A Neurobiological and Computational Analysis of Target Discrimination in Visual Clutter by the Insect Visual System

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THESIS ABSTRACT

Some insects have the capability to detect and track small moving objects, often against cluttered moving backgrounds. Determining how this task is performed is an intriguing challenge, both from a physiological and computational perspective. Previous research has characterized higher-order neurons within the fly brain known as ‗small target motion detectors' (STMD) that respond selectively to targets, even within complex moving surrounds. Interestingly, these cells still respond robustly when the velocity of the target is matched to the velocity of the background (i.e. with no relative motion cues).

We performed intracellular recordings from intermediate-order neurons in the fly visual system (the medulla). These full-wave rectifying, transient cells (RTC) reveal independent adaptation to luminance changes of opposite signs (suggesting separate ‗on' and ‗off' channels) and fast adaptive temporal mechanisms (as seen in some previously described cell types). We show, via electrophysiological experiments, that the RTC is temporally responsive to rapidly changing stimuli and is well suited to serving an important function in a proposed target-detecting pathway.

To model this target discrimination, we use high dynamic range (HDR) natural images to represent ‗real-world' luminance values that serve as inputs to a biomimetic representation of photoreceptor processing. Adaptive spatiotemporal high-pass filtering (1st-order interneurons) shapes the transient ‗edge-like' responses, useful for feature discrimination. Following this, a model for the RTC implements a nonlinear facilitation between the rapidly adapting, and independent polarity contrast channels, each with centre-surround antagonism. The recombination of the channels results in increased discrimination of small targets, of approximately the size of a single pixel, without the need for relative motion cues. This method of feature discrimination contrasts with traditional target and background motion-field computations. We show that our RTC-based target detection model is well matched to properties described for the higher-order STMD neurons, such as contrast sensitivity, height tuning and velocity tuning. The model output shows that the spatiotemporal profile of small targets is sufficiently rare within natural scene imagery to allow our highly nonlinear ‗matched filter' to successfully detect many targets from the background.

The model produces robust target discrimination across a biologically plausible range of target sizes and a range of velocities. We show that the model for small target motion detection is highly correlated to the velocity of the stimulus but not other background statistics, such as local brightness or local contrast, which normally influence target detection tasks.

From an engineering perspective, we examine model elaborations for improved target discrimination via inhibitory interactions from correlation-type motion detectors, using a form of antagonism between our feature correlator and the more typical motion correlator. We also observe that a changing optimal threshold is highly correlated to the value of observer ego-motion. We present an elaborated target detection model that allows for implementation of a static optimal threshold, by scaling the target discrimination mechanism with a model-derived velocity estimation of ego-motion.

Finally, we investigate the physiological relevance of this target discrimination model. We show that via very subtle image manipulation of the visual stimulus, our model accurately predicts dramatic changes in observed electrophysiological responses from STMD neurons.

THESIS DECLARATION

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to this copy of my thesis when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

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(1) Wiederman S.D., Shoemaker P.A., O'Carroll D.C. (2008) A model for the detection of moving targets in visual clutter inspired by insect physiology. PLoS ONE 3(7): e2784 doi:10.1371/journal.pone.0002784

(2) Wiederman, S., Shoemaker, P. and O‘Carroll, D.C. (2007) Biologically inspired small target detection mechanisms. Proceedings IEEE, Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP) Conference, pp 269 - 275

(3) Wiederman, S.D., Brinkworth, R.S.A. and O‘Carroll, D.C. (2008) Bio-inspired small target discrimination in high dynamic range natural scenes. IEEE Proceedings, Bio-inspired Computing: Theories and Applications (BIC-TA), in press.

(4) Wiederman, S.D., Brinkworth, R.S.A. and O‘Carroll, D.C. (2008) Bio-inspired target detection in natural scenes: optimal thresholds and ego-motion, in Biosensing, Proceedings of the SPIE Vol.7035, 70350Z

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Tanner Research Inc., California, USA

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Victorian Research Labs, The University of Melbourne

Statement of Contributions of Jointly Authored Works

The following states the contribution of the authors to the following published works.

Steven Wiederman	SDW	Patrick Shoemaker	PAS
Russell Brinkworth	RSAB	David O‘Carroll	DO‘C

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(1) Wiederman S.D., Shoemaker P.A., O'Carroll D.C. (2008) A model for the detection of moving targets in visual clutter inspired by insect physiology. PLoS ONE 3(7): e2784 doi:10.1371/journal.pone.0002784

Conceptualisation: SDW wished to understand the functionality of ‗on-off‘ units, whether as non-directional motion detectors, inputs to correlator motion detectors, or feature detectors. Upon discussion with DO‘C, SDW agreed to model these units as contrast gain controllers in the arms of motion correlators (poster presentation), whilst SDW discussed the relevance of ‗on-off‘ units as feature detectors and as possible inputs to motion detectors with DO‘C and PAS. SDW and PAS suggested that the presence of ON- and OFF-signaling pathways with independent adaptation might well be relevant for small feature extraction (by the novel on and off contrast phases (independent and unadapted) ‗hitting‘ of the small subunits within the ‗on-off‘ unit). PAS‘s immediate interest was in small target detection which was reinforced by the presence of inhibitory surrounds in the receptive fields of these cells (as indicated by the previous literature). SDW conceptualized elaborated models for this spatial filtering. These various ideas coalesced into a suitable nonlinear matched filter for small moving targets. This required a model to test for this target discrimination which was then designed and implemented in Simulink/Matlab by SDW.

Realisation: All electrophysiological investigation undertaken by SDW, under the tutelage of DO‘C. Modeling: Lipetz function PAS, with varying midpoint parameter by SDW. Original model for fast depolarisation, slow repolarisation adaptive mechanism developed by PAS. Implementation of nonlinear filter was provided in SPICE by PAS that coincidentally was mathematically equivalent to gradient ‗switched‘ filter designed by SDW. All simulation and analysis tools written by SDW. Suggested use of natural scenes and panoramic inputs by DO‘C. ROC analysis suggested by PAS. Examining temporal responsiveness of RTC by DO‘C, SDW and PAS with PAS suggesting ‗doublet‘ stimulus. All Python coding of new visual stimuli by SDW. All electrophysiological data analysis and model analysis by SDW.

Documentation: First writing by SDW, with both PAS and DO‘C providing strong written contributions and review.

(2) Wiederman, S., Shoemaker, P. and O'Carroll, D.C. (2007) Biologically inspired small target detection mechanisms. Proceedings IEEE, Intelligent Sensors, Sensor Networks and Information Processing (ISSNIP) Conference, pp 269 – 275

Conceptualisation and Realisation: this is an engineering publication of the modelling results as seen in the PLoS research, therefore see (1) above.

Documentation: written by SDW

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(3) Wiederman, S.D., Brinkworth, R.S.A. and O'Carroll, D.C. (2008) Bio-inspired small target discrimination in high dynamic range natural scenes. Proceedings IEEE, Bio-inspired Computing: Theories and Applications (BIC-TA), in press.

Conceptualisation: Idea to test model across varying target sizes and velocities by SDW. Interest in seeing capability for target discrimination with HDR stimulus (due to photoreceptor dynamics) by RSAB and SDW. Idea to test for correlations with image luminance and contrast values, and panorama velocities by SDW.

Realisation: Translation of overall modelling efforts to Matlab was a collaboration by SDW and RSAB. All elaborated photoreceptor modelling by RSAB. Extended modelling of LMC dynamics by SDW and RSAB. All analysis of results by SDW.

Documentation: written by SDW, with RSAB providing editing and review. Useful suggestions by D'OC.

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(4) Wiederman, S.D., Brinkworth, R.S.A. and O'Carroll, D.C. (2008) Bio-inspired target detection in natural scenes: optimal thresholds and ego-motion, in Biosensing, Proceedings of the SPIE, Vol 7035, 70350Z

Conceptualisation: The model elaborations were conceptualised by SDW. Insightful mathematical interpretation and helpful analysis of ideas provided by RSAB.

Realisation: Target discrimination model design, implementation and analysis by SDW. All EMD/Wide-field components of the model written by RSAB. Interactions between the two written by SDW. All analysis of results by SDW.

Documentation: written by SDW, with RSAB providing editing and review Useful suggestions by D'OC.

I agree with the above statement of contribution and give permission for the paper(s) to be included in this thesis.

Steven Wiederman: SIGNATURE _______________ DATE______

Patrick Shoemaker: SIGNATURE _______________ DATE______

Russell Brinkworth: SIGNATURE _______________ DATE______

David O'Carroll: SIGNATURE _______________ DATE______

AUTHOR'S COMMENTS

- Publications within this thesis are exact copies of the original article except for the following considerations
    1. The typesetting is changed to provide a consistent format across the chapters of the thesis.
    2. References at the end of each article are removed and can be found at the end of the thesis. I changed the format of citations within the articles, to be consistent throughout the thesis.
    3. Some figure titles have been improved, to provide a clearer Table of Figures.
- Within journal articles, figures are cross referenced as they were published, e.g. figure 4 in Chapter 2 is captioned 2.4, but referenced in text as Figure 4.
- There are variations in spelling between the chapters, both Australian and United States versions (due to submission rules for article publications).
- In the jointly published articles (see ‗Statement of Contributions of Jointly Authored Works'), I use the plural form of the personal pronoun. In the rest of the thesis, I return to the singular form. In some cases, when referencing work performed over the duration of the research (for example, the thesis abstract), it is more appropriate to use the plural personal pronoun.

COMMON ACRONYMS

AUROC	Area Under the Receiver Operating Characteristic (Curve)
CSTMD	Centrifugal Small Target Motion Detector
EMD	Elementary Motion Detector
ESTMD	Elementary Small Target Motion Detector
FD	Figure Detection (Cell)
HDR	High Dynamic Range
HPF	High-Pass Filter
LED	Light Emitting Diode
LMC	Large Monopolar Cell
LPF	Low-Pass Filter
LPTC	Lobula Plate Tangential Cell
ROC	Receiver Operating Characteristic (Curve)
RTC	Rectifying Transient Cell
SMC	Small Monopolar Cell
STMD	Small Target Motion Detector

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