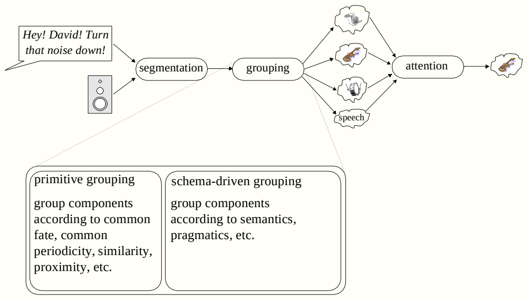
A Neural Oscillator Model of Auditory Selective Attention

Stuart N. Wrigley and Guy J. Brown
Department of Computer Science, University of Sheffield, UK
s.wrigley@dcs.shef.ac.uk http://www.dcs.shef.ac.uk/~stu g.brown@dcs.shef.ac.uk http://www.dcs.shef.ac.uk/~guy

Abstract

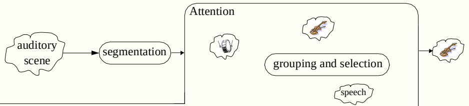
A model of auditory grouping is described in which auditory attention plays a key role. The model is based upon an oscillatory correlation framework, in which neural oscillators representing a single perceptual stream are synchronised, and are desynchronised from oscillators representing other streams. The model suggests a mechanism by which attention can be directed to the high or low tones in a repeating sequence of tones with alternating frequencies. In addition, it simulates the perceptual segregation of a mistuned harmonic from a complex tone.

'Classical' Auditory Scene Analysis



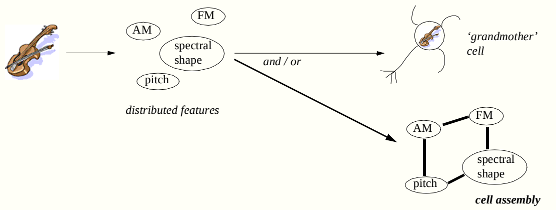
Attention in ASA

- It is now believed that attention plays a much more prominent role in ASA - attention does more than simply select a single stream (Carlyon *et al.*, 2001).



- *Exogenous* attention groups acoustic elements
- *Endogenous* mechanisms performs stream segregation and selection.
- Exogenous attention may overrule conscious (endogenous) selection (e.g. in response to a sudden, loud bang).

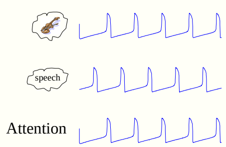
Binding problem



- Additionaly, only attended streams are encoded into memory and perceived (Moore and Egeth, 1997) - attention controls which percepts are to be encoded into memory.

Oscillatory Correlation Framework

- The oscillatory correlation theory (Wang, 1996) suggests that neural oscillations encode auditory grouping - i.e. a solution to the binding problem (see also von der Malsburg, 1981).



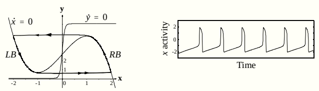
Can implement attentional selection by synchronising attentional activity with the stream of interest.

Relaxation Oscillator (Wang, 1996)

- Reciprocally connected excitatory unit and inhibitory unit whose activities are represented by x and y.
- Conceptually, the oscillator represents mean activity of a population of neurons. An alternative concept is that of the behaviour of a neuron's membrane potential and ion channels.

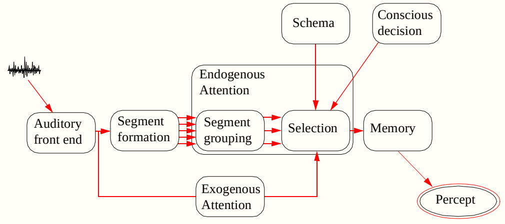
$$\dot{x} = 3x - x^3 + 2 - y + I_o$$

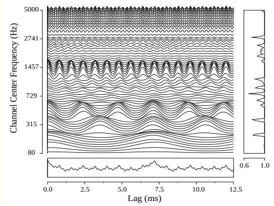
$$\dot{y} = \varepsilon\left[\gamma\left(1 + \tanh\frac{x}{\beta}\right) - y\right]$$



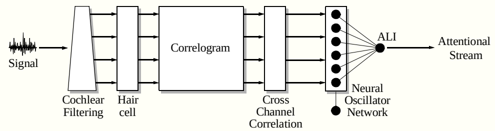
Model Overview

- Cochlear filtering is modelled by a bank of 128 gammatone filters with centre frequencies equally spaced on the equivalent rectangular bandwidth (ERB) scale between 50 Hz and 2.5 kHz.
- Auditory nerve firing rate is approximated by half-wave rectifying and square root compressing the output of each filter.





- Pitch information is extracted by computing the autocorrelation of the activity in each channel to form a correlogram (Brown and Cooke, 1994).
- The correlogram is used to identify formant and harmonic regions by locating areas which exhibit similar patterns of periodicity (Wang and Brown, 1999). This is achieved by computing the cross-channel correlation of the correlogram.
- Each cross-frequency area exhibiting similar patterns of periodicity is classed as a *segment*.
- The network consists of 128 oscillators; these are synchronised by placing local excitatory links between them (e.g. to group by common harmonicity).
- The global inhibitor ensures that only one block of synchronised oscillators can be active at any one time. Hence, separate blocks of synchronised oscillators - which correspond to the notion of a segment in ASA - arise through the action of local excitation and global inhibition.

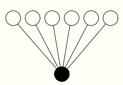


Oscillator Array

- Segment formation: excitatory and inhibitory connections promote synchronisation and desynchronisation of oscillator groups.
- Segments are (primitively) grouped on the basis of harmonicity and stimulus 'age' (old-plus-new heuristic).
- Input I_o to each oscillator is combination of raw input (I_r - based on segments), global inhibition and network activity.

$$I_o = I_r - W_z S(z, \theta_z) + \sum_{k \neq i} W_{ik} S(x_k, \theta_x)$$

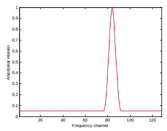
where x_k is oscillator activity at channel k and S is a 'squash' function. W_{ik} is the connection strength between oscillators i and k and W_z is the weight of inhibition from the global inhibitor z.



- Each oscillator in network feeds excitatory input to global inhibitor (a leaky integrator). Global inhibitor, in turn, feeds inhibitory input back to each oscillator.
- When one group of synchronised oscillators is active, all others are suppressed; i.e. only one group can be active at any one time.

Attentional Leaky Integrator

- The strength of the oscillator to ALI connection is determined by 'conscious' attentional interest which is directed toward a particular frequency region.
- Interest vector has a Gaussian cross-frequency 'shape' - A_k.
- Initial connections have equal (maximum) strength. These decay to the attentional interest peak in an activity dependent manner. When a stimulus ceases, the connection strengths relax back to the maximum level.



$$\dot{ali} = H\left(\sum_k S(x_k, \theta_x) T_k - \theta_{ALI}\right) - ali \qquad T_k = 1 - (1 - A_k)L$$

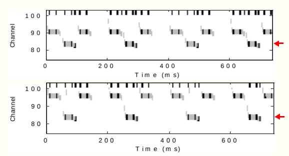
where L is a leaky integrator and H is the unit step function.

- Only the activity of oscillators whose connections fall under this attentional peak (and any synchronised oscillators) influence the ALI: the attended stream is synchronised with the activity of the ALI.

Results

Figures show a pseudo-spectrogram output from the model. Gray areas denote segments as created by the model. Each black pixel represents an oscillator in the active phase - an oscillator can only be active if it is part of a segment. The top row of black blocks represents ALI activity. Any active oscillators which are synchronised with the ALI are considered to be in the attentional foreground.

Two tone tone streaming (*auditory streaming*)

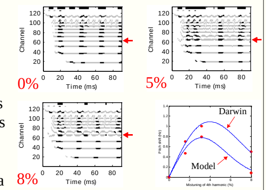


Each diagram shows model response to an ABA sequence of tones (van Noorden, 1975). At low frequency separations (3 semitones), temporal coherence (1 stream) is observed. At higher frequency separations (5 semitones), auditory streaming (2 streams) is observed. Note that a finite duration is required for streaming to occur (Anstis and Saida, 1985).

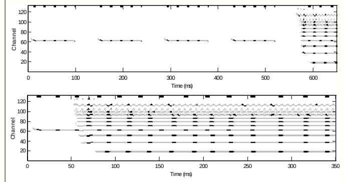
The timescale of adaptation for the attentional interest has been reduced to aid the clarity of the figures.

Mistuned harmonic and associated pitch shift (Darwin *et al.*, 1995)

Responses to complex tones. In each diagram, the complex tone has the fourth harmonic mistuned by a certain percentage. Below 8% (+50Hz), the mistuned harmonic remains grouped with the complex - all the oscillators are synchronised. Beyond 8%, the fourth harmonic segregates (represented by desynchronised activities). Associated with such segregation, listeners report a change in the pitch quality of the complex. This pitch *shift* reaches a maximum at approximately 4%. When the autocorrelation channels of the attended complex in the model are used to calculate the pitch, a quantitative match the pitch shift is seen.



Old-plus-new



The segregation of a harmonic by captor tones and asynchronous onset is accounted for by the incorporation of the *old-plus-new* heuristic: the auditory system's preference to '*interpret any part of a current group of acoustic components as a continuation of a sound that just occurred*' (Bregman, 1990). This segregation is indicated by the desynchronisation of the harmonic from the rest of the complex. Furthermore, this behaviour decays over time and eventually the harmonic re-fuses with the complex.

Summary

- A model of auditory attention has been presented which is based on previous neural oscillator work by Wang and colleagues (Wang, 1996; Wang & Brown, 1999).
- Our model regards attention as a key factor in the stream formation process.
- Employs a unidimensional network which avoids a two dimensional time-frequency grid for which there is weak physiological justification.
- Sequential grouping is an emergent property of the model.
- Ability to incorporate other simultaneous grouping cues to promote oscillator synchronisation.

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