temporale as well as an additional non-primary area lateral to Heschl's gyrus. Activation of the parietal cortex (already implicated in several studies to be involved in the perception of auditory motion: see Griffiths and Green, 1999; Griffiths et al., 2000; Griffiths et al., 1998) was dependent on the task of motion detection, not simply on the presence of the acoustic cue for motion. These data suggest that the parietal cortex is part of a spatial attention network rather than an area specialised for processing the cues for auditory motion.

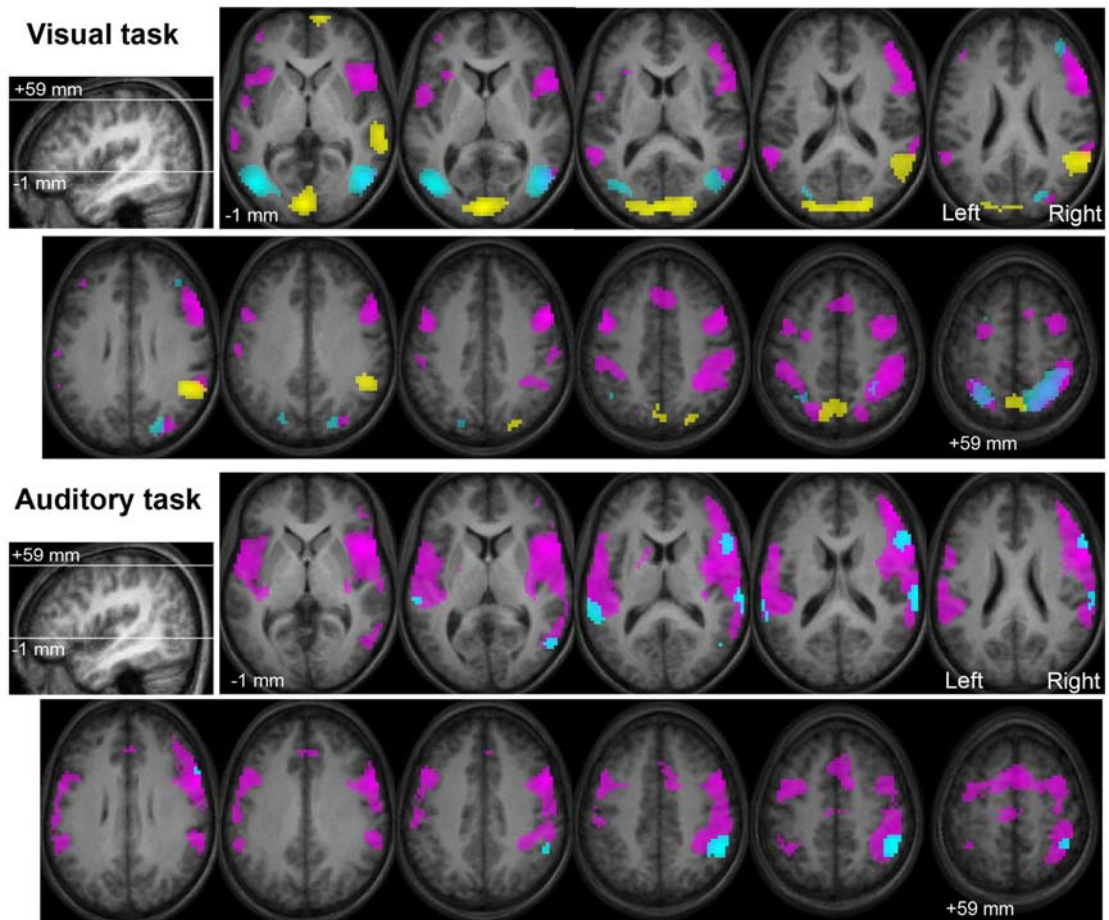


Figure 1. Distributed cortical activation driven by bottom-up (stimulus) and top-down (attentional) factors ($P < 0.001$). Activation in yellow represents the response to the presence of the fixed-location stimulus. Activation reached significance only for the visual task, indicating that the auditory response rapidly habituates to a static signal. Cyan coloured regions reflect motion-sensitivity in the passive condition and include visual (V5) and auditory (planum temporale) cortices. Activation in pink is specifically linked to attending to the moving stimulus. Data are taken from a recent unpublished study in our laboratory and are overlaid onto the mean anatomical image for this set of listeners (horizontal slices separated by 6 mm).

Figure 1 presents a direct comparison of the effects of auditory and visual spatial attention; a study that was recently conducted in a Philips 3 T scanner. In this experiment six participants underwent matched auditory and visual tasks, each comprising four stimulus conditions. (i) empty track/silence, (ii) watch/listen to a static stimulus, (iii) watch/listen to a rotating stimulus and (iv) the same rotating stimulus with specific instructions to attend to the changes in the rate of the rotation. In fact, there were never any changes in rotation speed, but prior training had induced this expectation. The auditory stimulus was a diotic noise continuously presented at a constant level at a fixed location in the azimuthal plane (static) or convolved with head-related transfer functions (rotating). The visual stimulus was a coloured arc continuously presented at a fixed location on a circular track (static) or moving around this track (rotating). Each condition lasted 32 seconds and images were acquired every 4 seconds. The data from all six listeners were subjected to a fixed-effects analysis. The response to the presence of the static stimulus was computed from (ii) – (i) and the response to the stimulus motion was computed from (iii) – (ii),

while the effect of attention to the motion from (iv) – (iii). Figure 1 demonstrates that motion-sensitivity was revealed in visual area V5 and auditory planum temporale; both areas that are traditionally linked with spatial analysis. In contrast, spatial attention engaged many regions of the frontal and parietal lobes that were not activated when passively watching or listening to the same moving stimulus. These could be the ‘sources’ of attention discussed previously. Critically we also found attention-related increases to be overlapping with areas of motion-sensitivity. These regions are candidates for ‘sites’ of attention. For example in the planum temporale, the regions showing significant motion sensitivity (cyan, see horizontal slices 5-24 mm) also increased their response when attention was directed to the speed of motion. To quantify the magnitude of this attentional modulation, the average contrast-weighted beta values were calculated across those voxels that both responded to the moving sound and were modulated by attention. The resulting values support the assertion that the response to the moving sound in planum temporale is enhanced when attention is directed towards that auditory feature (Figure 2). We observed the same pattern of response in the right inferior parietal region (horizontal slices 41-59 mm) indicating that both stimulus-driven and attentional responses additionally engage higher cortical sites, not just within those regions traditionally viewed as ‘the auditory cortex’.

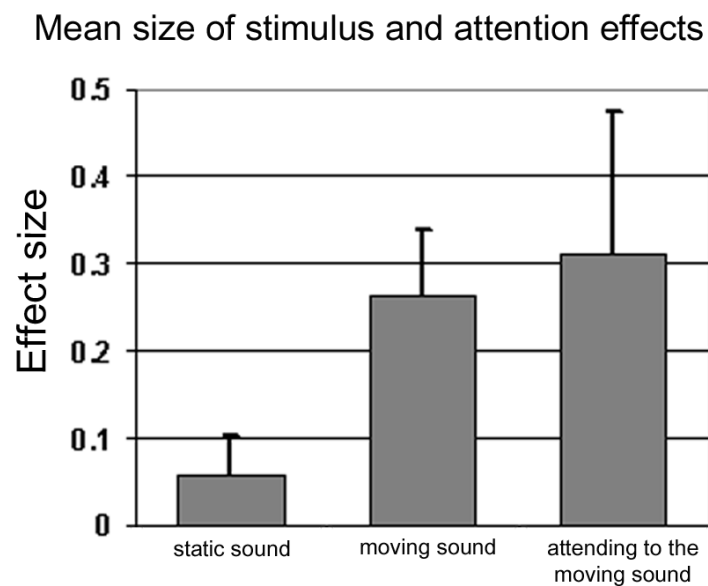


Figure 2. Mean effect size is plotted for three different stimulus and task contrasts (see text for a description of the contrasts). Error bars indicate the standard error across listeners.

Corticofugal modulation of auditory processing

It has long been assumed that the profuse descending system (e.g Winer, 2005; Winer et al., 2001; Winer and Larue, 1987) from the cortex that reaches all the way down to the level of the cochlear nucleus is likely to play a role in selective attention, among other things. We are currently investigating the mechanisms of such corticofugal modulation. Following earlier work at lower levels of the system, in acute experiments we are characterising the different regions of the guinea pig auditory cortex (Rutkowski et al., 2002; Rutkowski et al., 2000; Wallace et al., 1999, 2000a, 2002a, 2005a; Wallace et al., 2000b; Wallace et al., 2005b; Wallace et al., 2002b). However, we have recently begun to bridge the gap between our earlier work

in lower levels of the auditory pathway (up to and including the inferior colliculus) and the cortical work with a series of studies of the auditory thalamus. Having characterised further the guinea pig auditory thalamus (e.g. Anderson et al., 2006) we are now assessing the role of the descending system from the cortex on the processing in the thalamus and inferior colliculus.

Apart from a role in selective attention, several possible functions for the descending systems have been proposed and each has received some experimental support. There are several ways in which the descending system to the thalamus has been manipulated. In the visual system Sillito and colleagues (e.g. Murphy et al., 1999; see Sillito and Jones, 2002 for review) chemically switched off the descending influences while recording from cortical and thalamus cells. Two major effects were observed in the thalamus: the spatial tuning of the cells became broader and their output was less synchronised. Sillito and Jones (2002) interpreted the change in synchronisation as affecting the binding (or grouping) together of elements of the visual scene optimising the thalamic contribution to segmentation and global integration. In the bat auditory thalamus the descending influences from the cortex were deemed responsible for systematic shifts in the echo-delay tuning (Yan and Suga, 1996).

He and his colleagues (He, 2003; He et al., 2002) used focal electrical stimulation of the auditory cortex and showed that it was possible to both facilitate (mainly in the ventral division of the medial geniculate body) and suppress (in nonlemniscal parts of the medial geniculate body) different thalamic neurons. They suggested that such modulation of the ascending information could play a role in attentional processes by selectively gating the information passing through the lemniscal pathways, while switching off other unwanted sensory signals.

Suga and his colleagues (Yan and Suga, 1996; Zhang et al., 1997) focally stimulated or applied lidocaine to focally suppress auditory cortical output in the bat and showed that the frequency and duration tuning of thalamic and collicular neurones changed in reciprocal ways. When the cortex was electrically stimulated at a frequency region distant from the characteristic frequency (CF) of the simultaneously recorded thalamic neurones, the thalamic CF shifted away from that of the stimulated region. When the cortex was chemically switched off in a similarly distant focal region the CF of the thalamic neurones moved towards that of the suppressed region. In both cases the tuning recovered to the pre stimulation/suppression condition. Similar effects were also found for duration tuning in inferior colliculus (Ma and Suga, 2001). These results were interpreted as demonstrating plasticity and memory effects. It had previously been suggested by Suga that the basis of various changes he saw in the thalamus was cortico fugal feedback.

Our preparation is an acute fully anaesthetised guinea pig and *a priori* our expectation was that the descending systems from cortex would not be very active under these conditions. Further, based on the earlier findings, we had anticipated that it would be necessary to focally stimulate the cortex while recording in an appropriate frequency region in order to see any effects of the descending system. We even considered the possibility that we might well have to search for linked pairs of thalamus and cortex neurons. However, our initial experiments showed that the corticofugal system was indeed active under our anaesthetic conditions and that by globally switching off the cortex we could expose quite complicated effects on the activity of virtually all thalamic neurones. That is not to say that focal suppression or stimulation will necessarily have exactly the same effect, but that is for later

investigation. We used two ways to deactivate the cortex while recording with a multielectrode array in the thalamus: bathing the cortical surface with lignocaine, which was almost irreversible, and cooling with a cryoloop which was rapidly reversible. The advantage of the latter technique is that the rapidity of the reversibility allowed us to use each neuron as its own control. During these cooling experiments we also recorded cortical activity (either isolated cells or evoked potentials) with a single extracellular electrode in the deeper layers (about 1 mm below the cortical surface) to ensure that the cooling process did in fact suppress cortical activity.

Switching off the whole cortex with lignocaine produced a surprising result. We were measuring full frequency response areas in response to signals presented to ipsilateral, contralateral or both ears. We found profound effects of suppressing the cortex, but only on the responses measured with presentations to the ipsilateral ear. In one instance a neuron in which there was virtually no response at all to the ipsilateral stimulus developed a strong well frequency-tuned response that was almost as strong as that to the contralateral stimulus. Binaural responses were generally dominated by the contralateral response and since this changed little neither did the binaural responses.

Moving to the cooling experiments has allowed us to collect vastly more data as we can conduct many cycles of cooling in different electrode positions within the thalamus. Initially, we continued to measure the full frequency response area, but later to increase the yield we found that we could see profound effects simply by measuring the response to a short click. We again found ear specific changes in the thalamic neural activity. However, with a much larger sample we were now able to demonstrate that removal of descending influences from the cortex could suppress or facilitate the activity from either ear. In some notable examples, the effects were reciprocal: the contralateral ear was facilitated while the ipsilateral response was suppressed and *vice versa* in other neurons.

Figure 3 shows two examples of such reciprocal responses. The neuron shown on the left responded poorly to the clicks presented to the contralateral ear: indeed contralateral stimulation appeared to suppress what little spontaneous activity was present. When the cortex was cooled a prominent response appeared to the contralateral clicks as shown by the upward arrow. At the same time the weak ipsilateral response was completely suppressed as shown by the downward arrow. When the cortex returned to normal temperature, the responses reverted to that before cooling and if anything were slightly stronger. The neuron shown on the right of the figure had a strong response to contralateral clicks which was almost completely suppressed by cooling the cortex (downward arrow). The ipsilateral response was slightly stronger when the cortex was cooled. Again the precooling levels of response returned when the cortex returned to normal temperature. Activity monitored by the single microelectrode situated in the cortex completely stopped during the cooling. In our current sample we have found almost all combinations of facilitation and suppression of the response from each ear and have found that the effect of the cortex could modulate activity within discrete time windows located at short (arrows in columns 3 and 4 of Figure 3 ~50 ms) medium (arrow in first column in Figure 3 near ~100 ms) or long (arrow in second column of Figure 3 ~200ms) times after the click stimulus. Both neurones in Figure 3 were recorded simultaneously on different electrodes. We are currently relating the different types of corticofugal modulation to the topographical position within the thalamus to enable us to link this back to the exact sources within the cortex.

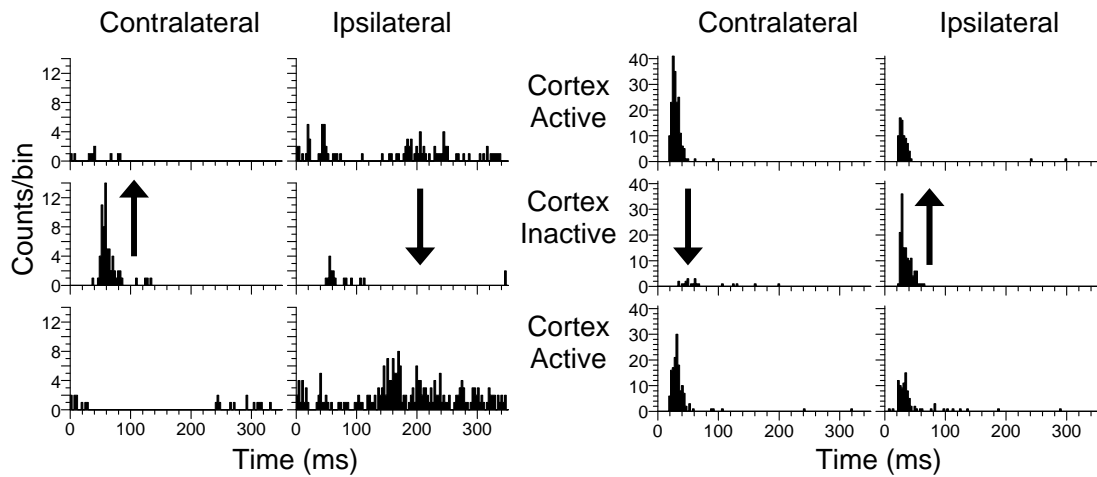


Figure 3. Post stimulus time histograms of the responses of two neurons recorded simultaneously at different places in the auditory thalamus to short clicks presented to either ipsilateral or contralateral ears. The top row shows the responses before cooling the cortex, the middle row when the cortex was cooled and the bottom row when the cortex has returned to normal temperature.

The ear specificity of the modulation was somewhat of a surprise given that most of the commissural connections in the ascending auditory pathway are below the thalamus. So although the descending system from cortex to thalamus is extremely extensive, to assess whether the input to the thalamus was already modulated by the cortex in an ear specific manner we repeated the experiment while recording at the level of the inferior colliculus. In response to the same click stimuli we were again able to identify cortical effects on the responses in the inferior colliculus that were occurring in discrete time windows as shown by the arrows in Figure 4. However, our initial analyses have not revealed any corticofugal effects at the very long latencies that we found in some thalamic neurons. Deactivation of the cortex suppressed or facilitated peaks in the response to the click that occurred at different times. In Figure 4, for example, the very large peak at about 30 ms latency in response to either ear or both was suppressed when the cortex was deactivated. The longer latency small peak (near 70 ms) was facilitated. In this instance if cooling generated an inhibitory effect at the 30 ms latency the peak that appears at around 70 ms could be an inhibitory rebound.

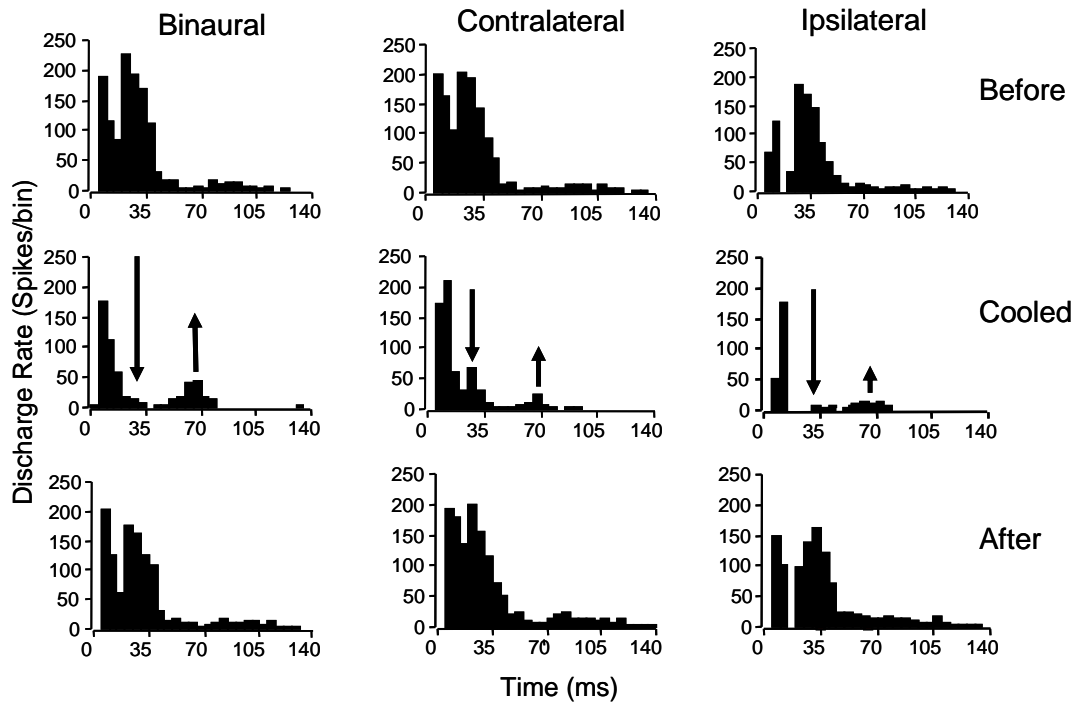


Figure 4. *Effect of deactivating the cortex by cooling on the responses of an inferior colliculus neuron to short clicks*

We have now extended these studies to simultaneous recording with multielectrodes in inferior colliculus and thalamus while monitoring and cooling the cortex. These studies are at an early stage but should provide the means of separating the effects of corticofugal modulation at the input to the thalamus from that due to the profuse projection to the thalamus directly from the cortex. While we have not yet fully examined the current data, it seems quite likely that using eight electrodes simultaneously in each of the thalamus and inferior colliculus and sampling many sites in each nucleus that we should be able to isolate cells that are directly connected. This would be a very powerful tool to unravel the site of corticofugal effects. What we cannot do in this preparation is activate the descending system in ways that are likely to mimic its normal activity.

An animal model of listening

There are a number of drawbacks to anaesthetised preparations. It is generally assumed that much of the descending control is not active or not as active under anaesthesia. Notwithstanding the data described above this is likely to be the case. Certainly, even if active, the descending systems will not be fulfilling their usual role when the animal is asleep. Anaesthesia also shifts the overall balance of excitatory and inhibitory processes (Populin, 2005). The dominant effect is a reduction in activity under anaesthesia (Pfungst et al., 1977), although details of the effects are undoubtedly more complex (Gaese and Ostwald, 2001; Syka et al., 2005). High sustained firing rates not traditionally associated with cortical neurons under anaesthesia are now being recorded from awake animals (Wang et al., 2005).

There may also be key differences in neural processing that occurs when passively hearing compared to actively listening. Most studies show that performance in a behavioural task increases the reliability of auditory responses (Benson et al., 1981; Pfungst et al., 1977; Ryan and Miller, 1977). Training can also have a profound

effect on auditory neural responses (Miller et al., 1972). It seems logical that such performance would properly activate descending systems whenever necessary.

Examining the effects of selective attention requires a conscious, active animal and a behavioural task that manipulates the focus of attention, ideally without changing any other parameters. The reported effects of attention in auditory cortex have been mixed: for example, there is a wide range in the reported percentages of neurons which are affected by attention (Benson and Hienz, 1978; Hocherman et al., 1976; Hubel et al., 1959). In one study (Hocherman et al., 1976) monkeys attended to simultaneous sounds and lights from left and right, and indicated the stimulus location. They were able to show that the responses of 2/3 of neurons were modulated by the choice of relevant stimuli.

A number of correlations between psychophysical thresholds and the information contained in neural firing have been found in anaesthetised preparations (e.g. Ehret and Merzenich, 1985; Pressnitzer et al., 2001; Shackleton et al., 2003). Differences between these measures are often quantitative rather than qualitative and performance is often best predicted by most sensitive neurons. These studies nevertheless suffer from the limitations above. There is also the concern that these correlations may break down in a more appropriate awake-behaving preparation. Furthermore, they most often compare human psychophysical performance with neural responses in animals: given the frequent lack of exact correspondence in human and animal behavioural measures, this may be inappropriate. Clearly, in an awake behaving preparation, where neural and psychophysical data can be collected simultaneously from the same individual this problem does not arise. In area MT of the visual cortex, for example, this paradigm has shown that behavioural responses to near-threshold stimuli weakly correlate with individual neural responses on a trial-by-trial basis (Newsome et al., 1989).

The paucity of studies in awake-behaving animals is such that we do not really know what the relative effects are of manipulations of consciousness, active or passive states, or selective attention. Likewise, the awake behaving preparation is not a panacea for linking perception to neural responses: it can only show a correlation. Nevertheless, it is clear that such techniques allow us to study listening properly at the level of the single neuron.

We are in the process of developing an awake behaving ferret preparation from which we can record activity while the animal is freely moving and responding to behaviourally relevant stimuli. So far, we have developed the enabling technology. Figure 5 shows the device we have developed for awake freely moving recordings. A specially-designed amplifier PCB amplifies and filters 15 channels from a 16 channel microwire implant. The 16th channel is connected to an infrared receiver that receives a coded synchronisation pulse from an infrared LED array. These analogue signals are then sent via a DSP controlled analogue-to-digital converter that samples each channel at 12 kHz and saves the waveform data to a compact flash card. The current version will take a 4 GB CF card which allows for up to 3 hours continuous recording. This should be more than enough as we are training ferrets to do behavioural tasks to earn water rewards and they only work for about 30-45 minutes at a time. For the behavioural part of the work we have built a circular arena equipped with loudspeakers and water spouts at 12 spatial positions. This allows us to run various localisation and detection paradigms with only software changes between tasks. Our current localisation task uses an approach to target method of determining the animals response (similar to Kacelnik et al., 2006). Detection experiments use a 1-interval 2-alternative choice procedure with ferrets approaching

one spout to indicate the presence of a signal, and another to indicate its absence (similar to Hine et al., 1994). At present we have several fully trained ferrets taking part in signal detection and localisation tasks and are now ready to implant the microwire electrodes.

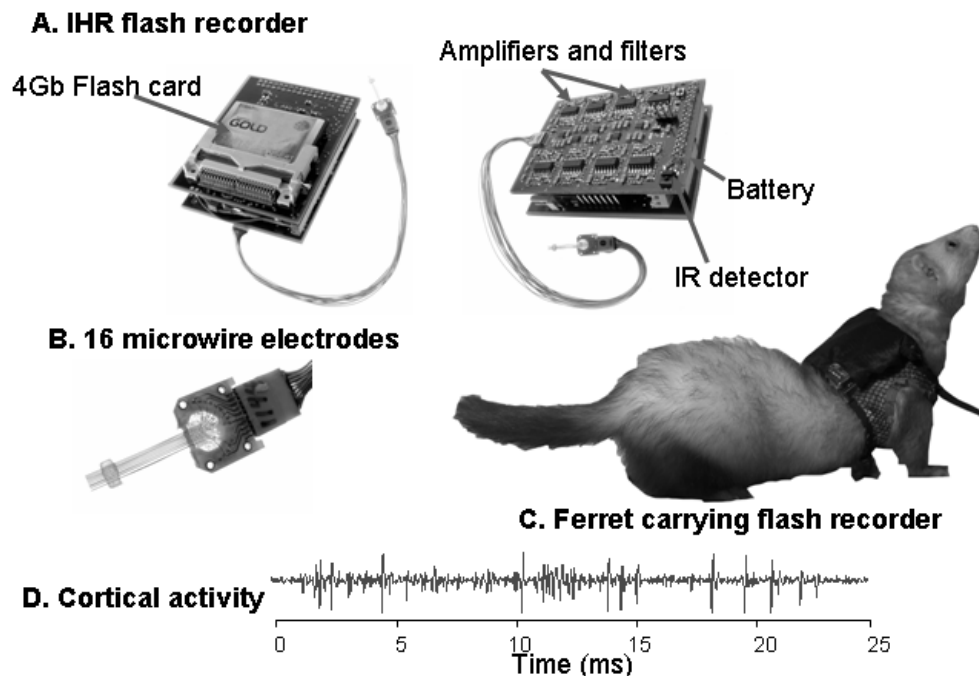


Figure 5 A. A. IHR flash recorder showing the 4 GB flash card, the amplifiers, filters and IR detector used to record synchronization pulses. B. TDT 16 channel microwire array. C. Ferret wearing a backpack containing the IHR flash recorder D. Activity recorded in guinea pig cortex with the flash recorder and TDT electrodes .

Conclusions

The use of acute anaesthetized preparations has, over several decades, revealed much of the processing of auditory signals in the ascending auditory pathway. Behavioural studies and the advent of various non-invasive techniques for studying the human brain have demonstrated the self evident fact that merely passively processing the information provided by the sense organs is only part of the story where perception is concerned. Our combination of human neuroimaging with awake and anaesthetized animal preparations will provide a powerful approach to understanding the neural basis of auditory perception.

The activation of the supra-temporal plane, an area that includes both primary and secondary auditory cortical areas in the human, is hugely affected by the listening task. In general, attending to different aspects of an auditory signal selectively activates areas that are likely to be involved in processing those specific aspects of sound. We are using high-resolution fMRI (1.5 x 1.5 x 2.5 mm) to quantify the cortical effects of auditory attention with better spatial precision than has hitherto been achieved. In addition, tasks that require the listener to selectively attend reveal at least two networks that project from the auditory cortex to the frontal cortex. Whether these represent the exact homologue of the dorsal and ventral processing streams in vision remains to be confirmed. It seems highly likely that the descending systems to all levels of the auditory brain will also be engaged when there is enhanced

auditory cortical activation by selective attention. We are using an acute preparation and cryoloop deactivation of the cortex to reveal the manner of the corticofugal modulation of auditory processing in the auditory midbrain and thalamus. We have found facilitative and suppressive modulation of the ascending activity that is specific to the ear of presentation. We are planning to use more ecological stimulation probably using signals with spectral complexity and spatial position to further investigate what effect this rich descending modulation has on the processing of such signals. In parallel we are developing an awake behaving preparation that will naturally engage the mechanisms of listening including attentive modulation of sensory processing. This area of research is quite immature and there are many basic questions to be addressed, and challenging experimental issues to be overcome. Hopefully, this will ultimately allow us to approach to some of the thornier problems of active listening such as segregation and grouping.

References

- Anderson, L.A., Malmierca, M.S., Wallace, M.N., Palmer, A.R. 2006. Evidence for a direct, short latency projection from the dorsal cochlear nucleus to the auditory thalamus in the guinea pig. *European Journal of Neuroscience* 24, 491-498.
- Anllo-Vento, L., Schoenfeld, M.A., Hillyrad, S.A. 2004. Cortical mechanisms of visual attention. In: Posner, M.I., (Ed.), *Cognitive neuroscience of attention*. Guilford Press, Posner, M.I. pp. 180-193.
- Benson, D.A., Hienz, R.D. 1978. Single-unit activity in the auditory cortex of monkeys selectively attending left vs. right ear stimuli. *Brain Research* 159, 307-20.
- Benson, D.A., Hienz, R.D., Goldstein, M.H., Jr. 1981. Single-unit activity in the auditory cortex of monkeys actively localizing sound sources: spatial tuning and behavioral dependency. *Brain Research* 219, 249-67.
- Ehret, G., Merzenich, M.M. 1985. Auditory midbrain responses parallel spectral integration phenomena. *Science* 227, 1245-7.
- Gaese, B.H., Ostwald, J. 2001. Anesthesia changes frequency tuning of neurons in the rat primary auditory cortex. *Journal of Neurophysiology* 86, 1062-6.
- Griffiths, T.D., Green, G.G.R. 1999. Cortical activation during perception of a rotating wide-field acoustic stimulus. *Neuroimage* 10, 84-90.
- Griffiths, T.D., Green, G.G.R., Rees, A., Rees, G. 2000. Human brain areas involved in the analysis of auditory movement. *Human Brain Mapping* 9, 72-80.
- Griffiths, T.D., Rees, G., A., R., Green, G.R., Witton, C., Rowe, D., Buchel, C., Turner, R., Frackowiak, R.S.J. 1998. Right parietal cortex is involved in the perception of sound movement in humans. *Nature Neuroscience* 1, 74-79.
- Hall, D.A., Haggard, M.P., Akeroyd, M.A., Summerfield, A.Q., Palmer, A.R., Elliott, M.R., Bowtell, R.W. 2000. Modulation and task effects in auditory processing measured using fMRI. *Human Brain Mapping* 10, 107-119.
- Hart, H.C., Palmer, A.R., Hall, D.A. 2004. Different areas of human non-primary auditory cortex are activated by sounds with spatial and nonspatial properties. *Human Brain Mapping* 21, 178-190.
- He, J. 2003. Corticofugal modulation on both on and off responses in the nonlemniscal auditory thalamus of the guinea pig. *Journal of Neurophysiology* 89, 367-381.

- He, J., Yu, Y.-Q., Xiong, Y., Hashikawa, T., Chan, Y.-S. 2002. Modulatory effect of cortical activation on the lemniscal auditory thalamus of the guinea pig. *Journal of Neurophysiology* 88, 1040-1050.
- Hine, J.E., Martin, R.L., Moore, D.R. 1994. Free-field binaural unmasking in ferrets. *Behav Neurosci* 108, 196-205.
- Hocherman, S., Benson, D.A., Goldstein, M.H., Jr., Heffner, H.E., Hienz, R.D. 1976. Evoked unit activity in auditory cortex of monkeys performing a selective attention task. *Brain Research* 117, 51-68.
- Hubel, D.H., Henson, C.O., Rupert, A., Galambos, R. 1959. Attention units in the auditory cortex. *Science* 129, 1279-80.
- Kacelnik, O., Nodal, F.R., Parsons, C.H., King, A.J. 2006. Training-induced plasticity of auditory localization in adult mammals. *Public Library of Science Biology* 4, e71.
- Kanwisher, N., Wojciulik, E. 2000. Visual attention: insights from brain imaging. *Nature Reviews Neuroscience* 1, 91-100.
- Ma, X., Suga, N. 2001. Corticofugal modulation of duration-tuned neurons in the midbrain auditory nucleus in bats. *Proceedings of the National Academy of Science* 98, 14060-14065.
- Maeder, P.P., Meuli, R.A., Adriani, M., Bellmann, A., Fornari, E., Thiran, J.-P., Pittet, A., Clarke, S. 2001. Distinct pathways involved in sound recognition and localisation: a human fMRI study. *NeuroImage* 14, 802-816.
- Miller, J.M., Sutton, D., Pfingst, B., Ryan, A., Beaton, R., Gourevitch, G. 1972. Single cell activity in the auditory cortex of Rhesus monkeys: behavioral dependency. *Science* 177, 449-51.
- Milner, A.D., Goodale, M.A. 1995. *The visual brain in action* Oxford University press, New York.
- Murphy, P.C., Duckett, S.G., Sillito, A.M. 1999. Feedback connections to the lateral geniculate nucleus and cortical response properties. *Science* 286, 1552-1554.
- Naatanen, R., Alho, K. 2004. Mechanisms of auditory attention as revealed by event-related potentials of the brain. In: Posner, M.I., (Ed.), *Cognitive neuroscience of attention*. Guilford Press, Posner, M.I. pp. 194-206.
- Newsome, W.T., Britten, K.H., Movshon, J.A. 1989. Neuronal correlates of a perceptual decision. *Nature* 341, 52-4.
- Pfingst, B.E., O'Connor, T.A., Miller, J.M. 1977. Response plasticity of neurons in auditory cortex of the rhesus monkey. *Experimental Brain Research* 29, 393-404.
- Populin, L.C. 2005. Anesthetics change the excitation/inhibition balance that governs sensory processing in the cat superior colliculus. *Journal of Neuroscience* 25, 5903-14.
- Pressnitzer, D., Meddis, R., Delahaye, R., Winter, I.M. 2001. Physiological correlates of comodulation masking release in the mammalian ventral cochlear nucleus. *Journal of Neuroscience* 21, 6377-86.
- Rutkowski, R.G., Wallace, M.N., Shackleton, T.M., Palmer, A.R. 2000. Organisation of binaural interactions in the primary and dorsocaudal fields of the guinea pig auditory cortex. *Hearing Research* 145, 177-189.
- Rutkowski, R.G., Shackleton, T.M., Schnupp, J.W.H., Wallace, M.N., Palmer, A.R. 2002. Spectro-temporal receptive field properties of single units in the guinea pig auditory cortex. *Audiology and Neuro-Otology* 7, 214-228.

- Ryan, A., Miller, J. 1977. Effects of behavioral performance on single-unit firing patterns in inferior colliculus of the rhesus monkey. *Journal of Neurophysiology* 40, 943-56.
- Shackleton, T.M., Skottun, B.C., Arnott, R.H., Palmer, A.R. 2003. Interaural time difference discrimination thresholds for single neurons in the inferior colliculus of guinea pigs. *Journal of Neuroscience* 23, 716-724.
- Sillito, A.M., Jones, H.E. 2002. Corticothalamic interactions in the transfer of visual information. *Proceedings of the Royal Society of London B* 357, 1739-1752.
- Syka, J., Suta, D., Popelar, J. 2005. Responses to species-specific vocalizations in the auditory cortex of awake and anesthetized guinea pigs. *Hearing Research* 206, 177-84.
- Tootell, R.B., Hadjikhani, N., Hall, E.K., Marrett, S., Vanduffel, W., Vaughan, J.T., Dale, A.M. 1998. The retinotopy of visual spatial attention. *Neuron* 21, 1409-1422.
- Wallace, M.N., Rutkowski, R.G., Palmer, A.R. 1999. A ventrorostral belt is adjacent to the guinea pig primary auditory cortex. *Neuro Report* 10, 2095-2099.
- Wallace, M.N., Rutkowski, R.G., Palmer, A.R. 2000a. Identification and localisation of auditory areas in guinea pig cortex. *Experimental Brain Research* 132, 445-456.
- Wallace, M.N., Rutkowski, R.G., Palmer, A.R. 2002a. Interconnections of auditory areas in the guinea pig neocortex. *Experimental Brain Research* 143, 106-119.
- Wallace, M.N., Shackleton, T.M., Palmer, A.R. 2002b. Phase-locked responses to pure tones in the primary auditory cortex. *Hearing Research* 172, 160-171.
- Wallace, M.N., Rutkowski, R.G., Palmer, A.R. 2005a. Responses to the purr call in three areas of guinea pig auditory cortex. *Neuro Report* 16, 2001-2005.
- Wallace, M.N., Rutkowski, R.G., Shackleton, T.M., Palmer, A.R. 2000b. Phase-locked responses to pure tones in guinea pig auditory cortex. *Neuroreport* 11, 1-5.
- Wallace, M.N., Shackleton, T.M., Anderson, L.A., Palmer, A.R. 2005b. Representation of the purr call in the guinea pig primary auditory cortex. *Hearing Research* 204, 115-126.
- Wang, X., Lu, T., Snider, R.K., Liang, L. 2005. Sustained firing in auditory cortex evoked by preferred stimuli. *Nature* 435, 341-6.
- Westbury, C.F., Zatorre, R.J., Evans, A.C. 1999. Quantifying variability in the planum temporale: A probability map. *Cerebral Cortex* 9, 392-405.
- Winer, J.A. 2005. Decoding the auditory corticofugal systems. *Hearing Research* 207, 1-9.
- Winer, J.A., Larue, J.T. 1987. Patterns of reciprocity in auditory thalamocortical and corticothalamamic connections: study with horse-radish peroxidase and autoradiographic methods in the rat medial geniculate body. *Journal of Comparative Neurology* 257, 282-315.
- Winer, J.A., Diehl, J.J., Larue, J.T. 2001. Projections of auditory cortex to the medial geniculate body of the cat. *Journal of Comparative Neurology* 430, 27-55.
- Yan, J., Suga, N. 1996. Corticofugal modulation of time-domain processing of biosonar information in bats. *Science* 273, 1100-1103.
- Zhang, Y., Suga, N., Yan, J. 1997. Corticofugal modulation of frequency processing in the bat auditory system. *Nature* 387, 900-903.

- Carlyon RP, Cusack R, Foxton JM, Robertson IH (2001) Effects of attention and unilateral neglect on auditory stream segregation *Journal Of Experimental Psychology-Human Perception And Performance* 27 (1): 115-127.
- Carlyon RP, Plack CJ, Fantini DA, Cusack R (2003) Cross-modal and non-sensory influences on auditory streaming *Perception* 32 (11): 1393-1402
- Macken WJ, Tremblay S, Houghton RJ, Nicholls AP, Jones DM (2003) Does auditory streaming require attention? Evidence from attentional selectivity in short-term memory *Journal Of Experimental Psychology-Human Perception And Performance* 29 (1): 43-51
- Cusack R, Carlyon RP, Robertson IH (2000) Neglect between but not within auditory objects *Journal Of Cognitive Neuroscience* 12 (6): 1056-1065
- Karnath H-O, Zimmer U, Lewald J (2002) Impaired perception of temporal order in auditory extinction *Neuropsychologia* 40:1977–1982.
- Zatorre, R. J., Mondor, T. A., & Evans, A. C. (1999). Auditory attention to space and frequency activates similar cerebral systems. *Neuroimage*, 10(5), 544-554.
- Degerman A, Rinne T, Salmi J, Salonen O, Alho K (2006) Selective attention to sound location or pitch studied with fMRI *Brain Research* 1077: 123-134.