A report on the Centre for Theoretical Neuroscience at the University of Waterloo

prepared by Britt Anderson, Director

May 26, 2023

1 Executive Summary

The University of Waterloo's internationally recognized Centre for Theoretical Neuroscience (CTN) receives hundreds of thousands of dollars annually in research funding in support of its mission to develop robust explanatory theories of mind and brain through education and research. The CTN (founded in 2006) has 18 members and is an administrative unit of the Faculty of Arts. The CTN was the first Canadian research institute dedicated to theoretical neuroscience and the first to offer a graduate diploma for Theoretical Neuroscience. Hundreds of University of Waterloo students with diverse educational backgrounds have benefited from the interdisciplinary educational opportunities the CTN provides, which include formal courses, a colloquium series, an annual Brain Day, an annual Research Day, and graduate supervision. Core and Affiliate CTN faculty have achieved a vigorous interdisciplinary program that represents five of the university's six faculties. The faculty of the CTN in the aggregate consistently receive between half a million to a million dollars a year in direct research funds, and are growing new programs. The recent establishment of a new NRC initiative on campus is a direct result of the activities and research of current and former Centre members, post-docs and students. While the university has a number of programs and institutes devoted to applications, the University of Waterloo's CTN is a world class Centre, and one of only a few such Centres in the world, devoted to developing and testing new theories of brain and general intelligence at a fundamental level using mathematical models. Such advances are the pre-requisites for the next generation of practical advances.

2 Membership

2.1 Notable Member Achievements (summary)

CTN faculty include

- 2 Members of the Royal Society.
- 2 Fellows of the Cognitive Science Society
- 1 Winner Killam Prize for the Humanities
- 1 Winner of the John C. Polyani award
- 2 Tier II Canada Research Chairs
- 1 Tier 1 Canada Research Chair
- President of the Canadian Applied and Industrial Mathematics Society

CTN faculty have trained 100s of graduate students, occupy leading editorial roles, direct workshops, organize international courses, publish widely and in

prestigious outlets (CVs are in a separate attachment), and in the last year the six core faculty alone received over 800,000 CAD in research funding. Funding sources include: National Science and Engineering Research Council of Canada, National Research Council Canada, American Institute of Mathematics, Office of Naval Research (US), Canada Foundation for Innovation, Air Force Office of Scientific Research (US), Mitacs, Microsoft-AI Institute, Canadian Statistical Sciences Institute, Intel, and the Centre for Effective Altruism

2.2 Types of Membership

The CTN has two categories of members: core (7 = 6 active / 1 emeritus) and affiliate (11). This reflects a growth of 50% since the last report (all growth coming from affiliate members). Current members are listed in Table 1. CVs are attached separately.

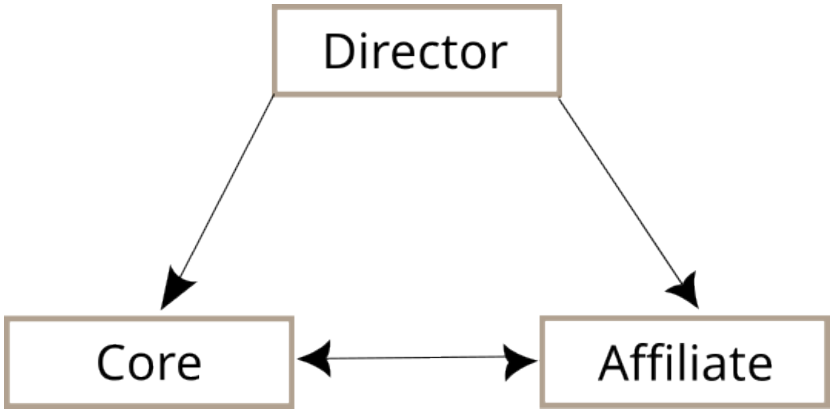

Figure 1: CTN Organization. A director administers the centre and communicates with both categories of membership (core and affiliate). Core and Affiliate members jointly participate in the educational and research programs and collaborate. The Core members form an executive committee for the setting of CTN policy and membership.

2.2.1 Core Members

Core faculty are actively engaged in theoretical neuroscience research or teaching. Core members are essentially the executive governing body. There is a minimum of one meeting per term to address open administrative issues and additional ad hoc meetings as required. Core members attend and participate in the yearly research day, the colloquium series, and Brain Day activities. Core members supervise graduate students working in the area of theoretical neuroscience, and teach the principal courses required for the Graduate Diploma in Theoretical Neuroscience. Core members can come via invitation or self-nomination and require unanimous approval of current core members.

2.2.2 Affiliate Members

Affiliate members are typically scientists with an empirical research program that provides data for theoretical neuroscientific investigation *or* faculty with a computational or theoretical research program that informs empirical or theoretical neuroscience. Affiliates' membership is voted on by the current core members. Affiliates are expected to foster ties that support the academic and research work of the Centre. Collaboration, cooperation, communication, and community building are the purposes served by affiliation. Affiliates are expected to play a role in the academic life of the Centre by attending some of the seminars, Brain Day, and encouraging their students to do the same. Affiliate membership requires majority support of current core members.

Name	Dept	Faculty	CTN Role
Britt Anderson	Psychology	Arts	Director
Sue Ann Campbell	Applied Mathematics	Mathematics	Core
James Danckert	Psychology	Arts	Affiliate
Kaylena Ehgoetz Martens	Kinesiology	Health	Affiliate
Chris Eliasmith	Philosophy/SYDE	Arts/Engineering	Founding Director
Jonathan Fugelsang	Psychology	Arts	Affiliate
Jesse Hoey	Computer Science	Mathematics	Affiliate
Brian Ingalls	Applied Mathematics	Mathematics	Affiliate
Roxane Itier	Psychology	Arts	Affiliate
Nachiket Kapre	ECE	Engineering	Affiliate
Paul Marriott	Statistics	Mathematics	Core
Chrystopher L. Nehaniv	SYDE	Engineering	Affiliate
Jeff Orchard	Computer Science	Mathematics	Core
Reza Ramezan	Statistics	Mathematics	Affiliate
David Spafford	Biology	Science	Affiliate
Terry Stewart	NRC / Adjunct Psych.	NRC/Arts	Affiliate
Paul Thagard	Philosophy (emeritus)	Arts	Core (emeritus)
Bryan Tripp	SYDE	Engineering	Core

Table 1: CTN Membership List (alphabetical)

3 Research Accomplishments

3.1 CTN's Exceptional Publication Record

Members of the Centre have excellent individual research records, having published hundreds of articles across the relevant disciplines in top journals. A selection of the 65 books and papers published in the last 5 years by the core faculty of the CTN are shown in Appendix 7.2.

The entire output of CTN faculty can be found in the attached collection of faculty CVs. Note the journals with CTN publications includes: *Science, Journal of Neuroscience, Neuron, Current Opinion in Neurobiology, Journal of Neurophysiology, Cerebral Cortex, Neurology, Brain, Vision Research, Journal of Cognitive Neuroscience, Psychological Review, Psychological Science, Neuropsychology, Neural Computation,* and *Journal of Computational Neuroscience.*

3.2 The CTN Fosters Interdisciplinary Research Collaborations

An example of the CTN as a catalyst for interdisciplinarity is the collaboration of CTN Affiliate Member Roxane Itier and CTN Core Member Jeff Orchard. A member of the Department of Psychology studying the neurophysiological responses to human faces, Prof. Itier was unlikely to have met Prof. Orchard, a CS department member interested in neural networks and predictive coding, if had not been for the CTN and its programs. Now the two scientists have a joint inter-faculty research project that will see them jointly supervising a Computational Math graduate student and investigating how predictive coding theory may explain differences in neural latencies.

There are numerous other interdisciplinary successes that demonstrate the collaborative opportunities due to the CTN. Many span faculties / departments and the core and affiliate memberships of the CTN. Almost all also involve graduate students. A condensed list includes: Spafford (Science/Biology) & Campbell (Math/Applied Math); Orchard (Math / CS) & Eliasmith (Arts | Engineering / Philosophy | SYDE); Hoey (Math / CS) & Stewart (NRC | Arts / Psychology); Ehgoetz Martens (Health / Kinesiology) & Anderson (Arts / Psychology) & Danckert (Arts / Psychology); Marriott (Math / Statistics) & Danckert (Arts / Psychology); Marriott (Math / Statistics) & Moffat (graduate student Science / Biology); and Tripp (Engineering / SYDE) & Ehgoetz Martens (Health / Kinesiology).

Many of these collaborations are directly due to the shared space of the CTN that brings together students and faculty from departments across campus to a common location to meet, talk, share ideas, and grow collaborations. Initially funded with CFI funds and a grant from University Provost Amit Chakma, the CTN piloted this model with custom built space in the new extension to the University's PAS building. Recently, the CTN's consolidated student, faculty and seminar space moved to the University's newly constructed E7 building.

In addition to the intramural collaborations within the University of Waterloo, CTN faculty have established a wide variety of collaborations with international companies (BMW, SWRI, Google DeepMind, Intel, Magna, Brain Corporation), Canadian companies (Applied Brain Research, Open Text, DossierView, Kindred, Smile Digital Health), and academic partners both in Canada and internationally (NRL, Dresden University, Groningen University, NRC, Leiden University, Cardiff University, Carleton University, KIT, Raboud University, KTH Stockholm, University of Maryland, MIT, Yale, Stanford, and the Allen Institute for Brain Science).

The CTN features highly in salient Google searches. Searching "theoretical neuroscience Canada" on google.ca returns University of Waterloo's CTN as the first result from 18 million results[1].

3.3 Developing Tools for Theoretical Neuroscience

A particularly important CTN success has been the development of what is now one of the most used neural simulation packages in the world: Nengo (`https://nengo.ai`)[2]. Nengo was downloaded over 60,000 times in 2022 and is in use around the world in top institutes including Yale, Stanford, EPFL, Cambridge, MIT, Johns Hopkins, UCL, and UCSD, among many others. It is has also generated a CTN spin-off company, Applied Brain Research, but remains free for research and personal use. Nengo has also served as the foundation for student led projects to grow and develop the tools for theoretical neuroscience. NengoBio is a recent extension to Nengo that adds to Nengo a number of features to permit modelers to create neural models within the Nengo framework, but enforcing common biological constraints. The major impetus behind this add-on was a graduate student in the lab of a CTN member.

4 Educational Programs and Achievements

4.1 Graduate Students

The CTN provides education, mentorship, and networking opportunities for large numbers of graduate students. While many of these students do not pursue formal recognition via the diploma, they do attend the colloquium meetings, Brain Day, and lab meetings, often held in conjunction with the labs of other CTN affiliated faculty. In addition, many of these students are housed in common graduate student space provided to the CTN via a collaboration between the Faculty of Arts and the Faculty of Engineering (via their Dept. of Systems Design Engineering) that provides office space and desk space to CTN members regardless of their faculty. This allows psychology graduate students to work side-by-side with engineering students, and math and computing science students to interact with post-docs and faculty from all the Centre's disciplines. Currently 23 graduate students and 3 post-doctoral fellows have their primary office space in the communal graduate student space provided to the CTN.

4.1.1 Details of the Educational Program

The educational opportunities of the CTN are diverse, and extend beyond the formal program organized around the graduate diploma. Many more students participate in, and benefit from, the educational activities of the CTN than formally pursue the graduate diploma in Theoretical Neuroscience.

[1] (search conducted: 2023-03-16)

[2] Additional statistics on Nengo's use can be found in the appendix.

The educational opportunities include the courses offered by CTN members, the colloquium series featuring visiting scholars, the annual Brain Day, as well as the informal consultations that take place in joint lab meetings and at the nearest whiteboard.

For an overview of educational plan for the graduate diploma and the offered courses please follows these links. Additional details on the colloquium series and Brain Day are below.

Currently (see Table 2) there are six graduate students actively working towards the graduate diploma in Theoretical Neuroscience[3]. Since the last report four graduate students have been awarded the diploma.

Term	Year	Number
Winter	2018	2
Winter	2019	1
Spring	2022	1
ACTIVE	On-going	6

Table 2: Graduate Diplomas in Theoretical Neuroscience awarded by term.

4.1.2 Recent Graduate Students And Where They End Up

Graduate students working in the area of Theoretical Neuroscience with CTN faculty have gone on to successful academic and non-academic careers. A sampling of recent CTN students is:

1. **Sixuan Chen** (MA 2022 with Graduate Diploma in Theoretical Neuroscience diploma) worked with Director Britt Anderson. She is currently a research associate at New York University in the lab of Wei Jei Ma.

2. **Alex van de Kleut**, (MMath 2021), studied with core member Jeff Orchard and is now a Software Engineer at ApplyBoard.

3. **Ivana Kajic**, (PhD 2020) studied with founding director Chris Eliasmith and is currently at Google DeepMind.

4. **Nolan Dey** (MASc 2020) studied with core member Bryan Tripp and is currently a Machine Learning Research Scientist at Cerebrus Systems, a prominent developer of AI accelerator hardware.

5. **Aaron Voelker**, (PhD 2019) who also studied with Chris Eliasmith has his own local start-up: Voelker Block Consulting.

[3]A Tier II Graduate Diploma is a diploma that is awarded in addition to a traditional graduate degree; it is not a primary degree. Thus, students completing the diploma receive their Masters or PhD in, for example, Psychology or Engineering *with a diploma in Theoretical Neuroscience.*

6. **Syaheed Jabar** (PhD 2018 with Graduate Diploma in Theoretical Neuroscience) studied with Britt Anderson. He went on to pursue post-doctoral work at NYU Abu Dhabi in the laboratory of Daryl Fougnie. Currently Syaheed works at a medical start-up, Neuroglee. Syaheed is based in Singapore.

7. **Sugandha Sharma**, (MASc 2018) worked with Chris Eliasmith and is now pursuing a PhD at MIT and spoke of her experiences at the University of Waterloo's CTN on the podcast Generally Intelligent.

8. **Ahmed Khan**, (MMath 2018), studied with core member Jeff Orchard and is now pursuing a PhD in Neuroinformatics and Personalized Medicine at McGill University.

9. **Alex Filipowicz** (PhD 2016 with Graduate Diploma in Theoretical Neuroscience) also studied with Britt Anderson, and went on to post-doctoral work at the University of Pennsylvania in the laboratories of Joshua Gold and Joe Kable. Currently, Alex is a research scientist at Toyota Research Los Altos, California, USA.

10. **Wilton Nicola**, (PhD 2016) studied with core member Sue Ann Campbell and is currently holds a Canada Research Chair at the Hotchkiss Brain Institute in Calgary.

4.2 Colloquium Series

The Colloquium series of the CTN is a series of presentations by, mostly, external speakers that occurs 4 times in each of the Fall and Winter terms. Invited speakers visit the campus and, in addition to a formal presentation, lunch with the graduate students, attend a dinner with a subset of CTN faculty, and meet with individual graduate students and faculty during the day of their visit.

The presenters since our last report are in table 3.

4.3 Brain Day

Brain Day is an annual event that has been a flagship program for the CTN since its inception[4]. The general structure is that four eminent scholars of international renown are invited to the University of Waterloo campus for a day of talks and informal interactions with students (graduate *and* undergraduate). We invite one scholar from each of the four main topics: philosophy of mind, empirical neuroscience, cognitive neuroscience/psychology, and computational neuroscience. Each speaker presents a 75 minute presentation followed by questions. Graduate students meet the faculty at scheduled informal coffees, as well as a more formal dinner. A reception is held for the speakers at which they can again interact with undergraduate and graduate students from across the

[4]Annually except for the gap due to pandemic cancellation of in-person visits.

Term	Year	Speaker
Winter	2023	Sara Solla (Northwestern)
Winter	2023	Eric Shea-Brown (Washington)
Winter	2023	Maurizio de Pitta (UofT)
Winter	2023	Jeff Orchard (UWloo)
Fall	2022	Adrien Peyrache (McGill)
Fall	2022	Yalda Mohsenzadeh (Western)
Fall	2022	Leyla Isik (Johns Hopkins)
Winter	2022	Richard Naud (UOttawa)
Winter	2022	Mayank Mehta (UCLA)
Winter	2022	Karim Jerbi (UdeM)
Fall	2021	Kohitij Kar (MIT/York)
Fall	2021	Lyle Muller (Western)
Fall	2021	Andreas Burkhalter (Wash U. St. Louis)
Winter	2020	Randy McIntosh (Univ of Toronto)
Winter	2019	Joel Zylberberg (York)
Winter	2019	Javier Medina (Baylor)
Fall	2019	Mayzar Fallah (York)
Fall	2019	Wilten Nicola (Calgargy)
Fall	2019	Xaq Pitkow (Baylor)
Fall	2019	Morris Moscovitch (UofT)
Fall	2018	Subutai Ahmad (Numenta Inc.)
Fall	2018	Doug Crawford (York)
Fall	2018	Roland Memisevic (Twenty Billion Neurons)
Fall	2018	Stefan Mihalas (Allen Institute)
Fall	2018	Yan Wu (Deep Mind)

Table 3: Colloquium Speakers Since 2018

campus. The event is open to community members as well as students and faculty from other nearby universities. Attendance is generally excellent, and the talks are recorded and made available on the CTN's youtube channel. Recent speakers can be found in Table 4 as well as a list of all speakers since the event's inception[5].

Year	Speaker
2023	Rafal Bogacz (Oxford)
2023	Dora Angelaki (NYU)
2023	Nartascha Rajah (McGill)
2023	Serife Tekin (UT San Antonio)
2022	Lila Davachi (Columbia)
2022	Viktor Jirsa (Aix-Marseille Université)
2022	Jacqueline Gottlieb (Columbia)
2022	Frances Egan (Rutgers)
2019	John Maunsell (U Chicago)
2019	Paul Thagard (UWloo)
2019	Vinod Menon (Stanford)
2019	Michael Arbib (USC)
2018	Brian Knutson (Stanford)
2018	Carrie Figor (U Iowa)
2018	Olaf Sporns (Indiana U. Bloomington)
2018	Adrienne Fairhall (U Washington)

Table 4: Brain Day Speakers Since 2018

4.4 Nengo Summer School

Annually, the CTN hosts a two week program in the summer for researchers from around the world to learn how to use Nengo for neural modeling and theoretical neuroscience research. A full time program, the course draws attendees from industry and academia, with the majority being early to mid-stage graduate students and early stage faculty. The school is typically over-subscribed with fewer than half of the applicants being admitted to the summer school. Enrollment is typically 25-30 students, who hail largely from Europe and North America, with one to two participants from South America or Asia per year. Although the in-person school was cancelled due to COVID in 2020-2022, the

[5](2017) William Seager, Marisa Carrasco, Konrad Kording, James DiCarlo; (2016) Berit Brogaard, Stephen Read, Sabine Kastner, Larry Abbott; (2015) Tom Griffiths, Valerie Hardcastle, Thilo Womelsdorf, Ken Miller; (2014) Daniel Dennett, Elizabeth Phelps, Barry Richmond, Randall O'Reilly; (2013) Paul Glimcher, Wolfgang Maas, Daniel Schacter, Owen Flanagan; (2012) Gyorgy Buzaki, Michael Hasselmo, Michael Tarr, Ian Gold; (2011) Jonathan Cohen, Peter Strick, Sebastien Seung, Ned Block; (2010) Mel Goodale, Jack Gallant, Ken Miller, Carl Craver; (2009) Larry Barsalou, John Hopfield, Jesse Prinz, David Sheinberg; (2008) Patricia Churchland, Keith Holyoak, David van Essen, Terry Sejnowski; (2007) James McClelland, William Bechtel, Geoffrey Hinton, Tony Movshon

CTN posted videos for the 2020 school, which have received over 11,000 views to date. The summer school is being held in June 2023.

5 Finances

The CTN was founded with 75,000 CAD of support from the Provost's office in 2006. Further grants of 25,000 CAD were made by the Provost's office for the three years 2011, 2012, and 2013. In addition, the Dean of Arts made an annual contribution of 2,000 CAD yearly until 2014.

Since that time, a single additional contribution of 15,000 CAD was awarded in 2022 to the CTN for Brain Day and its seminar series by the acting Associate VP Research for Interdisciplinary Programs. CTN members contribute about 20,000 CAD annually as well from their research funding in support of the visitors for the colloquium series and Brain Day.

With its initial funding the CTN developed a model of interdepartmental and inter-faculty collaboration for research and education by constructing with its initial CFI and university funds purpose built seminar, research, and office space in the new extension to the University's PAS building. Subsequently, this space was traded for equivalent space in the University's newly constructed E7 building where the space costs are generously funded equally by the Faculty of Arts and the Department of Systems Design Engineering (SYDE)[6].

6 Future Directions

The CTN is an international leader in the area of theoretical neuroscience. Over the next five years, the CTN will continue to develop and preserve both its international reputation, and local collaborations. Locally, the CTN will continue to take a prominent role in neuroscience research at the university, and work in support of related applied initiatives (e.g. waterloo.ai). The CTN will expand its support of the research community by adding additional activities targeting earlier career researchers. A Research Day in the Fall (begun in Fall 2022) is an example of the outreach model to inform undergraduate and graduate students across campus of the breadth of educational and research opportunities in Theoretical Neuroscience. Continuing the seminars and Brain Day allows the CTN to expose the University of Waterloo community first hand to cutting edge theoretical neuroscience research while also sharing the collaborative opportunities at University of Waterloo with outside scholars (e.g. Brain Day speakers can become collaborators). The Nengo Summer School will continue development as an internationally attractive host for research and education on methods of theoretical neuroscience.

[6]The CTN space is in the SYDE area of E7 (an Engineering building). The total space allotted is 296 net assignable square meters (NASM; the 'unit' of space used at University of Waterloo for budgeting). This includes 138 NASM for offices, 147 for research and 38 for a robotics lab.

The Centre will continue to support a full suite of neural simulation software, demos, tutorials, and classroom materials to aid teaching of central theoretical neuroscience and neuromorphic computing concepts at all levels of training. The continuing goal of enhancing collaboration will be supported by stabilizing the CTNs space and budget and the CTN will strive to be the paradigmatic example of how a truly cross department/cross faculty research and educational centre can thrive despite institutional funding models centered on traditional departments.

7 Supporting Documentation

7.1 Potential Reviewers

- Jack Gallant https://vcresearch.berkeley.edu/faculty/jack-l-gallant
- Serge Thill https://www.ru.nl/en/people/thill-s
- Doug Tweed https://physiology.utoronto.ca/faculty/douglas-tweed
- Randy McIntosh https://www.armcintosh.com/
- John Tsotsos http://www.cse.yorku.ca/~tsotsos/Tsotsos/Home.html
- Konrad Kording http://koerding.com/
- Rafal Bogacz https://www.mrcbndu.ox.ac.uk/people/prof-rafal-bogacz
- Mac Shine https://macshine.github.io/
- Karl Friston (UCL - London - UK) https://www.fil.ion.ucl.ac.uk/~karl/
- Karim Jerbi (UdeM - Montreal) http://www.karimjerbi.com/
- Yoshua Bengio (UdeM - Montreal) https://yoshuabengio.org/
- Nick Swindale (UBC) https://neuroscience.ubc.ca/swindale-nicholas/
- Andre Longtin (University of Ottawa) https://mysite.science.uottawa.ca/alongtin/
- Rob Kass (CMU Statistics) https://stat.cmu.edu/~kass/
- Babak Shahbaba (UCI Statistics) https://www.stat.uci.edu/faculty/babak-shahbaba/

- Jörn Diedrichsen https://www.csd.uwo.ca/people/faculty/bios/diedrichsen.html
- David Noelle https://www.ucmerced.edu/content/david-c-noelle
- Niels Taatgen https://www.ai.rug.nl/~niels/
- Guido Zarrella https://www.linkedin.com/in/guidoz/
- Lisa Feldman Barrett https://www.affective-science.org/lisa-feldman-barrett.shtml

7.2 CTN Recent Publications

Al-Darabsah, I., & Campbell, S. A. (n.d.). M-current induced bogdanovtakens bifurcation and switching of neuron excitability class. *The Journal of Mathematical Neuroscience*, *11*(1), 126year2021.

Al-Darabsah, I., Chen, L., Nicola, W., & Campbell, S. A. (2021). The impact of small time delays on the onset of oscillations and synchrony in brain networks. *Frontiers in Systems Neuroscience*, *15*, 688517.

Antonova, E., Holding, M., Suen, H. C., Sumich, A., Maex, R., & Nehaniv, C. (2022). EEG microstates: Functional significance and short-term test-retest reliability. *Neuroimage: Reports*, *2*(2), 100089. https://doi.org/10.1016/j.ynirp.2022.100089

Blouw, P., & Eliasmith, C. (2018). Using neural networks to generate inferential roles for natural language. *Frontiers in Psychology*, *8*. https://doi.org/10.3389/fpsyg.2017.02335

Carson, L., Filipowicz, A., Anderson, B., & Danckert, J. (2019). Representational drawing following brain injury. *Neuropsychologia*, *133*, 107154. https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2019.107154

Carson, L., Siva, P., & Danckert, J. (2021). Drawing portraits and still lifes from 2D and 3D sources. *Psychology of Aesthetics, Creativity, and the Arts*, *15*(4), 746757. https://doi.org/10.1037/aca0000345

Chen, L., & Campbell, S. A. (2022). Exact mean-field models for spiking neural networks with adaptation. *Journal of Computational Neuroscience*, *50*(4), 445469.

Cody, R. A., Tolson, B. A., & Orchard, J. (2020). Detecting leaks in water distribution pipes using a deep autoencoder and hydroacoustic spectrograms. *Journal of Computing in Civil Engineering*, *34*(2), 04020001. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000881

Craig, B. T., Morrill, A., Anderson, B., Danckert, J., & Striemer, C. L. (2021). Cerebellar lesions disrupt spatial and temporal visual attention. *Cortex*, *139*, 2742. https://doi.org/10.1016/j.cortex.2021.02.019

Dammann, O., Poston, T. L., & Thagard, P. (2019). How do medical researchers make causal inferences? *What Is Scientific Knowledge?*

Davari, S., DCosta, N., Ramezan, R., & Mielke, J. (2023). Chronic early-life social isolation enhances spatial memory in male and female rats. *Behavioural Brain Research*.

DeWolf, T., Jaworski, P., & Eliasmith, C. (2020). Nengo and low-power AI hardware for robust, embedded neurorobotics. *Frontiers in Neurorobotics*, *14*. https://doi.org/10.3389/fnbot.2020.568359

Duggins, P., & Eliasmith, C. (2022). Constructing functional models from biophysically-detailed neurons. *PLoS Computational Biology*, *18*(9), e1010461. https://doi.org/10.1371/journal.pcbi.1010461

Dumont, N. S.-Y., Stöckel, A., Furlong, P. M., Bartlett, M., Eliasmith, C., & Stewart, T. C. (2023). Biologically-based computation: How neural details and dynamics are suited for implementing a variety of algorithms. *Brain Sciences*, *13*(2), 245. https://doi.org/10.3390/brainsci13020245

Durston, A. J., & Itier, R. J. (2021). The early processing of fearful and happy facial expressions is independent of task demands - support from mass univariate analyses. *Brain Research*, *1765*, 147505. https://doi.org/10.1016/j.brainres.2021.147505

Filipowicz, A., Valadao, D., Anderson, B., & Danckert, J. (2018). Rejecting outliers: Surprising changes do not always improve belief updating. *Decision*, *5*(3), 165176. https://doi.org/10.1037/dec0000073

Gosmann, J., & Eliasmith, C. (2019). Vector-derived transformation binding: an improved binding operation for deep symbol-like processing in neural networks. *Neural Computation*, *31*(5), 849869. https://doi.org/10.1162/neco_a_01179

Gosmann, J., & Eliasmith, C. (2021). Cue: a unified spiking neuron model of short-term and long-term memory. *Psychological Review*, *128*(1), 104124. https://doi.org/10.1037/rev0000250

Hudson, A., Durston, A. J., McCrackin, S. D., & Itier, R. J. (2021). Emotion, gender and gaze discrimination tasks do not differentially impact the neural processing of angry or happy facial expressions-a mass univariate ERP analysis. *Brain Topography*, *34*(6), 813833. https://doi.org/10.1007/s10548-021-00873-x

Kaji, I., Schröder, T., Stewart, T. C., & Thagard, P. (2019). The semantic pointer theory of emotion: Integrating physiology, appraisal, and construction. *Cognitive Systems Research*, *58*, 3553. https://doi.org/10.1016/j.cogsys.2019.04.007

Leopold, H. A., Orchard, J., Zelek, J. S., & Lakshminarayanan, V. (2019). PixelBNN: Augmenting the PixelCNN with batch normalization and the presentation of a fast architecture for retinal vessel segmentation. *Journal of Imaging*, *5*(2). https://doi.org/10.3390/jimaging5020026

Liu, Y., Milton, J., & Campbell, S. A. (2019). Outgrowing seizures in childhood absence epilepsy: Time delays and bistability. *Journal of Computational Neuroscience*, *46*, 197209.

MacKinnon, N. J., & Hoey, J. (2021). Operationalizing the relation between affect and cognition with the somatic transform. *Emotion Review*, *13*(3), 245256. https://doi.org/10.1177/17540739211014946

Malhotra, A., Stewart, T. C., & Hoey, J. (2020). A biologically-inspired neural implementation of affect control theory. *International Conference on Cognitive Modelling, Toronto*.

McCrackin, S. D., & Itier, R. J. (2021a). Feeling through anothers eyes: Perceived gaze direction impacts ERP and behavioural measures of positive and negative affective empathy. *Neuroimage*, *226*, 117605. https://doi.org/10.1016/j.neuroimage.2020.117605

McCrackin, S. D., & Itier, R. J. (2021b). I can see it in your eyes: Perceived gaze direction impacts ERP and behavioural measures of affective theory of mind. *Cortex*, *143*, 205222. https://doi.org/10.1016/j.cortex.2021.05.024

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7.3 Nengo Usage Statistics

Nengo is the free (for personal use and research use) neural simulator produced by CTN students and faculty (Eliasmith and Tripp). This research tool consists of 50,000+ lines of code and a full GUI for construction and simulation of large-scale, biologically realistic neural models. It is accessible from Github where the usage statistics attest to its popularity and high regard:

Github Stars	879
Github Clones	655
Pypi Downloads / month	5593
Used in other Github Repos	224

Table 5: Github Nengo Usage Statistics

Since 2018 Google Scholar lists over 600 papers making use of or reference to this neural simulation platform.

7.4 Member Comments (alphabetical)

7.4.1 Sue Ann Campbell

- I believe being a member of the CTN has helped me attract better students, specifically students interested in neuroscience.
- The course offerings associated with the CTN diploma are very beneficial for my students, enabling them to gain knowledge and connect with students outside their discipline.

7.4.2 James Danckert

- The colloquia/seminars are extremely valuable bringing in speakers or broad relevance to CTN members.
- The Centre promotes collaboration across disciplines (and ultimately that means across campus).
- My students and I have benefitted enormously from these interdisciplinary links.
- Brain Day is the flagship event the Center holds and is ubiquitously excellent. It has become a prestigious event for invitees and attendees alike.

7.4.3 Kaylena Ehgoetz-Martens

- The CTN provides a conduit for my students and myself to come in contact with multidisciplinary research in neuroscience, which has sparked new ideas, broadened their course selection, and encourages cross-silo communication, collaboration and inquiry.

7.4.4 Chris Eliasmith

- Brain Day is great community outreach. I also had several students say they took my class because of the CTN Research Day.
- The CTN provides international recognition to my core area of research, and has drawn top collaborators and students from around the world to work on research with my group.
- Having a strong representation in this specific area is extremely attractive to those in the discipline.
- The CTN signals to funders the commitment of the University to the research areas I work in.

7.4.5 Jesse Hoey

- The CTN is really a center for interdisciplinary work I think - it provides my students a different perspective on artificial intelligence and machine learning, one that brings in elements of neuroscience and cognitive science.
- This is really important for computer science students who can get "stuck" in the silo of CS-based machine learning research

7.4.6 Roxane Itier

- Brain Day is a fantastic venue with talks spanning diverse areas linked to the CTN.
- I also appreciate very much the diversity of the regular CTN talks offered throughout the year.

7.4.7 Jeff Orchard

- Brain Day has been an excellent way to meet some of the central figures in computational and theoretical neuroscience.

7.4.8 Paul Thagard

- Although Im retired, I still benefit greatly from CTN activities, especially the speaker series which helps keep me keep up to date on cutting edge research in theoretical neuroscience.

- Waterloo Brain Day is a wonderful institution for bringing together researchers from neuroscience, computer modelling, psychology, and philosophy.

7.4.9 Reza Ramezan

- I particularly like the hub CTN provides to both meet students, and researchers in the field but from other departments (UW faculty and those from other institutions)
- My graduate students have also benefitted from interacting with both PIs and other students from departments other than Statistics and Actuarial Science.

7.4.10 Bryan Tripp

- The CTN provides an environment to quickly exchange ideas with people who have diverse perspectives on intelligence.

8 Appendix

8.1 Letters of Support

UNIVERSITY OF WATERLOO

FACULTY OF ARTS | OFFICE OF THE DEAN
uwaterloo.ca/arts

21 April 2023

Re: Centre for Theoretical Neuroscience (CTN)

Dear Members of Senate Research Council,

I am pleased to provide this letter of support from the Faculty of Arts for a renewal of the Centre for Theoretical Neuroscience (CTN). A key objective of research centres is to serve as the catalyst for interdisciplinary collaboration. By any measure, the CTN has fulfilled this goal and it has achieved an impressive international reputation. Its cross-faculty participation (engaging five of the university's six faculties), innovative graduate programming, and interdisciplinary scholarship exemplify the kind of innovative research and impact to which the University of Waterloo is dedicated. The Centre has helped to advance the research of the core and affiliate members across the faculties, and it has provided an excellent platform for the undergraduate and graduate students from across the university over the past five years who have benefitted from the unique opportunities it has afforded them. Students and faculty associated with the CTN have enjoyed great success in securing external funds that have helped further its activities, and graduate students have launched successful academic and non-academic careers. I would also like to single out the annual Brain Day as an important means of outreach developed by CTN, particularly as a means of bridging the gap between undergraduate and graduate education.

In summary, the Faculty of Arts enthusiastically supports renewing the CTN for a further five years, and we look forward to working with colleagues across the campus to identify ways of ensuring its budget sustainability.

Sincerely,

Dr. Sheila Ager
Dean, Faculty of Arts

Cc: Dr. Britt Anderson, Director, Centre for Theoretical Neuroscience
Dr. Ramona Bobocel, Acting Associate Dean of Arts, Research

UNIVERSITY OF WATERLOO

FACULTY OF MATHEMATICS | Office of the Dean
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April 17, 2023

Prof. B. Anderson, Director
Centre for Theoretical Neuroscience
University of Waterloo

Dear Professor Anderson:

I am writing to express my strong support for the Centre for Theoretical Neuroscience.

Faculty members in Mathematics have been involved with the Centre, both as core members (at least three, from Applied Math, Statistics & Actuarial Sciences, and Computer Science) and as affiliate members. They have benefited from the interdisciplinary research that the Centre fosters. These cross-Faculty collaborations are critical to a deeper understanding of complex problems, such as theoretical neuroscience.

In the coming years and decades, I'm confident theoretical neuroscience will remain an area of great opportunity, benefitting both individuals and society, and the Centre for Theoretical Neuroscience is poised to play a global leadership role in this area.

Yours truly,

Mark Giesbrecht
Dean, Faculty of Mathematics
Professor, David R. Cheriton School of Computer Science

UNIVERSITY OF WATERLOO | Department of Psychology

May 18, 2023

Dear Review Committee Members,

I am writing to express my strongest support for the UW Centre for Theoretical Neuroscience (CTN) as it undergoes its standard 5-year review. Since its inception, the CTN has provided extraordinary benefits to faculty, post doctoral fellows, graduate students, and undergraduate students in the Department of Psychology. Four faculty members in Psychology are involved in the CTN, serving as the Director/Core Member (Anderson) and Centre Affiliates (Danckert, Fugelsang, Itier).

The CTN provides a physical and intellectual hub for members of our Department wishing to pursue interdisciplinary research in neuroscience. The activities of the CTN, including the colloquium series and Brain Day event, have fostered new inter-faculty research collaborations involving members of our Department. For example, Roxane Itier (Associate Professor, Psychology, CTN Affiliate) and Jeff Orchard (Professor, School of Computer Science, CTN Core Member) recently initiated a collaborative research project using EEG data collected in Dr. Itier's lab to test a computational model of predictive coding during face processing. Thus, the opportunity to share ideas and learn about methodologies is directly enhancing the research activities of faculty across campus.

Far beyond the impact on individual faculty members' programs of research, our students and trainees benefit from the myriad training opportunities provided by the CTN. Many of our students participate in the colloquium series and Brain Day conference where they welcome the opportunity to network with other students and scholars from across campus and around the world. It is notable that Psychology students make up the majority of students who formally pursue the graduate diploma in Theoretical Neuroscience, clearly indicating the perceived value of this specialized training for our students. Further, the collaborative research projects fostered via the CTN allow our faculty members to offer unique and innovative training opportunities for students. For example, in Fall 2023 Drs. Itier and Orchard will co-supervise an incoming graduate student in Computational Math.

In summary, the CTN provides an exceptional professional and intellectual space for many of our faculty members and students. We are thankful to the Director and Core members for their intellectual leadership and believe the CTN serves as a model for what University Centres are designed to accomplish.

If I can provide any additional information, please do not hesitate to contact me by email (hhenderson@uwaterloo.ca) or by phone (519) 888-4567 ex. 41597.

Sincerely,

Heather A. Henderson

Heather A. Henderson, Ph.D.
Professor & Chair
Department of Psychology

UNIVERSITY OF WATERLOO

FACULTY OF ENGINEERING | Systems Design Engineering
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April 26, 2023

To: Charmaine Dean, Vice-President, Research and International

The Department of Systems Design Engineering (SYDE), within the Faculty of Engineering at the University of Waterloo, is pleased to continue extending enthusiastic support to the Centre for Theoretical Neuroscience (CTN) and its status as a research centre.

The CTN is the leader in neuroscience research at Waterloo and has developed an international reputation at the cutting edge of this growing field. By engaging faculty members and departments from across campus, the CTN has become a hub for interdisciplinary partnerships and outreach within the community of neuroscience researchers. This priority is shared by SYDE, and we are proud to continue to be involved and support these research activities.

Currently, SYDE has three faculty members involved with the CTN, Dr. Christopher Eliasmith (founding director), Dr. Chrystopher Nehaniv (affiliate member), and Dr. Bryan Tripp (core member). They are all research active faculty members and have expressed how working with the CTN has benefited their research by garnering international recognition and attracting top graduate students to their research groups.

The CTN faculty members have advanced how we understand the brain through their tremendous research output. We commend the CTN's efforts to mobilize these findings and build community through outreach activities. Their flagship research seminar, Brain Day is a valuable way for Waterloo students to connect with and learn from a broad spectrum of notable theoretical neuroscience researchers. The Brain Day presentation recordings are added to an online library, further expanding the potential outreach.

We are encouraged by the CTN's steady growth and believe they will continue to enhance Waterloo's presence in neuroscience research. Please accept this letter in support of the Centre for Theoretical Neuroscience and the recommendation for its continued status as a centre.

Sincerely,

Lisa Aultman-Hall
Professor and Chair
Systems Design Engineering

UNIVERSITY OF WATERLOO

Department of Applied Mathematics,
University of Waterloo,

April 14, 2023

Professor Britt Anderson,
Department of Psychology,
University of Waterloo.

Dear Professor Anderson,

I am writing to express my strong support for the Centre for Theoretical Neuroscience, which has been instrumental in fostering interdisciplinary connections and advancing ground-breaking research programs since its inception in 2006.

As Core members of the Center, Jeff Orchard, Sue Ann Campbell and affiliate member Dr. Brian Ingalls from Applied Math, have consistently demonstrated their dedication to the Center's mission of facilitating cross-faculty collaborations and innovative research in neuroscience. Their contributions have been invaluable in propelling the Center to new heights.

Furthermore, they have also made significant contributions to the Center's research programs, demonstrating their deep understanding of the complex and dynamic interactions between mathematical models and neuroscience. The Centre's group of faculty, spanning Mathematics, Engineering, Health, and Arts, has uniquely positioned it, to address critical questions in neuroscience and to tackle emerging challenges in the field. The Centre's research on diseases, such as Epilepsy, has the potential to revolutionize our understanding of these conditions, and their work on brain models and AI promises to yield exciting breakthroughs in the future.

In conclusion, I would like to reiterate my unwavering support for the Centre for Theoretical Neuroscience, a beacon of excellence in interdisciplinary research and a source of inspiration for all those seeking to extend the boundaries of human knowledge.

Sincerely,
Siv Sivaloganathan,
========
Professor & Chair,
Department of Applied Math

UNIVERSITY OF WATERLOO

FACULTY OF MATHEMATICS | David R. Cheriton School of Computer Science
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cs.uwaterloo.ca

April 18, 2023

To whom it may concern,

I have read the draft report on the Centre for Theoretical Neuroscience dated March 21, 2023, and have consulted the members of the Centre for Theoretical Neuroscience in the David R. Cheriton School of Computer Science. The School continues to see great value in this centre, because it encourages and supports important inter-disciplinary and thus inter-faculty research. It has been successful in facilitating collaboration between faculty members in the David R. Cheriton School of Computer Science's and other researchers on campus as well as external partners. Interdisciplinary collaboration is critical to sustain Waterloo's current reputation and strategic plan for the future such as the Waterloo 100. A concerted effort, such as the Centre for Theoretical Neuroscience, is important to develop world-leading interdisciplinary research. Overall, the centre has a positive impact on research programs and grad studies and I very much support its continuation.

Sincerely,

Raouf Boutaba, Professor and Director
David R. Cheriton School of Computer Science
University of Waterloo

WATERLOO ARTS
UNIVERSITY OF WATERLOO
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March 27, 2023

Dear Members of the Senate Graduate and Research Council,

The Centre for Theoretical Neuroscience is obviously an important asset to the University of Waterloo, as will surely be attested by the other letters of support it will receive.

CTN is also an asset to UW's Department of Philosophy. Some department members working in CTN, where they find the interdisciplinary collaborators and specialized equipment they need for their work; supported this way they have established high impact, internationally recognized research programs. Some philosophy graduate students take courses through CTN and engage in research supervised by CTN faculty; they benefit greatly from these opportunities. Many more of our graduate students benefit from CTN programming, especially its popular annual Brain Day. CTN is highly deserving of continued support.

Thank you,

Patricia Marino

Patricia Marino
Professor and Chair, Department of Philosophy
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March 30, 2023

Britt Anderson, PhD & MD
Director, Centre for Theoretical Neuroscience
Associate Professor, Department of Psychology
University of Waterloo, Canada

Dear Professor Anderson,

I am writing, as Chair of the Department of Statistics and Actuarial Science, to express my strong support for the Centre of Theoretical Neuroscience (CTN).

Faculty members in the Department of Statistics and Actuarial Science and a good number of graduate students have been active members of the CTN and their research has greatly benefited from activities in the Centre. The Centre is indeed an excellent example of cross Faculty interdisciplinary research activities which the University, and in particular our Department, strongly encourages.

In the future the area of Theoretical Neuroscience, and the role of Statistics in linking theory with evidence, will remain an area of great opportunity. The Centre will continue to play an important role in this exciting area.

Sincerely Yours,

Changbao Wu, Professor and Chair
Department of Statistics and Actuarial Science
University of Waterloo
Email: cbwu@uwaterloo.ca