A role for cortical spiral waves in visual attention?

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Abstract

We are investigating possible functional roles for spiral wave activity in visual cortex. Our initial findings suggest that spiral wave formation could contribute to visual salience analysis, in particular for mediating attention to human body features. Exploiting travelling wave dynamics for visual processing offers many advantages, including template-free sensitivity to spatial patterns, robustness and suitability for parallel and physical implementation.

Keywords: travelling wave computing, spiral wave, visual attention

1. Introduction

[1] showed that travelling waves and standing waves respectively distinguish the spatial from orientation maps in cat V1. [2] recently reported existence of spiral waves in visual neo-cortex, and found that spiral centres drifted much faster in vivo than in vitro, suggesting active modulation in the intact brain. The functional relevance of cortical spiral activity remains unknown. Our preliminary results from computational simulations suggest that stimulus induced spiral wave formation in a simulated oscillatory medium can mediate visual salience analysis, also suggesting a potential functional role - modulation of attention - for the increased spiral drift observed in vivo [2]. The image essentially sets the initial phase conditions for the oscillator network. Dynamical instabilities in the starting conditions can lead to phase collapse and spiral wave formation. This offers a loose criteria for salience which can be exploited by evolving morphology, establishing a dynamical relationship between senser and sensee.

2. Sensory oscillatory medium

The harmonic Hopf oscillator [3] is a dynamical system of the form:

$$\begin{aligned} \dot{x} &= \gamma(\mu - r^2)x - \omega y \\ \dot{y} &= \gamma(\mu - r^2)y + \omega x \\ r^2 &= x^2 + y^2 \end{aligned}$$

where μ=1 controls amplitude, ω=0.14 determines frequency, and γ=8 is a recovery parameter. Our spatial map model consists of *n*m* such oscillators, where each oscillator maps to one pixel of the *n*m* pixel stimulus. Each oscillator is coupled to its von Neumann neighbourhood (*F(n)*) by a constant ε, and to *F(p)* - a bipolar representation of the intensity values in the stimulus image scaled to *[-1 1]* - via κ, giving a system described by;

$$\begin{aligned} \dot{x}_{ij} &= \gamma(\mu - r_{ij}^2)x_{ij} - \omega y_{ij} + \varepsilon F(n_{ij}) + \kappa F(p_{ij}) \\ \dot{y}_{ij} &= \gamma(\mu - r_{ij}^2)y_{ij} + \omega x_{ij} \end{aligned}$$

with

$$\begin{aligned} F(n_{ij}) &= x_{i+1j} + x_{i-1j} + x_{ij+1} + x_{ij-1} \\ F(x) &= \sum_{i=0j=0}^{i=nj=m} x_{ij}/nm \end{aligned}$$

$\varepsilon = 0.025$, $\varphi = 0.1$ here. κ is set to unity for one time step, and then to zero, decoupling the stimulus image by analogy with suppression of vision during saccade. The system then relaxes towards a local attractor region, and the evolving two dimensional dynamics are used to define a salience landscape, in this case using frequency distribution. Spiral centres are characterised by high frequency, low amplitude oscillations.

2.1. Preliminary findings

Figure 1 gives an example of the different dynamics induced by a nose and plain black and white stripes. The image is first contrast filtered with a centre surround kernel, then imprinted pixelwise as a phase perturbation of the corresponding oscillator (each oscillator in the sensory surface maps to one pixel of the input stimulus). The phase mask/image is then decoupled. The black and white stripes induce plane waves, while the nose image contains

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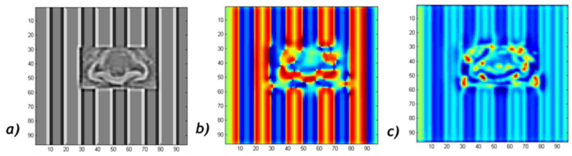

Figure 1: *Different dynamics induced by a human nose vs. plain stripes. (a) Contrast filtered image of a nose on a background of black-white stripes. (b) Snapshot of phase distribution. The stripes induce plane waves, while the nose pattern induces spiral waves. (c) Frequency map. The nose 'pops out' due to high frequency at spiral centres.*

richer contours which induce spiral activity. See Fig. 8 in [2] for more details on how particular phase topologies can collapse to spiral formations.

3. Applications

We are applying the model to visuo-motor control and active perception [4]. The newly emerging face-to-face paradigm is designed to explore infants' understanding of the interactions of others [5]. Infants observe two interactors who are either facing each other or facing away from each other, and infants' gaze shifts between the actors are recorded. We added a motor module which chooses a target fixation point by a stochastic best first method based on the salience map. Eye movement is then controlled by two terms; error reduction between target and current location, and gradient descent across the intervening salience landscape. A new fixation occurs whenever a sufficiently salient location is reached, regardless of whether it is the target location.

The model produces more gaze shifts in the social condition, as do infants at 16 months. Image pairs can be classified into social and non-social with 85% accuracy simply by relative number of gaze shifts. 2a shows an example of an image pair with 10 simulated eye movements overlaid. Figure 2b shows an example of the salience map structuring eye movement. The spiral wave salience model attributes greater salience to the facial regions in these images, whilst active vision explores the topology of the salience map, enabling the behavioural distinction between conditions. Socially sensitive eye movements need not indicate the existence of social representations.

4. Discussion

The role of cortical spiral waves in cognition is just beginning to be explored [2],[6]. Our initial results indicate that sensory induced spiral wave formation could play a surprisingly direct role in structuring visual attention. This in turn raises the possibility that modulation of spiral drift could mediate modulation of attention. Our findings suggest that the role of the eyes in social cognition need not be confined to sending image information to higher level modules. Sensitivity to social cues can be embedded in the action-perception cycle. This lends support to arguments from the enactive perspective that interaction patterns can be constitutive of cognition [7].

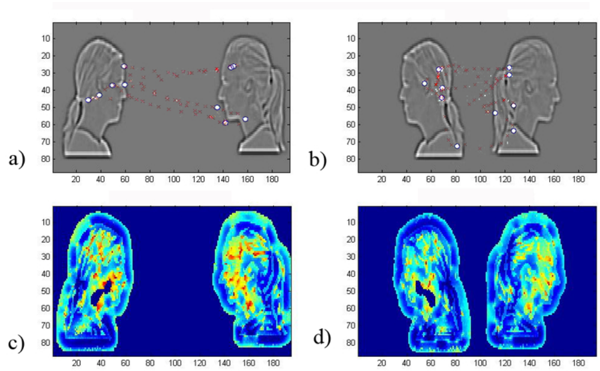

Figure 2: *(a), (b) Face-to-face and back-to-back contrasted image pair, with eye movements overlaid. (c), (d) The salience maps guiding eye movements. Colour scheme runs from red (most salient) to blue (least salient).*

We will implement the model on the iCub platform (icub.org) to model active perception and the visual preferences of infants for human features in an embodied setting. The mechanisms we are using are intrinsically parallel and are suitable for analogue and physical implementation, building bridges between emerging computing technologies, cognitive development, visual neuroscience and robotics. In conclusion, this work may lead to greater understanding of how neural population dynamics can support adaptive behaviour, and how animal bodies have coevolved with the sensory systems that perceive them.

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5. References

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