Auditory Neuroscience: unravelling how the brain gives sound meaning

Jennifer K Bizley

The brain must be able to assign sounds in the world to behaviourally meaningful categories. A new study reveals that sensory pathways represent category information, but that selectivity for sound classes emerges first in the frontal cortex.

To make sense of the world the brain must be capable of categorising sensory stimuli. Categorisation is a critical stepping-stone from sensation to action allowing rapid and flexible responses to a stimulus, and allowing generalising to novel examples. Word recognition is an example of categorical perception in hearing: Despite considerable variation in the acoustic signal produced by talkers that result from differences in voice pitch, timbre and even regional accents, we are able to accurately categorise acoustic patterns into words. A key feature of categorical perception is that it is harder to discriminate stimuli that belong to the same category than to discriminate stimuli that are equivalently different physically but belong to different categories. How do such representations emerge in the brain? A new study by Yin and colleagues [1] examines how and when categorical responses emerge in the auditory system. They demonstrate that neural signatures of categorical selectivity first emerge in frontal cortex before cascading back to secondary, then primary sensory areas.

Yin et al., trained two ferrets in a go/no-go task that required the animals to make a response to a warning sound in order to avoid an electric shock. Animals licked at a spout from which water was continuously available. When a sound was presented the animal had the choice of continuing to lick (“no-go”) or cease licking (“go”) in order to avoid a shock. Safe sounds indicated the animal could continue licking. Warning sounds indicated the animal should desist from licking in order to avoid an electric shock. Ferrets therefore had to categorise the sounds according to their behavioural meaning. Both animals learned two tasks which both had the same rules, but different acoustic stimuli. Rather than divide the stimulus space in two (for example, consider high tones as “safe” and low tones as “warning”), the authors forced the animals to form a more arbitrary association: In the tone variant of the task low frequency and high frequency tones were “safe” but licking during the presentation of intermediary frequencies elicited a shock (Fig. 1A). In the amplitude modulation variant high and low modulation rates were ‘safe’ and intermediate rates ‘warning’ sounds.

The ferrets were able to learn this task for both types of stimuli ignoring safe stimuli and acting to avoid a shock in response to warning sounds. The authors used extracellular recording methods to measure single unit activity during the performance of the task. They recorded from two sensory regions: the primary auditory cortex, and a secondary auditory cortical region, and from a region of frontal cortex which is associated with decision-making and higher cognitive functions. Consistent with previous work from this lab [2, 3] engaging in the task enhanced the difference in neural responses to safe and danger sounds and these differences were more marked in non-primary auditory cortex and frontal cortex. For both tasks, and in all areas, danger sounds elicited larger neural responses than safe sounds, and these differences were greater during task performance than when passively listening. Interestingly, while the overall contrast between safe and danger sounds was increased in all areas, this emerged in different ways: In the primary auditory cortex the response to safe sounds was supressed during behaviour, while the spike rate to warning sounds was relatively unchanged. In contrast, in the secondary auditory areas and the frontal cortex the response to the danger sound was enhanced while the response to safe sounds was unchanged.

In order to quantify where and when neural responses conveyed information about sound category, the authors applied an approach pioneered in the visual system [4]. Here, the authors demonstrated that sensory information was conveyed as a bottom-up sweep of information through visual cortex to higher brain areas, whereas task information emerged as a top-down cascade. Using a similar approach, Yin et al., calculated a "category index" which first quantified how similar neural responses were for stimulus pairs that were equivalently different physically but that either fell within the same behavioural category or belonged to different categories. A feature of categorical perception is that stimuli that fall at the category boundary are more discriminable than those that fall within a category [5]. Positive Category Index indicated that neural responses to across-category stimuli were more discriminable than within-category stimuli, indicating a categorical response. Values around or less than zero indicate a response that is dominated by veridical stimulus differences and is uninfluenced by the category membership. To complement this measure the authors also calculated a sensory index which quantified how much of the neural response variance was explained by the stimuli. Both indexes were calculated over time in each cortical field.

In keeping with a feedforward flow of sensory information, sensitivity to physical stimulus characteristics peaked shortly after sound onset in single neurons in the primary and secondary auditory cortex, falling back to baseline when the sound terminated (Fig.1B). In frontal cortex sensory information emerged more slowly, and persisted after sound offset. Information about which category of sound had been presented showed a very different timecourse: in all three areas category index values accumulated through the trial and remained positive after sound offset. Importantly, category information emerged first in frontal cortex, then secondary auditory cortex and finally in primary auditory cortex. Thus, there was a feedforward pattern of sensory information propagating up to frontal cortex, and a feedback pattern of category information from frontal to sensory cortex. The animals were trained in two tasks with physically distinct stimuli. The authors therefore asked whether cells that were recorded in both conditions were category sensitive in both tasks. Such cells were observed in the frontal cortex, where roughly half of the cells encoded information in both tasks. In contrast, in auditory cortex cells that encoded category information typically did so only in one of the two tasks.

Does long-term training on a categorisation task result in hard-wired changes in the representation of these categories? As Yin et al., recorded before and after task performance they were able to ask whether category selective responses exist in the absence of task performance: such responses might indicate a long-term memory trace for the behavioural relevance of the learned sounds. A subset of cells in auditory cortex did demonstrate significant category information prior to task performance. However, closer examination of these responses suggested that this could be accounted for by considering their underlying acoustic selectivity, (i.e. they were simply tuned to sounds near a category boundary).

The authors extended their approach from single cells to neural populations. They asked how different population responses were to stimuli that fell within or across category boundaries, and how this changed during task performance. Stimuli that were adjacent in physical stimulus space but that sat either side of the category boundary elicited the most different population responses. Moreover, the distances between responses to stimuli between categories were larger than those within a category whether the animals were passively listening or actively engaged in the task. Behaviour led to the population responses to stimuli that spanned category boundaries becoming more distinct.

One open question is the causal relationship between the observed category selectivity and behavioural judgments. Making the correct behavioural choice does of course require accurate stimulus categorisation. Neural activity in auditory cortex correlates with perceptual judgments and, like categorical information, choice related information builds through the course of a trial[6-8]. Importantly, just because an area conveys choice information doesn't mean its integrity is critical for task performance [8]. Disentangling whether categorical and choice related information are independent signals requires the ability to assess both factors and while Yin et al., have elegantly measured the former, go/no-go tasks are not optimally suited to measure the latter.

A recent study that employed a two—alternative forced choice paradigm in which animals discriminated high versus low frequency tones was able to link trial-by-trial fluctuations in neural activity with behavioural responses [9]. In doing so, these authors observed a subset of neurons whose responses were categorical only during task performance, and observed that neural populations in auditory cortex encoded sufficient information for stimulus categorisation. However, this study recorded activity only in primary auditory cortex and signals were measured with two-photon imaging which meant that they lacked the temporal resolution to observe the flow of category sensitivity from frontal to early sensory cortex that Yin et al., documented. Training animals in a two-choice variant of the task used by Yin et al while observing – and potentially perturbing – neural activity would provide further insight into how, and at what time points, auditory cortical activity contributes causally to categorical perception.

1. Yin, P., Strait, D., Radtke-Schuller, S., Fritz, J.B., and Shamma, S. (2020). Dynamics and Hierarchical Encoding of Non-Compact Acoustic Categories in Auditory and Frontal Cortex. Current Biology, xx-xxx.

2. Fritz, J., Shamma, S., Elhilali, M., and Klein, D. (2003). Rapid task-related plasticity of spectrotemporal receptive fields in primary auditory cortex. Nat Neurosci *6*, 1216-1223.
3. Elgueda, D., Duque, D., Radtke-Schuller, S., Yin, P., David, S.V., Shamma, S.A., and Fritz, J.B. (2019). State-dependent encoding of sound and behavioral meaning in a tertiary region of the ferret auditory cortex. Nat Neurosci.
4. Siegel, M., Buschman, T.J., and Miller, E.K. (2015). Cortical information flow during flexible sensorimotor decisions. Science *348*, 1352-1355.
5. Repp, B. (1984). Categorical Perception: Issues, Methods, Findings. Speech and Language: Advances in Basic Research and Practice. *10*, 243-335.
6. Bizley, J.K., Walker, K.M., Nodal, F.R., King, A.J., and Schnupp, J.W. (2013). Auditory cortex represents both pitch judgments and the corresponding acoustic cues. Current biology *23*, 620-625.
7. Niwa, M., Johnson, J.S., O'Connor, K.N., and Sutter, M.L. (2012). Activity related to perceptual judgment and action in primary auditory cortex. J Neurosci *32*, 3193-3210.
8. Tsunada, J., Liu, A.S., Gold, J.I., and Cohen, Y.E. (2016). Erratum: Causal contribution of primate auditory cortex to auditory perceptual decision-making. Nat Neurosci *19*, 642.
9. Xin, Y., Zhong, L., Zhang, Y., Zhou, T., Pan, J., and Xu, N.L. (2019). Sensory-to-Category Transformation via Dynamic Reorganization of Ensemble Structures in Mouse Auditory Cortex. Neuron *103*, 909-921 e906.

Jennifer K. Bizley,
Ear Institute, University College London,
332 Gray's Inn Road, London, WC1X 8EE.
j.bizley@ucl.ac.uk

Figure 1: Testing neural category selectivity
A Task design: Ferrets learned an abstract rule that defined some sounds as "safe" and other sounds as "warning". Ferrets were free to continue drinking water during the presentation of safe sounds but were required to cease licking during warning sounds, in order to avoid an electric shock.
B Temporal evolution of information about physical stimulus features and category membership in sensory and frontal cortex.