HBP INNOVATION MANAGEMENT ANALYSIS

THE EDUCATIONAL POTENTIAL OF NEST DESKTOP: INVESTIGATING THE INNOVATION MANAGEMENT AND EXPLOITATION STRATEGIES FOR THE EDUCATIONAL SIMULATOR TECHNOLOGY IN THE HUMAN BRAIN PROJECT

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Abstract:	Amplifying the impact and expanding the international footprint of the innovations generated by the Human Brain Project is one of the aims of the project's Innovation team. This report has been produced as part of the innovation workflows of the Innovation team and focuses on investigating the educational potential of NEST Desktop, a web-based Graphical User Interface for the Spiking Neural Network simulator NEST. The purpose of this technology is to serve as an accessible classroom tool that allows students to complement their computational neuroscience education with experimental learning by building neuronal models without the need of advanced programming skills. The present work describes the engagement between the HBP Innovation team and the NEST Desktop team, as part of the project's aim to devise effective and efficient innovation management and exploitation strategies. After performing an analysis of NEST Desktop and its innovation ecosystem, as well as conducting semi-structured and exploratory interviews with relevant stakeholders, it is concluded that the main barrier preventing the tool from amplifying its scientific and social impact and expanding internationally was the lack of awareness and market visibility by other Higher Education institutions that could potentially integrate the tool in their neuroscience curricula. The most effective innovation management and exploitation strategy is recognised to be a marketing exercise intended to raise awareness of NEST Desktop amongst other European universities and germinate potential collaborations.
Keywords:	
Target Users/Readers:	

Summary

CHAPTER I. INTRODUCTION

1.1 Purpose of the work and problem definition

Understanding the human brain is one of the greatest scientific challenges of our time. By rising to the challenge, profound insights into what it means to be human can be gained, and such pioneering knowledge will revolutionise the way we harness our current technology. Understanding the brain will have significant repercussions in a wide range of areas, from catalysing the discovery of new methodologies for diagnosing and treating brain diseases to guiding the development of new neuromorphic computing architectures and enhancing robot performance through cognitive-based technologies. The Human Brain Project's mission is to deepen our understanding of the human brain structure and function by building a multidisciplinary European research infrastructure that combines state-of-the-art neuroscience and computing to advance our knowledge of brain-derived applications in health, computing, and technology, to the benefit of society.

The Human Brain Project (HBP) aims to put in place a collaborative and integrated ICT- based scientific Research Infrastructure (EBRAINS) that allows researchers across Europe to advance knowledge in the fields of brain research, cognitive neuroscience, brain-inspired computing, and brain-related medicine. The HBP was born in October 2013 after being selected as one of the two Future and Emerging Technologies Flagships in the seventh EU Framework Programme for Research and Development (Amunts et al., 2016). Flagships projects are the largest scientific projects ever funded by the European Union, running for a period of 10 years, mobilising hundreds of researchers across Europe and benefiting from an overall financial support of around 1 billion euros (Markram et al., 2011), and are financed through a specific partnering model by both the EU Framework Programmes for Research and Innovation and the Member States.

The last Core Project Special Grant Agreement (SGA) under H2020, SGA3 (sustained operations), began on 1 April 2020 and will run for a further three years, until April 2023. The project is now narrowing its focus on Computing the Brain, with an emphasis on brain connectivity and its multi-level organisation, as well as on its relationship to cognition and consciousness and its relevance for artificial neuronal networks. The HBP's current explicit goal is to develop its main legacy product, the EBRAINS RI, and provide the scientific research community with a comprehensive set of digital tools and services to continue advancing our knowledge and understanding of the brain after the end of the HBP FET Flagship in 2023. EBRAINS will capitalize on the work performed by the Human Brain Project teams in digital neuroscience, brain medicine and brain-inspired technology, and will take it to the next level. Innovation will become a crucial part of the operations during this final phase, as the HBP now aims to channel the knowledge developed by the Flagship during seven years of arduous research work into tangible applications that have an impact, exploiting its technology for the betterment of society.

Increasing the visibility of the efforts made in innovation by HBP research groups is a key objective in the SGA3 phase. Due to the multidisciplinary nature of the HBP there have been a wide range of high-quality results produced by each of the Work

Packages, with each focusing on the development of a specific state-of-the-art technology in neuroinformatics, simulation, neuromorphic computing, neurorobotics, or high- performance analytics and computing. As part of the global HBP strategy to ensure the commercial and non-commercial exploitation of these technologies and accelerate innovation, a dedicated HBP Innovation Team was created within the Polytechnic University of Madrid. The team's objective is to support the academic community in translating scientific discoveries into research outputs aligned to the market demands, and its activities range from assessing the maturity levels of selected technologies and presenting them to the European Commission Innovation Radar to identifying and contacting potential interested stakeholders external to the organisation, such as industrial players, hospitals or other research institutions.

Another key deliverable of the Innovation Team is conducting a series of market analyses tailored to the specific technologies, since the success of the exploitation or diffusion of a technology is largely contingent on the corresponding socio-economic ecosystem, the diffusion channels, and the innovation management strategy (Rogers, 1962) (D'Alvano and Hidalgo, 2012). As such, it is vital to characterise the potential markets that HBP innovations will try to penetrate, investigating their corresponding technology landscape; the main players, trends, and drivers that will affect the innovation's positioning in the market; and the stakeholder ecosystem surrounding the innovation (ranging from competitors to start-ups, venture partners, institutions, and user communities). The analyses aim to devise effective and efficient strategies to protect and commercialise the innovation and identify potential business opportunities. Academic researchers sometimes lack the time, resources and expertise to tackle these issues and define technology-specific roadmaps, and are therefore encouraged by the HBP to collaborate and consult with the Innovation Team to inform their strategic decisions.

The Innovation team engaged researchers from the NEural Simulation Technology (NEST) project, a Spiking Neural Network (SNN) simulator used throughout the HBP, with regards to the potential exploitation opportunities of their technology. The present work aims to contribute to the Innovation Team's market analysis strategy and support the NEST team through the provision of a detailed picture of their positioning within their technological ecosystem, as well as through the identification of relevant market insights, key actors, and possible innovation management and exploitation strategies that support the present and future of the HBP innovation. The paper was produced with the support of the Innovation team's professionals and will focus on researching the market potential of a specific technology developed by NEST researchers. The Innovation team closely collaborated with the NEST team to tailor the approach to their preferences and maximise the utility of the present work.

The NEST team had developed an install-free, interactive web-based application that provides a Graphical User Interface (GUI) for the NEST Simulator, called NEST Desktop. This allows users to rapidly perform construction, parameterisation, and instrumentation workflows of neuronal network models from their laptop through an intuitive GUI, as well as to visualise the simulation results to support and improve the analysis of the models. This technology has significant potential in computational

neuroscience education, as it is an accessible classroom tool that allows students to explore neuroscience concepts and complement their education with experimental learning by building neuronal models without the need of advanced programming skills or knowledge of a simulator control language.

NEST Desktop had been successfully trialled in the University of Freiburg and is used in two computational neuroscience courses at the university: the Simple Neuron Models BSc course and the Biophysics of Neurons and Networks MSc course. The use of NEST Desktop resulted in faster learning processes and greater student motivation, allowing them to systematically explore the biophysics of neurons, synapses, and small-scale networks of the brain via numerical simulations and put their theoretical knowledge to practice. The NEST team was interested in exploring the opportunities to maximise the tool's impact and expand it internationally to other university curricula, and as such the present work is centred on investigating the educational potential of NEST Desktop.

1.2 Main objectives of the report

The present work was motivated and elaborated as a part of the HBP Innovation team's market analysis operation and was produced with the support of the team's professionals. It will therefore focus on researching the market potential of NEST Desktop, combining a series of qualitative methodologies to present useful information aimed at guiding the future developments of the tool. The main question this report aims to answer is therefore formulated as follows:

- **What are the innovation management and exploitation strategies that amplify NEST Desktop's scientific and social impact and expand its international footprint?**

The aim of the report will be to perform a series of complementary analyses that will allow to devise strategies for innovation management and exploitation of NEST Desktop. As such, the main objectives of the report will be to:

i. **Explore how the HBP has contributed to the development of NEST Desktop and provide an overview of the main features and services offered by the tool.**
ii. **Explore the potential of NEST Desktop as an educational simulator, analysing its use in the University of Freiburg and its competitor landscape, interviewing relevant stakeholders, and detailing the co-creation of a showcase-based marketing strategy for the tool.**
iii. **Probe the Higher Education market for the compatibility of NEST Desktop with other European computational neuroscience curricula, performing a matching exercise between the tool and institutions offering relevant courses.**

CHAPTER II. CONTEXT AND BACKGROUND

The present chapter will first focus on providing the theoretical framework surrounding the use of simulation education technology and its benefits, as well as its use in neuroscience curricula. The review will then explore the different approaches to investigating the innovation management, diffusion and commercialisation strategies for neuroscience educational simulators, and will present the novelties introduced in the approach of this work. The chapter will then shift its focus on the theoretical framework behind Spiking Neural Networks and the role of NEST Desktop within the project, exploring and explaining the context within which this report is performed.

This chapter's analysis was conducted with the aim to consolidate the knowledge around the range of thematic areas underlying NEST Desktop and guide the investigation design and execution. Developing a comprehensive understanding of the tool also required researching and synthesising the underlying theory behind spiking neural networks and their applications, as well as investigating the current state-of-the-art in neuroscience education simulation technologies.

2.1 The history of simulation technology in education

The use of simulation technology for educational purposes has been on the rise for almost a century and continues to prove its utility when complementing theoretical knowledge with experimental analysis and experiential learning (Lateef, 2010). Simulation use for educational purposes was first adopted in the discipline of business studies, with earliest uses going back to the mid twentieth century with the likes of Chamberlin's imperfect competition laboratory simulation allowing students to test the microeconomic principles taught in class through interactive role-playing (Chamberlain, 1948). Formal academic research gathered momentum with Schild's seminal work on the use of simulation-based tools and games to enhance teaching and learning (Schild, 1968), and adoption steadily increased as professors noticed that simulations allowed students to gain deeper insights into the underlying mechanisms of the processes being simulated.

During the 80s, advances in computational capability drove the diffusion of such technologies with Queen stating that "students actively participating in a simulation can vicariously experience a reality paradigm of scientific discoveries, social issues, and world events" (Queen, 1984). The latest decades have seen an extraordinary surge of simulation education as a result of the exponential increase in software power, complexity and flexibility, coupled with the proliferation of personal and portable computers (Qudrat- Ullah, 2010) with STEM subjects experiencing the fastest rate of integration into their curricula (Nance, 2000), (Martin and McEvoy, 2003). The future of simulation education is promising, and efforts will keep being made to support, complement and enhance teaching and learning through more immersive, interactive and effective technology (Campos et al., 2020).

It is no surprise therefore that the interest on behalf of the scientific community to study the benefits of simulation-based education still persists and arguably increases as the possibilities of simulation technology continue to grow. Active learning, when

compared to the traditional passive method of text-book based independent studying, boosts students' interpersonal and collaborative skills, as well as decision making and critical thinking skills (Scottile and Brozik, 2004). Such methods can also enhance self-efficacy, with researchers finding better knowledge retention rates and written communication skills when comparing simulations to case method approaches due to the increased impact of visual interactive stimuli (Thompson and Thompson, 1995), as well as increased intrinsic motivation and involvement due to the gamified nature of the experience (Stipek, 2002).

The integration of complementary mechanisms such as feedback is also a crucial aspect of the benefits derived from simulation education, as they allow for more personalised tracking, feedback and reinforcement dynamics that improve the overall quality of the learning experience (Jay Samuels and Wu, 2003), as well as allow the teacher to access more granular insights and metrics of their students' performance (González Vega, 2002). Finally, simulation virtual spaces also allow to integrate multimedia components such as text, audio, images, animations, video to increase the degree of immersion and sensory stimulation of the experience, resulting in increased efficacy when helping students understand abstract concepts and improve their performance and sensory (Jay Samuels and Wu, 2003).

Simulation education is being integrated into a wide range of disciplines, as modern curricula increasingly aim to expose students to the complexities of real-world situations. There is detailed and recent documentation in the academic literature covering its use in educational settings, ranging from business and commercial simulation training (Avramenko, 2012) (Tao and Wu, 2017) to supply chain management and logistics (Tvrdoň and Jurásková, 2015) (Perera and Rupasinghe, 2015), electronic engineering (Mavinkurve and Patil, 2016), civil engineering and architecture (Alsaadani and Bleil De Souza, 2019), computer science (Schäfer et al., 2013) and even at school-level education such as teaching algebra and geometry (Rozhkova, Rozhkova and Chervach, 2016). All of these studies highlight the benefits of its use, and the heterogeneity of its potential applications emphasises the impact and reach that simulation technology is having on global education standards and student learning.

Narrowing the focus now to neuroscience education, the increasing need to integrate simulation technology into the curricula is correlated with the increasing importance of computational neuroscience and neural modelling as tools to understand the inner workings of the brain (Lorenz and Egelhaaf, 2008). Such simulations provide insights into the complex, dynamic, and highly abstract processes that could not be produced by laboratory experiments, as even though a simple neuron membrane action-potential experiment is accessible and straightforward to perform, the ability to directly parametrise a wide range of neuron properties and explore biologically unfeasible situations allows for a deeper understanding of neural dynamics (Av-Ron, Byrne and Baxter, 2006). Simulations also allow to introduce artificial uncertainty and dynamism, mostly in the form of noise or randomised variations, that mimic the behaviour of real-life systems, thus training students in reacting and circumventing potential experimental issues without having the need for costly state-of-the-art apparatus and facilities (Gruler et al., 2019).

This growing demand for simulation technology in is coupled with the continued growth in undergraduate education, with Rochon et al noticing a 40.7% increase in the amount of US institutions offering undergraduate "neuro" programs between 2013 and 2019, (an increase from 157 institutions to 223) and gathering qualitative data that indicates universities are more inclined to invest in undergraduate neuroscience programs over more traditional life sciences programs (Rochon et al., 2019).

A series of neural simulation tools have been developed and adapted to teaching environments to meet this growing demand. The scientific literature has comprehensively documented the development, use and implementation of some of the most used simulators, such as for Neuron (Hines, M. L., & Carnevale, 2001), NeuroSim (Lytton, 2002), NeuroLab (Moore and Stuart, 2004), SNNAP (Baxter and Byrne, 2006), GENESIS (Bower and Beeman, 2007), BRIAN (Goodman, D. F., & Brette, 2009), or Nengo (Bekolay, T., et. al, 2014) There have also been private companies (mostly in the form of academic spin-offs) that, acknowledging the potential of such tools, have developed fully fledged independent products such as Ovilab's Neuronify (Dragly et al., 2017).

However, although there is wide coverage of the inner technical workings of the tools and how they are being integrated in neuroscience curricula to enhance the teaching and learning experience (Lorenz and Egelhaaf, 2008), (Helikar et al., 2015), and even seminal books on the implementation of such simulators such as the work done in Implementing a Web-Based Simulator with Explicit Neuron and Synapse Models to Aid Experimental Neuroscience and Theoretical Biophysics Education (Sridharan et al., 2016), most articles are purely descriptive and non-comparative case studies that cannot be generalised to the wider neural simulation market, and therefore offer little guidance for new simulator developers when aiming to manage and exploit their innovations.

As a result, the present work aims to contribute to filling in the current knowledge gap surrounding the strategies that the developers of these simulations have leveraged to expand the international footprint and amplify the impact of their innovations. This will be done by firstly gathering insider insights from the tools development to explore the internal processes that precede the diffusion of such technologies and identify the main barriers to their exploitation and expansion. It will be followed by describing the co- designing of a showcase-based marketing strategy that engages professors from other universities aimed at gauging their appetite for NEST Desktop and its compatibility with other neuroscience curricula, and will finish by exploring the potential of the tool through exploratory interviews with the aforementioned professors as well as companies that have developed similar educational neural simulation technologies.

2.2 A brief introduction to Spiking Neural Networks

Spiking neural networks (SNN) first emerged in computational neuroscience as an attempt to model the behaviour of biological neurons by describing neuronal activity as the integration of received spike voltages and weak dissipations (leakages) to the environment. As opposed to classical Deep Learning multi-layer perceptron networks where neurons receive inputs from every neuron in the

previous layer and signal every neuron in the subsequent layer, transmitting information every propagation cycle, SNNs operate using spikes and incorporate the time dimension into their computation, thus mimicking biological systems (Caporale and Dan, 2008). These are discrete events that take place at points in time, rather than continuous values. SNNs incorporate time into their operating model and only transmit information when the neuron's membrane potential reaches a specific value. When the neuron's voltage reaches a threshold, the neuron fires a spike on its own, generating a signal that travels to other neurons which, in turn, increase or decrease their potentials in response to this signal (Esser et al., 2016).

Spiking neural networks are interesting for a few reasons. First, information can be transmitted using very weak signals since SNN rate encoding is very robust to noise. Second, they bring new learning algorithms for unsupervised learning, as they allow the implementation of bio-inspired local learning rules such as Hebbian learning and Spike- Time-Dependant-Plasticity (STDP) (Caporale and Dan, 2008). These learning rules resume to enhancing the weight of a synapse if the activities of the two neurons that it connects seem to be correlated (and decreasing it otherwise). It thus allows the network to learn in real time and by itself.

In hardware neuromorphic computing, SNNs are the most broadly adopted brain-inspired models. However, they have not met a large interest in software artificial neural networks as of yet, since Deep Learning Networks use neurons characterized by a single, static, and continuously valued activation function (Stewart and Gu, 2020). SNN originally struggled due the lack of efficient training algorithms for their supervised learning, since in order to apply a commonly used learning algorithm such as gradient descent with backpropagation one needs to define a continuously valued differentiable variable for the neuron output (which SNN output is not). Although this can be done by calculating the spike arrival time or its rate, it adds in computational complexity and thus makes them less appealing for implementation in DLNN. Finally, thanks to the spatio-temporal information encoding that they use, spiking neural networks open possibilities to exploit the network dynamics for learning. For example, synchronization of spike trains allows to decode the network outputs from synchronization patterns (Choe, 2014) (Esser et al., 2016). Such dynamical phenomena are present in brain and allow it to compute with a smaller number of neurons, making SNNs effective at studying the operation of biological neural circuits and modelling Central Nervous System functions.

2.3 NEural Simulation Technology (NEST) and NEST Desktop

NEST is an open-source software tool designed to simulate large-scale models of spiking neural networks, and a beacon for open innovation in the HBP. A NEST simulation follows the logic of a laboratory electrophysiological experiment, where the neural network is generated from neurons and their connections. These can either be static or exhibit synaptic plasticity (as observed, for example, during learning). NEST focuses on the dynamics, size and structure of neural systems rather than on the exact morphology of individual neurons since, to represent biologically realistic levels of connectivity where each neuron has thousands of connections to other neurons, the complexity of individual neuron representation had to be

reduced. Thus, NEST looks at either single-compartment or few-compartment models, offering a range of standard models from which researchers can build neural architectures from. It also allows researchers to create complementary modules that, in EBRAINS's collaborative spirit, are incorporated into the open-sourced platform for others to exploit and harness.

Originally, the NEST team focused exclusively on simulating the propagation of synfire chains using single-processor workstations (SYNOD), but in the past decades they have continuously expanded NEST's capabilities to address new scientific questions and computer architectures (Gewaltig and Diesmann, 2007). Prominent examples include studies on spike-timing dependent plasticity in large simulations of cortical networks, the verification of mean-field models, models of Alzheimer 's and Parkinson's disease, and tinnitus. Recent developments include a significant reduction in memory requirements, as demonstrated by the record-breaking simulation performed in 2013 by a German- Japanese team led by researchers from Forschungszentrum Jülich, which succeeded in simulating a neuronal network consisting of 1.86 billion nerve cells connected by 11.1 trillion synapses using the simulation software NEST on the Japanese K supercomputer (Kunkel et al, 2014). NEST is ideal for networks of spiking neurons of any size, ranging from models of information processing (visual or auditory cortex of mammals), models of network activity dynamics (laminar cortical networks or balanced random networks), or models of learning and plasticity.

NEST includes over 50 neuron models, many of which have been published. These range in complexity and granularity, from simple integrate-and-fire neurons with current or conductance-based synapses to more complex models like the Izhikevich, AdEx or Hodgkin-Huxley models. In addition, NEST also includes over 10 synapse models, including short-term plasticity (Tsodyks & Markram) and different variants of spike- timing dependent plasticity (STDP). NEST has been used (within HBP) to validate results from neuromorphic systems (van Albada et al, 2018). NEST allows researchers to inspect and modify the state of each neuron and each connection at any time during a simulation, improving the flexibility of neural simulations and granting deeper insights into synapse signal propagation and neural dynamics.

The software is scalable and works on any type of hardware, from laptops to the largest supercomputers, allowing researchers to develop complex, biologically plausible networks for simulations with any system that fits their needs. The user interface is Python-based, one of the most well-known programming languages in the scientific community, which simplifies the network simulation script-writing process significantly. The NEST team aims to ensure compatibility and interoperability with other modelling tools like PyNN, and support several platforms, with continuous developments to improve on- boarding with simplified installation procedures using virtual machines, Conda, and Docker. The technology of NEST is well documented by a large number of peer-reviewed technical papers, and the reliability and usefulness is proven by the large number of peer- reviewed neuroscience publications produced with NEST.

The development of NEST is coordinated by the NEST Initiative, a member-based organization that has been advancing computational neuroscience since 2001. In 2012 the NEST Initiative was incorporated as a non-profit organization promoting

scientific collaboration in computational neuroscience. NEST tools for network level simulations are used throughout the HBP in various components, since NEST is the main simulator for all models of point-neuron networks in HBP, and it is used for a wide range of network dynamics studies, such as the multi-area model of vision related areas containing millions of neurons. It is also used by the CerebNEST project, which aims to provide important advancements to cerebro-cerebellar circuits functional modelling, eventually integrating the PyNEST codes into a virtual mouse robot in a closed-loop experiment (Gewaltig and Diesmann, 2007; Davison et al., 2009).

Additionally, other platforms and components, such as the Neurorobotics Platform, rely on NEST as a back-end, or use NEST for validation and comparison of hardware implementations as in the neuromorphic computing platforms. This is made possible by a direct transfer of models between the different platforms through common languages as PyNN and NESTML, and effort has been made in recent years to couple the brain model simulators to neurorobotic simulators like Gazebo for in silico experimentation, allowing researchers to design and run basic experiments in neurorobotics using simulated robots and simulated environments linked to simplified versions of brain models (Falotico et al., 2017).

Previously, non-expert computational neuroscientists that wished to begin using NEST could find it challenging, as network models and simulations had to be scripted using Python. NEST Desktop bypasses this restrictive requirement by offering a graphical approach to the construction and simulation of neuronal network models (Davison et al., 2009). NEST Desktop is a web-based graphical user interface (GUI) for the NEST simulation code that enables the rapid construction, parametrisation and analysis of a range of neural network models commonly used in computational neuroscience and neuroinformatics, allowing for early testing and fast prototyping of SNN models (Spreizer, Rotter, et al., 2021). The GUI gives students direct access to many important features of NEST in a highly intuitive fashion, without the need to dive into the details of designing, writing and debugging the underlying programs.

The main aim of this GUI was to provide an accessible classroom tool that would allow students to explore neuroscience concepts and complement their education with experimental learning by building neuronal models without the need of advanced programming skills. The GUI generates—invisibly to the user—a textual script in PyNEST that is then fed into the NEST Simulator, and the corresponding neural network activity can then be visualised in exportable graphs or tables. Students can visually and interactively model simulations from scratch or can import existent networks from a large and well documented repository and can therefore embark on SNN modelling and analysis even in the early stages of their computational neuroscience education. This opens the domain of NEST to a broader range of neuroscience students and higher education institutions across Europe, and possibly the world.

CHAPTER III. METHODOLOGICAL APPROACH

In order to accomplish the aforementioned objectives, the methodology will consist of semi-structured and exploratory interviews, and co-creation of ad-hoc solutions together with the NEST Desktop team. The methodology followed a sequential process where the focus was progressively narrowed down to achieve more actionable and specific insights. The present section aims to describe and justify the way that each method was used, as well as the value behind each technique used.

3.1 Semi-structured and exploratory interviews

Interviews have been widely used in managerial science as they allow to gather insightful information from key stakeholders and relevant agents, using structured or open-ended questions to converse with respondents and collect elicit data (Fontana and Frey, 2000). Interviews were deemed to be the most effective methodology to investigate the innovation management and exploitation strategies for NEST Desktop as the desired results were purely qualitative in nature: co-designing the most effective strategies that amplify the impact of the tool and exploring its compatibility with the neuroscience higher education market.

The interviews that were carried out during this research work were conducted in an online environment, due to both the pandemic and the geographical separation between most of the participants. The interviews were carried out with the NEST team, the HBP Innovation team and the HBP Education Committee before starting the analysis in order to fulfil three main objectives: to gather first-hand information from the developers of the tool and extract insights and guide future work; to ensure that the objectives of the analysis were aligned to the needs expectations and preferences of both parties; and to delimit the objectives of our engagement and co-design a strategy between the NEST team and the HBP Innovation team.

These interviews were designed to be semi-structured interviews, following the taxonomy laid down by (Qu and Dumay, 2011), as certain key elements had to be discussed with the different members of the NEST team but also a certain degree of open-endedness was necessary in order to drive the exploratory nature of parts of the discussion. This is because designing a strategy must result from a divergent-convergent process where initial sessions of brainstorming are followed by a progressive narrowing down of the most high-value and feasible options.

Due to the collaborative and supportive nature of the engagement, as well as to the breadth of stakeholders involved, the co-design process was iterative, and consensus had to be achieved before progressing on to the second phase of the analysis. Figure 1 on the next page shows a schematic of the individuals that were interviewed, with some individuals being interviewed more than once because of this aforementioned co-designed nature.

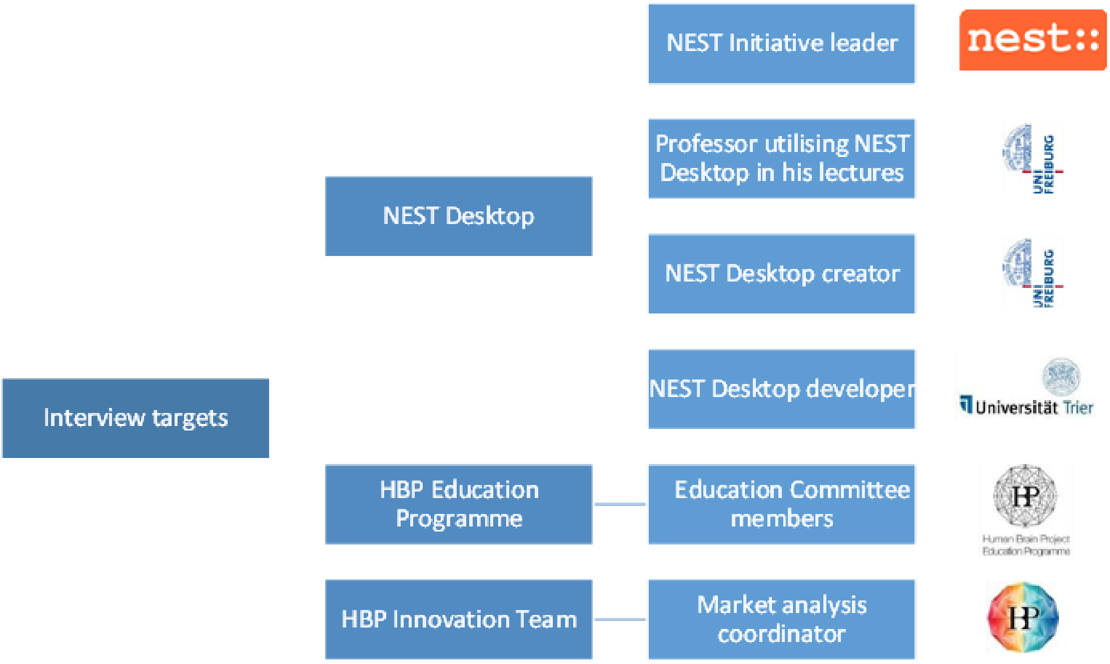


Figure 1. Interview targets and their corresponding organisations. Source: own elaboration.

CHAPTER IV. RESULTS

4.1 Internal analysis of NEST Desktop

NEST Desktop offers a network editor from which users can build models by creating and connecting nodes. Students use the right mouse button to create a new node and can create networks by connecting the nodes together through a click-and-drag operation. These nodes are divided into three main element types: stimulus devices, which produce signals towards target nodes; recording devices, which observe the states of the recordable nodes it is connected to; and neuron nodes, which receive inputs from other nodes and produce specific outputs using the intrinsic equations.

As one might expect, the latter are the core engines of the models, and may have different synaptic weight arrangements (positive weights for excitatory connections to other neurons, negative weights for inhibitory connections, or a mix between positive and negative weights). Each node is labelled in the controller view, where it can be edited and parametrised at the user's will. An example of the neural network modelling interface is shown in Figure 2.

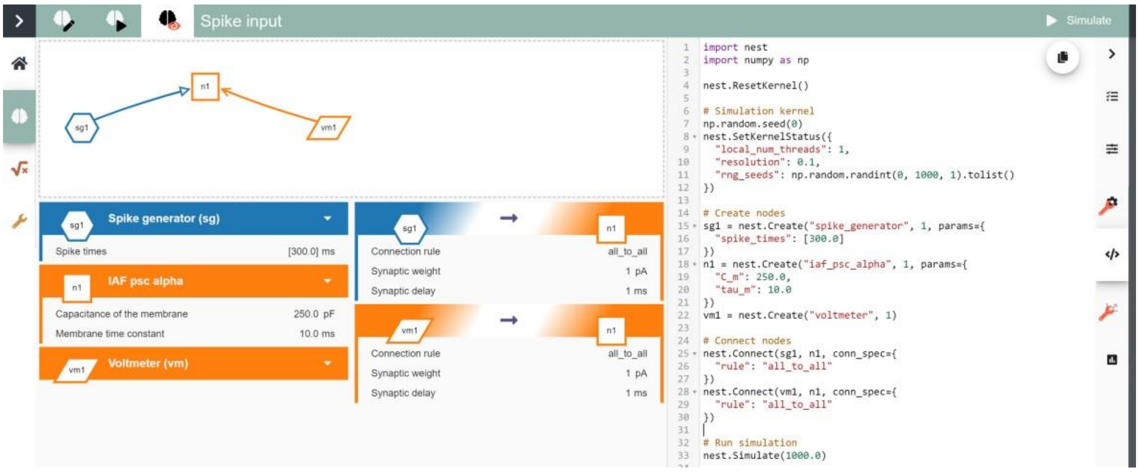


Figure 2. Snapshot of NEST Desktop's network editor. Source: (Spreizer, 2019)

The hexagon corresponds to a stimulus device (in this case, a spike generator); the square corresponds to a neuron and the trapezium corresponds to a recording device. The neuron's intrinsic properties, as well as its corresponding weights with respect to the other nodes, are parametrised in the controller panel. The right-hand side of the snapshot shows the PyNEST script code that will be generated by the visual network model created in the GUI, which will in turn be fed into the NEST Simulator to render the result. Once the network is simulated, the dynamics can be visualised and explored via graphs or tables, which are colour-coded in order to associate the network graph and the visualization of the network activity with the corresponding neuron and controller.

After simulation, network activity can be obtained from the recorder nodes, which can be either collectors (spike detectors) or analog samplers (voltmeters or

multimeters) and visualized. An example of an activity graph and table resulting from a simulation are shown in Figure 3.

Figure 3. Activity graph and spike statistics table produced by a NEST Desktop simulation. Source: (Spreizer, 2019)

The activity graph displays the activity topology given by the neuron ID and positioning and the chart graph shows a histogram of spike times or of inter-spike intervals through vertical stacks that aggregate the spike count over such intervals which can be further explored by hovering the mouse over specific bars. The statistics table gives further granularity about the behaviour of the network neurons. Finally, NEST Desktop also allows to explore the time evolution and dynamics of individual neurons through membrane potential-time graphs, as the one show below in Figure 4, through which students can analyse the outputs of different neuronal models like Hodgin-Huxley, simple linear integrate-and-fire or more complex leaky integrate-and-fire or point neuron models. This also allows them to explore how the membrane potential response depends on the different biophysical neuron parameters; experiment with introducing "noise" to account for additional effects seen in recordings, mimicking spontaneous channel openings through a Gaussian distribution current stimulator; or investigate the neuron behaviour resulting from different combinations of excitatory and inhibitory synaptic inputs, using spike generators whose parameters can be specified at will.

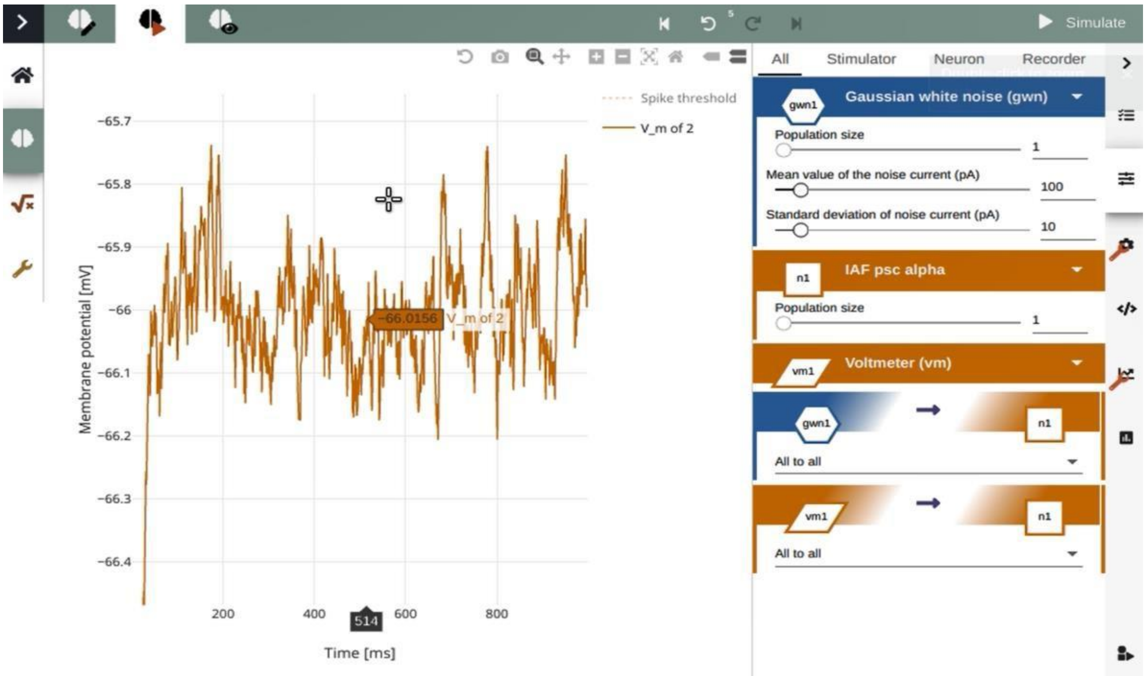


Figure 4. Membrane potential trace of a single neuron and corresponding parameters. Source: own elaboration from NEST Desktop online tool.

The main competitive advantage of NEST Desktop is that it has been successfully trialled in the University of Freiburg's Faculty of Biology, addressing undergraduate and postgraduate students from diverse backgrounds such as biology, physics, computer science and engineering. It continues being used in two computational neuroscience courses at Freiburg: The Simple Neuron Models BSc course and the Biophysics of Neurons and Networks MSc course, replacing the Mathematica Notebooks. It has had visible impact on the educational quality of both courses. The use of NEST Desktop resulted in faster learning processes and greater student motivation, allowing them to systematically explore the biophysics of neurons, synapses and small-scale networks of the brain via numerical simulations and put their theoretical knowledge to practice.

Another source of competitive advantage for the tool is the reproducibility of the activity of the same network on other machines, rendering the same simulation dynamics and results be it in student laptops or state-of-the-art HPC facilities. This is because NEST Desktop's network models generate equivalent textual codes that can then be applied in any Python interface (Spreizer, Rotter, et al., 2021). As a result, students using NEST Desktop can achieve the same simulations independent of their locations, allowing for an efficient expansion into other curricula as model tutorials, and results will be fully compatible between institutions. In addition, it also allows them to replicate and experiment with NEST-related frontier research, albeit limited by the power of their machines, as well as to start becoming acquainted with the corresponding NEST Simulator's PyNEST scripts syntax and semantics, should they wish to dive further into computational neurosciences down the line and use the fully fledged high-end tool.

NEST Desktop is currently integrated in the BSc curriculum through an intensive, week- long workshop, with the MSc workshop lasting double that time (two weeks). During these 7-hour daily sessions, students perform simulation experiments of increasing complexity following a predetermined list of assignments, which allows them to explore the intricacies of each simulation while accounting for the underlying biophysics and possible shortcomings of the numerical model used. These can be broken down into the scientific question or problem addressed by the simulation; the model design setup and component parametrisation used to answer the question; the outcome of the simulation and the analysis of the relevant data; and the conclusions to the original question in light of the simulation results.

The contents of the two courses are similar in nature. The BSc workshop comprises 5 main assignments, where the students are first introduced to (or remembered of) the theoretical background of the experiment and are then given a range of sub-experiments that they must perform. An example of such assignment would be using direct currents (DC) of various amplitudes to explore the response properties of a simple linear integrate- and-fire point neuron model, where the signal potential arriving at the neuron accumulates and aggregates until it reaches the membrane threshold, triggering a spike and a reset of the membrane potential. Students build a simple model with a DC stimulator, an integrate- and-fire neuron, an intracellular voltmeter to measure the membrane potential, and an extracellular spike detector that indicates the exact spike times; all of which can be easily constructed and parametrised through the GUI.

Students can then investigate the response of the membrane potential to changes in the neuron parameters, such as the leak conductance/resistance, the time constant of the membrane, the spike threshold, or the reset of the membrane potential after each spike and can characterize the neuron through an input-output curve that depicts the firing rate response as a function of the applied current. This allows students to test the theoretical models covered in class and allows them to establish deeper correlations between the different properties and factors governing neural dynamics.

Students in the MSc Biophysics of Neurons and Networks course tackle more challenging assignments in line with the demands of postgraduate education. During their two weeks using NEST Desktop, the students complete the BSc basic training and then move on to analyse more complex topics such as the Hodgin-Huxley model, which introduces the complexity of managing voltage-dependent sodium and calcium ion channels to generate the spikes, or more biologically-realistic, conductance-based synapses where the voltage is attenuated with distance due to leakage of electric charges, resulting in non-linear behaviour of the neurons (and thus expanding on the simple linear integrate-and-fire model described above).

In order to shed more light into the advanced capabilities of NEST Desktop as an education tool, a brief explanation of its application to investigate network dynamics will now be presented. In the central nervous system, neurons never act in isolation, and instead rely on using a combination of both electrical and chemical signals to communicate with each other. Fast electric signalling mostly depends on specific and precise synaptic transmission based on neurotransmitters. Depending on the transmitter system the presynaptic neuron is using, communication can be either

excitatory or inhibitory. Although polarity is the most salient property, other parameters of synaptic transmission are also important, such as the strength of the synapse, the transmission delay, the rise time of the postsynaptic potential, and different aspects of synaptic plasticity. Synapses are arguably one of the most components of networks, determining the properties and the function of brains in essential ways. A typical task of behavioural control rarely involves just one step of signal transduction. In most cases, several processing stages are needed. To achieve a complex task (e.g. produce spoken language) many neurons at different places in the brain eventually make their contribution. There is little agreement among researchers, however, how the communication is organized on the system level. In fact, different parts of the brain seem to employ very different strategies of collective signal processing. This is at least what the microanatomy of synaptic connectivity in brain circuits suggests. Whereas the cerebellum has a clear feedforward architecture, neuronal communication in the large recurrent networks of the neocortex is dominated by feedback. It is really a daunting task to characterize these networks of different types of neurons in the brain to help improving our understanding of their role for the control of behaviour. Numerical simulations of prototypic circuits help us exploring and refining theoretical ideas and aligning them with biological design principles.

The course leaders offer regular tutorials, but students have access to the detailed and concise documentation of the core features of NEST Desktop through its online domain, https://nest-desktop.readthedocs.io, which helps them to familiarise themselves with the important concepts of using the tool as well as follow the instructions to install the software and get started. This web page is free to access by anyone else who so desires and is enhanced with animated viewgraphs and short demonstration videos and tutorials. Each individual participant of the course is assigned a private virtual machine, which is temporarily provided by the Cloud services of Freiburg University. Once students log on to the system, the NEST server is started on the remote virtual machine, and the NEST Desktop client is run and controlled through the students' browsers. These two software systems communicate intensely with each other to produce the simulation interface.

NEST Desktop currently requires all users to install NEST in their machines and uses the laptop or desktop machine to power the simulation kernel (Spreizer, Rotter, et al., 2021). This severely limits the non-expert audience uptake as they may be reluctant to install the whole package; and also places a significant restriction on the range of networks that can be studied due to the limited computational capability and processing power of the audience devices (Davison et al., 2009; Spreizer, Rotter, et al., 2021). To tackle this issue, the NEST team has separated the GUI from the simulation kernel by rendering the GUI in the users' web browsers while running the kernel on a centrally-maintained server (Nowke et al., 2015). Streamlining the interaction between HPC facilities and the app will be key to ensure large datasets can be simulated and represented efficiently.

In July 2019 developers demonstrated that NESTML can be integrated into NEST Desktop. NESTML complements the GUI by enhancing the development process of neuron and synapse models. Advanced researchers often want to study specific features not provided by models already available in NEST. Instead of having to turn

to C++, using NESTML they can write down differential equations and necessary state transitions in the mathematical notation they are used to. These descriptions are then automatically processed to generate machine-optimised code. In addition, there is a strategy in place to integrate complementary tools with high technological maturity such as the NEST Instrumentation App and VIOLA as plugins to the GUI, extending the visual modelling and analytic functionalities (Oehrl et al., 2018). NEST Desktop is being integrated into the EBRAINS RI, and will leverage its user count to build its footprint and provide a broader student community with an easy-access tool to high-end SNN computing resources. This same open-source code of NEST Desktop is available as a standalone version for teaching and training purposes (Spreizer, Rotter, et al., 2021).

4.1.1 Interview results

The interviews were held in the first quarter of 2021. The interview with the professor utilising NEST Desktop in his lectures proved to be very useful, as first-hand experience on using the tool could be gathered, as well as feedback from students and plans for the future of the tool. There was significant emphasis placed on the positive feedback received, as well as in the perceived increased teaching efficacy. One of the main outcomes of the conversation was obtaining his permission to access the course scripts used in the lectures in order to explore the contents, structure and teaching methodology employed when teaching computational neuroscience with NEST Desktop.

Regarding the future developments of the tool, the professor made a reference to the potential creation of a new PyNEST programming course which started from NEST Desktop, using the intuitive GUI to help students quickly grasp the fundamentals, and then use the GUI-to-PyNEST functionality to swiftly transition to rapid prototyping and SNN research using the simulator control language. This would be very useful for doctoral students that wish to start using NEST but that lack advanced training in using PyNEST, and would serve a dual purpose as it would increase both the user base of NEST and NEST Desktop alike.

The interview with the NEST Desktop creator revealed the origins of the tool as a PhD project aiming to develop a GUI-enhanced SNN simulator and replace the Mathematica notebooks being used in the University of Freiburg. It also built the foundations for future collaboration on the NEST Desktop showcase and helped understand many of the inner workings of the tool. Both him and the tool's developer at the University of Trier mentioned that the current focus has now shifted towards making the tool more robust, reliable and scalable, bringing the technology to industrial strength and further improving the simulation visualisation capabilities.

During both meetings, one key detail was discovered: EBRAINS could not hold the necessary parallel sessions of NEST Desktop to accommodate for the Freiburg students, so they had to utilise their in-house computing infrastructure to host the servers. This is because the client-server architecture employed by NEST Desktop requires all the data of the simulation, including the network models and simulation results, must be stored exclusively on the user's site. The researchers mentioned that work was currently being done to perform stress tests on EBRAINS and improve its

robustness, but it was not fully operative, and should an institution want to use the tool tomorrow they would have to use their own computing power to run the courses.

The NEST Initiative leader expressed his motivation behind the tool's Intellectual Property Rights (IPR) strategy as they desire boost science through open-source technology and software. NEST Desktop is protected under the MIT License, with the 2016 copyright owned by its developer at the University of Freiburg. This permissive license only requires preservation of copyright and license notices, allowing for the modification, distribution, private use and commercial use of the tool free of charge, and protecting the developers from any liability or warranty issues arising from or in connection with the software, its use, or other dealings in the software. This allows for licensed works, modifications, and larger works to be distributed under different terms and without source code. For a more complete definition of the license, the following text has been copied from the NEST Desktop GitHub, under the license section:

" Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the "Software"), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:

The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.

The software is provided "as is", without warranty of any kind, express or implied, including but not limited to the warranties of merchantability, fitness for a particular purpose and noninfringement. In no event shall the authors or copyright holders be liable for any claim, damages or other liability, whether in an action of contract, tort or otherwise, arising from, out of or in connection with the software or the use or other dealings in the software."

This IPR strategy is consistent with the main aims and philosophy of the NEST Desktop team of diffusing their technology without pursuing a commercialisation strategy that limits its uptake and impact. He also expressed his interest in expanding the tool to secondary education, aiming for high school students with biology or possibly physics or psychology as their in-depth subjects. The tool can be configured to display a more restricted range of settings, parameters and possibilities, thus allowing to tailor the complexity of NEST Desktop to the audience. However, the challenge would lay in developing the appropriate exercises and adapting the educational contents to cater to their level of knowledge, as well as gamifying the experience to increase engagement in young pupils.

The interviews with the HBP market analysis coordinator served as steering meetings that ensured that the general approach and objectives of the present analysis were aligned with the overarching strategy of the UPM Innovation Team. It also helped to refine some of the methodologies used and channel the efforts into the most promising avenues. The interview with the HBP Education Committee allowed to have a broad vision of the educational strategy within the project and

revealed the HBP education network as a very promising internal distribution channel to expand the footprint of NEST Desktop.

Overall, the NEST team expressed their interest in a matching and prioritisation exercise with European neuroscience curricula that could be compatible with NEST Desktop, and the team recognised that marketing efforts have been scarce and that consequently there is not enough market awareness of their tool. There was also a degree of uncertainty surrounding the eventual inclusion of NEST Desktop into the EBRAINS infrastructure as the business model for EBRAINS was still being discussed, and NEST team members were unsure whether university institutions would have to subscribe and pay for the full services of EBRAINS to utilise NEST Desktop, or if an agreement to exclusively utilise certain products of EBRAINS could be made. It is expected that these issues will be resolved by the end of 2022, and the inclusion of EBRAINS into the ESFRI roadmap has bolstered the certainty of the project.

There was some reluctance to turn NEST Desktop into a start-up company, as the current IPR strategy meant that any external company could in practice use the software and turn it into a commercially exploitable product. A range of possible business models were discussed through the addition of monetizable value added activities such as providing ready-to-use teaching materials, providing teacher training and education consulting, and providing the infrastructure and servers to host the client simulations. Even though currently there is no desire to engage in such activities, NEST team members believed that once the HBP SGA3 funding finished and the developer capacity has to be reduced, the changes in staffing could incentivise the creation of a spin-off.

4.2 The competitor landscape of NEST Desktop

With the increase in importance and popularity of neuroscience educational simulators and the increasing interdisciplinary nature of computational neuroscience attracting students and scientists without strong programming backgrounds, together with the breadth of literature supporting an interactive and visually enhanced teaching style for education, it is no surprise to find that there have been many attempts to integrate GUIs into neural simulators. Most of these have been used as an educational tool, lowering the entry barrier for computational neuroscience students, and supporting researchers when designing new experiments.

The NEST Desktop team recently published an article about their tool where they performed a scan of the existing competitors, showing that they are already aware of the latest developments in GUI-driven SNN simulators (Spreizer, Senk, et al., 2021). They identified the positioning of each tool relative to NEST Desktop, and identified the niche in which they have a unique competitive advantage: the use of a standard simulation engine (NEST) as back-end, allowing students to directly operate with a high-end simulator used in state-of-the-art research, and allowing students to access the scripting language, granting them exposure and understanding to the underlying code and facilitating their transition to programming more complex neural networks directly using NEST, as in the case of most advanced scientific research use cases of the simulator.

Each tool has its own strengths and weaknesses, and it is safe to assume that the NEST team has learnt from these competitors, are aware of the main trends governing their market, and have integrated the functions that they deemed useful into NEST Desktop. As such, performing a traditional market analysis of each competitor would not create enough value or elucidate any clear actions that NEST Desktop should perform in order to amplify its reach and boost its impact. The aforementioned competitor scan is shown below.

Development	GUI	Simulator	Environment	Reference
1992	GENESIS GUI	GENESIS	x11	Bower and Beeman (2012)
1993	NEURON GUI	NEURON	x11	Hines (1993); Hines and Carnevale (1997)
1995	SLIDE	NEST	x11	Matyak (1996); Gewaltig et al. (1996)
2007	neuroConstruct	multiple	x11	Gleeson et al. (2007)
2008	SNN3DViewer	none	x11	Kasiński et al. (2009)
2009	Neuronvisio	NEURON	x11 (qt4)	Mattioni et al. (2012)
2011	nuSPIC	NEST	HTML	Vlachos et al. (2013)
2012	The Virtual Brain (TVB)	TVB	HTML	Sanzleon et al. (2013)
2013	N2A (Neurons to Algorithms)	multiple	x11 (qt5)	Rothganger et al. (2014)
2013	SpineCreator	PyNN	x11 (qt5)	Cope et al. (2017)
2013	VisNEST	none (NEST)	VR	Nowke et al. (2013)
2014	Neuronify	Neuronify	x11 (qt5)	Dragly et al. (2017)
2014	Open Source Brain (OBS)	PyNN	HTML	Gleeson et al. (2019)
2015	Nengo GUI	Nengo	HTML	Source code[1]
2015	ViSimpl	none	x11 (qt5)	Galindo et al. (2016)
2016	**NEST Desktop**	NEST	HTML	Source code[9]
2016	VIOLA	none	HTML	Senk et al. (2018)
2016	Visbrain	none	x11 (qt5)	Combrisson et al. (2019)
2017	NetPyNE UI	NetPyNE	HTML	Dura-Bernal et al. (2019)
2017	NEURON UI	NEURON	HTML	Source code[3]
2018	CellExplorer	none	x11 (qt5)	Petersen et al. (2020)

Figure 5. Chronological order of GUI-enhanced computational neuroscience tools. Source: (Spreizer, Senk, et al., 2021)

However, for the sake of contrasting some of the functionalities of NEST Desktop with other competitors and extract some of the drivers that enhance the usability, practicality and attractiveness of such tools, the following sections will focus on describing three of these educational simulators and highlighting any valuable takeaways.

4.2.1 GENESIS

The General NEural SImulation System (GENESIS) was the first GUI employed for SNN simulations and has been under Caltech development since 1985 (Bower and Beeman, 2007). The GENESIS GUI, XODUS, consists of a similar architecture to that of NEST Desktop, with an underlying programming language and a GUI that consists of a range of graphical modules that correspond to the scripted computational modules. The design of the tool is also modular, with simulations being constructed out of well-defined building blocks similar to NEST Desktop's Neuron, Stimulator and Recorder nodes.

GENESIS allows users to experiment with multi-level neural modelling, starting from investigating single pieces of neuronal axons using Hodgkin-Huxley models; and moving upwards to models of multiple synaptically activated channels using

excitatory and inhibitory dendrite channels; oscillatory properties of multi-neuron network models; and up to more realistic cerebral cortical networks.

The simulator is accompanied by a thoroughly comprehensive book called The book of GENESIS: exploring realistic neural models with the GEneral NEural SImulation System, which presents both students and lecturers with everything they may need to use GENESIS in the classroom (Bower and Beeman, 2012). The book is split into chapters, with half of the book dedicated to describing the range of possible neurobiological tutorials that can be performed with the tool. Each chapter focuses on a single topic such as "Cable and Compartmental Models of Dendritic Trees" or "Ion Channels and Bursting Neurons" and are meant to guide the student through the topic by first providing a detailed description of the underlying theory surrounding the experiment and how it can be implemented into a computational neuroscience experiment. The chapters also suggest a list of sequential exercises to be performed by the students, together with the implications of the expected outcomes, relevant hints and potential extensions to the exercises.

Providing a set of possible questions for the students to undertake after understanding the theory is a key point of attraction when expanding a tool to other curricula as it enables lecturers to get an impression of the type of evaluation methods that can be used to check the knowledge of their students, and can provide them with a structure upon which they can build a full course by integrating or modifying such questions, as well as inspiring them to devise alternative ones.

One of the main difficulties that this simulator presents is the installation of the UNIX operating system and its corresponding files, which often required the intervention of the administrators. This easy-to-install feature allowing students to run the simulations from their browser is one of the strengths of NEST Desktop, increasing its usability and scalability. However, most modern GUIs already run in web-browsers and therefore do not rely on complex installation or specific platforms.

4.2.2 Neuronify

Neuronify is an educational app that allows students without previous programming experience to explore SNNs and neural dynamics through an intuitive plug-and-play simulation environment. Students can select a range of parametrizable network elements from a menu (integrate-and-fire neurons, stimulators such as current sources or spike generators, and recording devices such as voltmeters or spike detectors). The app is compatible with laptops and PCs, but it was originally intended to be run in smartphones and tablets, both Android and iOS. One of Neuronify's competitive advantages is that it provides increased interactivity through touch-based input sensors and sound-based outputs using the devices' tactile screens and loudspeakers (Dragly et al., 2017)

The tool therefore provides a new low-threshold entry point for computational neuroscience students that do not possess coding skills through a click-and-drag interface directly on the user's personal devices. Students can change the properties of nodes and connections, adjust the playback speed of the simulations (with time conversions ranging from 5ms simulated per real time second to 50ms simulated per

real time second), and store and upload their projects. Neuronify offers a more restricted range of simulations than other tools but provides increased tangibility and interactivity as it allows to see the spiking propagation and results continuously, in real time, rather than just visualising an activity-time graph.

To facilitate the educational use of Neuronify, the tool provides users with a set of premade common network functions such as input summation, gain control by inhibition, and detection of direction of stimulus movement. Upon opening the app, users are walked through a series of simple tutorials that explain how to monitor the electrical activity of individual neurons and circuits, as well as how to add and remove components (such as leaky excitatory and inhibitory neurons) to create new circuits. The simulations use the integrate-and-fire model to model electrical activity through the circuits. Neuronify also complements these tutorials with in-depth documentation of the relevant neuroscience theory in their web domain, and focus mainly on 5 topics: General neuroscience, the integrate-and-fire model (on which Neuronify is based), adaptive neurons (variations in cell responsiveness to sustained current injections), Poisson Distributed Spike Generators (incorporating noise into the simulations) and Receptive fields (to investigate early visual system neurons).

Though the app provides users with great flexibility to create and explore their own circuits, the app includes eleven example networks that illustrate concepts like feedback inhibition, spike train transformation, and the refractory period. An example of such sample network is shown below in Figure 6, which is designed to allow users to experiment with inhibitory neurons. The network can show how neuron B can inhibit neuron C if it fires before the excitatory neuron A as it does not allow the downstream neuron to reach its threshold potential. Users can experiment tapping the two touch input sensors at different times, and in different orders, and see the resulting voltage reading in neuron C.

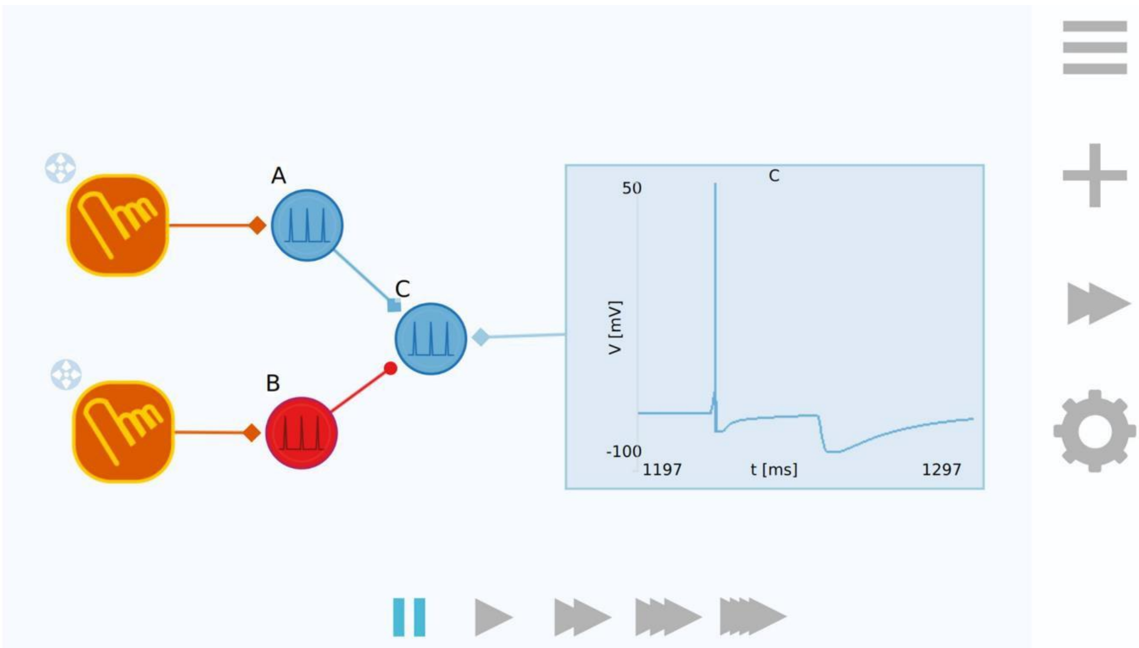


Figure 6. Neuronify workspace showing two touch input sensors connected to an excitatory neuron (A) and an inhibitory neuron (B), with the downstream neuron (C) connected to a voltmeter. (Dragly et al., 2017)

Neuronify is under constant development and its developers are planning to include a range of new features in the future. Some of these are long-term learning schemes such as synaptic plasticity, user-generated neurons and items (written as QML plugins, the language of the GUI) and new types of neurons such as Izhikevich or Hidgin-Huxley models to increase the range of simulations that can be performed in Neuronify, the possibility to share saved simulations with other devices and users in order to foster a community of users, and the provision of thematic exercises embedded into the app to allow for an easier implementation in educational courses. Neuronify is GPL licensed, allowing any user to modify and extend the tool's capabilities.

4.2.3 SimBrain

Simbrain is a visually-oriented framework that allows users to build, parametrise and analyse neural networks, supports models on the order of thousands of neurons and a million synapses, as well as to analyse the networks that control agents embedded in virtual environments and build biologically feasible networks to explore cognitive phenomena. The simulator supports most of the common models developed in the fields of neuroscience, machine learning, and psychology, and allows to combine them through an intuitive point and click GUI and keyboard shortcuts, as well as a scripting interface to allow for more permissive experimentation (Yoshimi, 2008) . It was developed at UC Irvine and trialled UC Merced, the tenth and newest of the University of California campuses and established in 2005, and its development has been supported by several grants, including an early grant (around 2005) from the Hewlett Foundation, several UC Merced faculty research grants, and a grant from the National Science Foundation between 2016 and 2019. It is an open-source software operating under a GPL.

Simbrain was conceived as a GUI-driven simulator from the start, as it was the developer's wish to create a tool that would allow to visually explore the dynamics of networks and biological processes, as well as to embed virtual agents in simulated environments without the need of advanced programming skills. In fact, among the main drivers that encouraged the Simbrain developers to integrate a GUI into their simulator, as is mentioned in their 2016 paper, was that they spotted the lack of GUI use in other programs, citing expressly that "Programs like Brian and Nest can produce detailed visualizations, but are not fundamentally GUI-based programs. With the emergence of HTML5, beautiful visualizations are more readily accessible directly in the browser, prompting some to create web-based interactive neural networks" (Tosi and Yoshimi, 2016).

Similar to NEST, Simbrain can also aid research professionals in the development of complex neural models by allowing them to build novel neural architectures using the GUI and fine tuning it with direct scripting as well as to extract deeper insights from the network visualisations (for instance, allowing to study plasticity mechanisms to account for the structure and dynamics of cortical microcircuits of both in vivo and in vitro observations). As an example, it was reported that one of Simbrain's developers first line of research was driven by a timely yet chance

observation of the Simbrain histogram plot which revealed unexpected changes of the synaptic structure.

In this sense, Simbrain enables researchers to benefit from similar advantages as NEST Desktop, namely fast prototyping and visual analysis, but Simbrain is targeted at simulating larger and more complex networks (the latest version of the tool, Simbrain 3.0, can be optimised to study networks in the order of 10,000 neurons) such as Self Organizing Recurrent Networks and cerebellum models, and can also serve to train backpropagation networks, simulate the behaviour of agents in virtual environments and even explore cognitive phenomena such as perceptual ambiguity or Kohonen maps, at the expense of lower granularity in the realm of point-neuron characterisation and analysis, where NEST Desktop shines thanks as a result of its specialisation. An example of how Simbrain can be used to analyse the spiking dynamics arising from different neuron models is shown in Figure 7.

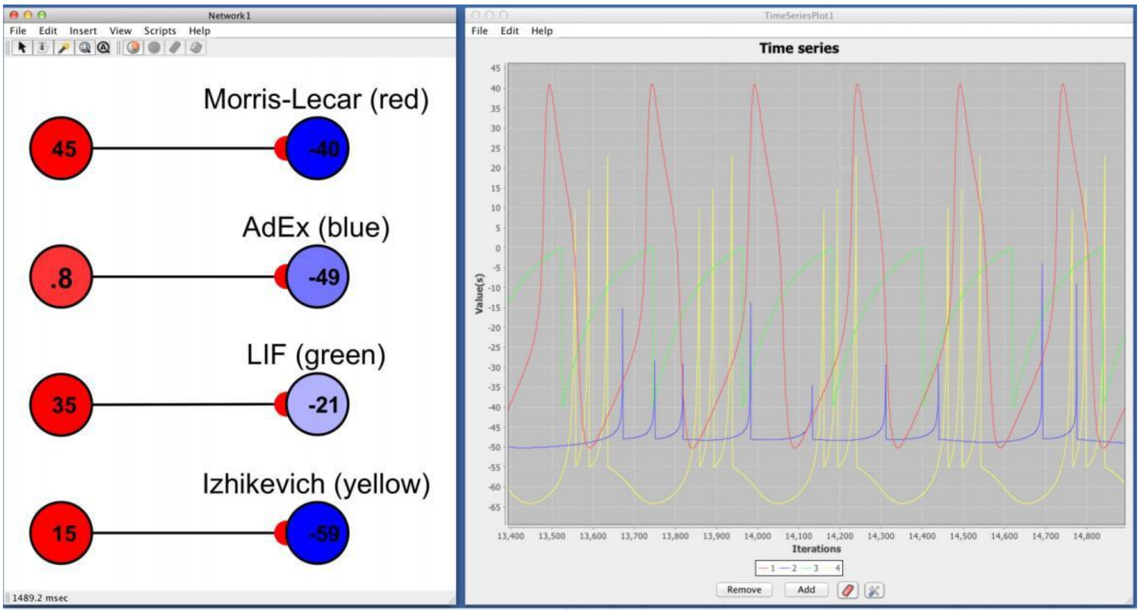


Figure 7. Simbrain simulation exploring the spiking activity resulting from 4 different neuron models: Morris-Lecar (red) producing more realistic membrane potential dynamics at evenly-spaced intervals; adaptive exponential integrate and fire - AdEx (blue) producing a chaotic spike train; a linear leaky integrate and fire neuron – LIF (green) producing spike trains at constant periods, and Izhikevich neurons (yellow) demonstrating bursting behaviour. Simbrain offers 16 different neuron types. Source:(Tosi and Yoshimi, 2016)

The emphasis placed by the developers on visualisation and ease of use through an intuitive GUI naturally led developers to pursue applications in education. Simbrain was trialled successfully during the inauguration of UC Merced, in Spring 2006, where a whole neuroscience course, “"Neural networks in cognitive science” was developed around the simulator (leveraging the fact that it was a new university, the common barriers to adapt the curricula to accommodate for the use of such a tool were inexistent). Each week students read 10 to 20 pages of material, which was followed by a practical workshop where they could put their theory to practice by building simple models in Simbrain and answering questions relating to these models. The members of the class, similar to the cohorts using NEST Desktop, was highly heterogeneous, involving students from a wide range of majors such as psychology, economics, and business administration.

The course consisted of 25 theory classes and 10 workshops, which were in turn broken down into 3 parts: Fundamental Concepts, Architectures and Learning Rules, and Applications to Biology and Psychology. The workshops were designed to be semi- autonomous in order to trial their feasibility in individual learning settings such as in community colleges or secondary education centres. For instance, the first sessions would focus on teaching the basic visual semantics of the interface and introducing students to sensory inputs and synapse weight dynamics that drive the learning of a neural system. The appendix of (Tosi and Yoshimi, 2016) provides a detailed description of four of the lessons taught during the course, should the reader wish to dive deeper into the contents and structure of the different modules taught.

However, towards the end of the course, students could build biologically plausible models that explain cognitive phenomena such as perceptual ambiguity (the perception of the same stimulus multiple ways, generally through the observation of an ambiguous figure such as the famous rabbit–duck illusion). Students were able to construct a 2-node winner-take-all network that showed how each neuron, supporting a different interpretation, suppressed the other until it died out during sustained activation as a result of adaptation, this oscillating between the two perceptions. Even though the course was aimed at students without a mathematical background, the key concepts behind ANNs such as gradient descent in backpropagation were taught. The effectiveness of the use of Simbrain was not measured formally, but the informal feedback gathered through questionnaires proved the trial to be successful, with students expressing their satisfaction by mentioning that being able to see and play with the different mechanisms helped reinforce the core concepts. Simbrain has been successful in diffusing its technology to other Higher Education institutions, amongst which stand the University of Sydney in Australia, LMU Munich in Germany, and the University of Indiana Bloomington in the USA.

Future plans of SimBrain that are relevant for the positioning and potential strategy of NEST Desktop include the development of an immersive 3D environment, allowing users to view networks, dentritic and axonal structures, and interactions with neuro-modulators, in three dimensions. Most importantly, there are plans to develop advanced self-guided tutorials and embed quizzes, knowledge-check questions and complementary or tutorial videos into Simbrain simulations to facilitate its integration into education courses (Tosi and Yoshimi, 2016). In addition, the Simbrain team has been seeking funding to develop educational modules for use in secondary education.

Again, one of the main features that enhances the educational potential of a simulator is the creation of ready-made lesson packages that support the use of the simulator with evaluative tools such as the quizzes, and video tutorials and demonstrations that allow for better autodidactic and self-paced learning sessions while taking away pressure from the workshop demonstrators (Tosi and Yoshimi, 2016). These pre-set educational packages also allow for a standardised and widespread diffusion of the simulator as it offers a proven structured and sequential approach to teaching the different concepts to be covered in the courses so that teachers need only to integrate it into their teaching plan and timeframes, and also

clearly divides the simulators' exercises into thematic areas so that teachers can complement each module with the corresponding practical workshop.

Other GUI driven ANN simulators include the work done by (Harley, 2015), who developed an Interactive Node-Link Visualization of Convolutional Neural Networks trained on handwritten digit recognition that allows users to interact with the network through a drawing pad, seeing and tracking how the activation patterns of the network respond to the input in real time, thus unearthing the commonly hidden dynamics and internal workings of the neural network. Another example is the ConvNetJS Javascript library, developed by a Stanford PhD (Karpathy, 2017), which allows users to build and train Deep Learning models directly from the browser with the help of a GUI.

Even though more competitors were analysed, providing studies for each of the simulators is beyond the scope of this work. However, a series of drivers that may boost the usability, attractiveness, and exploitation potential have been identified and are summarised in the table below to suggest possible future developments of NEST Desktop.

Takeaway	Rationale
Video tutorials and demonstrations	Increased engagement, increased scalability as the same videos can be played in any university, videos can be replayed as many times as necessary to ensure student has learnt the methodology.
Embedded quizzes	Continuous feedback and knowledge checkpoints, self-paced learning, provides a clear sequential structure easing its integration into other curricula, complements the formal lab reports.
Gather quantitative feedback on student experience	Corroborate the utility of the tool with statistically significant hard evidence (increased efficacy when marketing to other institutions), allows to track the performance of the tool and gauge the impact of new additions to its functionality
Introductory walkthrough of the interface	Ensures all students are comfortable with the layout, operative system and pathways before starting, preventing students from lagging behind, saves demonstrator time
Mixed teaching modality	Combination of slide-based theoretical lectures, interactive workshops with demonstrators, consultation hours and lab report submissions to increase the effectiveness of the teaching
Expansion onto secondary education	Requires a more gamified and simplified experience but allows for new funding or revenue streams, supporting the long-term sustainability of the tool's development
Ready-to-use educational packages	Course scripts covering the whole syllabus of a NEST Desktop course, covering everything from the theory slides, course scripts, assignments, and marking schemes. Ready to be used as-is by other lecturers requiring no further work.
Foster a user community	NEST Desktop can replicate its NEST developer community orienting it to students, through dedicated conferences, forums or online events

Table 1. Key takeaways from the competitor analysis of NEST Desktop

4.3 Intermediate conclusions and IM strategy

After performing the internal analysis of NEST Desktop, conducting the interviews and scouting the market, an intermediate conclusion was reached: the main barrier that NEST Desktop was facing was the lack of awareness and market visibility by other Higher Education institutions that could potentially use the tool in their neuroscience curricula.

This conclusion was aligned to the internal consensus amongst the NEST Desktop team, since they already had detailed knowledge of their market and competitor landscape and already had a mature tool that could be used in other institutions. In such cases, a traditional market analysis would not add sufficient value, as what mattered the most no longer was obtaining knowledge from what other players were doing in the market and performing a passive diagnostic of the tool (as the NEST team was already well aware of this and demonstrated it throughout the interview process, which facilitated this analysis).

In order to add value, an action plan with tangible deliverables and clear objectives was needed. In a nutshell, the NEST Desktop team now had to reach out to potentially interested institutions and communicate the utility and effectiveness of their tool as clearly and engagingly as possible, providing resources that facilitate the adoption and integration of their tool into new curricula.

This becomes urgent as the analysis of previous simulators showed that once an institution starts using a simulator, they are very unlikely to change to another one unless the perceived value exceeds the significant switching costs that involve adapting lecture content and evaluation to the new simulator, as well as the necessary infrastructure and logistics to use the new system. NEST Desktop may find itself in a race against time, but a strategy that helps it establish a foothold in a healthy portion of European institutions before other possible competitors will ensure its long-term sustainability and impact.

As such, the most effective innovation management and exploitation strategy that amplifies NEST Desktop's scientific and social impact and expands its international footprint would be a marketing exercise intended to raise awareness of NEST Desktop amongst other European Higher Education institutions and expand its presence in the neuroscience educational market.

4.3.1 The Exploitation strategy: showcasing NEST Desktop

Expanding NEST Desktop internationally to other curricula will require gauging the appetite for such a tool, exploring its compatibility with curricula, and incentivising professors from other universities to integrate the tool into their neuroscience curricula by raising awareness about NEST Desktop. In order to achieve this, the plan was to elaborate a showcase of NEST Desktop drawing on its use in the University of Freiburg trials, detailing how, when and why it is used.

For this, the BSc and MSc course scripts and previous work were used to produce a 3- pager introductory leaflet, and actions were coordinated with the NEST Desktop creator to record a series of introductory videos and practical demonstrations that can showcase its usefulness and capabilities, potentially germinating excitement on behalf of other neuroscience lecturers.

The videos were intended to show professors how their students will be able to use the tool to construct, parametrise and analyse SNN simulations, as this was deemed to be one of the most effective and engaging ways to convey how NEST Desktop will help in teaching and learning about neuroscience. Three video demonstrations were recorded, with lengths varying between 5 and 8 minutes, covering two BSc exercises (Direct current injection into single neurons and Excitatory and inhibitory synaptic input into single neurons) and one MSc exercise (large-scale network dynamics).

In the demonstrations, the developer shows how one can build the network from scratch and parametrise the different elements according to the objective of the experiment, commenting on the rationale of each action he is performing and guiding the viewer step by step. He follows this by showing how the GUI generates its corresponding PyNEST code and how one can directly check the scripting language and use it to modify the network directly and finishes by interpreting the results and commenting on its implications on the underlying theory. Such videos highlight the granularity and intuitiveness of the GUI experience, and its format could be adapted in the future to video tutorials embedded in the courses.

Before approving the showcase demonstration videos and making them public, a session of internal review was organised with the INM-6 professors from the Jülich Forschungszentrum who were also part of the HBP, in order to ensure that the videos were of good quality and properly conveyed the utility of NEST Desktop.

As mentioned before, the showcase comprised an introductory leaflet and the videos. One of the main deliverables of this engagement was the production of this 3-pager promotional leaflet of NEST Desktop, which was intended to introduce the tool to other university computational neuroscience lecturers and convey the utility of the tool. As such, the showcase had to describe the technology and the aim of the NEST Desktop team (expanding the tool into other computational neuroscience curricula), as well as its competitive advantages and pinpoint interested lecturers in the direction of additional documentation and material should they be interested in diving deeper into the details of the tool.

In addition, the showcase also had to convey the different capabilities of the tool, detailing how students will be able to use NEST Desktop's network editor, network construction, activity explorer and project archiving and export functions, as well as highlight the unique competitive advantage of the tool – the PyNEST code generation through the GUI. Snapshots of the GUI were also added in order to better portray the tool's interface and inner workings, as well as to make the showcase more visually attractive. The NEST Desktop showcase is shown in the following 3 pages.

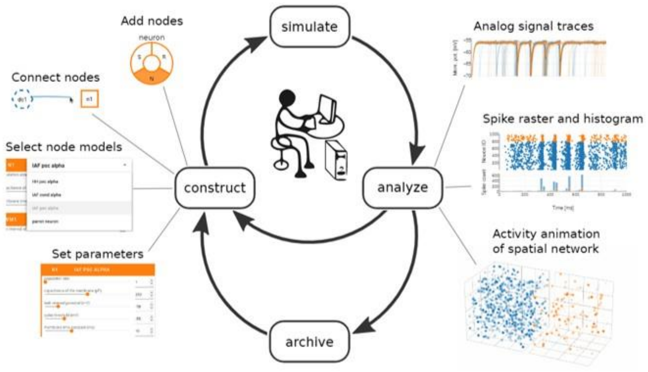
Receiving feedback on the showcase and iterating is critical as being able to further optimise its structure, mode of delivery, contents and general appeal and effectiveness at conveying the usefulness and attractiveness of NEST Desktop will enhance the showcase's power as a marketing tool to expand its footprint in the future. This is because once the showcase is done, it can also be sent to any other professor that the NEST Desktop team engages in (be it conferences, seminars, or other scientific events) to give him a good idea about what the tool is and what it can do, therefore saving time and effort to the NEST Desktop team when promoting and

expanding the footprint of their tool and helping them reinforce their presence in the market.

A professor from another university that receives the showcase (leaflet and videos) and has a positive impression of it may then have a desire to approach the NEST Desktop team to explore how they can integrate NEST Desktop workshops into their classes, which is the main aim of the engagement.

NEST Desktop

EASY-TO-USE WEB-BASED EDUCATIONAL TOOL FOR COMPUTATIONAL NEUROSCIENCE, ALLOWING TO PERFORM NEST SPIKING NEURAL NETWORK MODELLING, SIMULATION VISUALISATION AND ANALYSIS THROUGH A GRAPHICAL USER INTERFACE



TECHNOLOGY DESCRIPTION

NEST Desktop is a web-based GUI application for NEST Simulator, an advanced simulation tool for the computational neurosciences. NEST Desktop enables the rapid construction, parametrization, and instrumentation of neuronal network models. It is suitable for the application in educational context of computational neuroscience as it is easy to use, simple to install (using Docker or the online version in EBRAINS with no need for installation) and offers a comprehensive toolset for modeling, executing and analyzing spiking neural networks.

Our aim is to expand the international footprint of NEST Desktop to support the improvement of European neuroscience curricula. This leaflet, together with the annexed videos, showcase the utility of NEST Desktop so that university lecturers who wish to integrate it into their courses can get an overview of the tool and potentially collaborate with the NEST Desktop team in the future.

APPLICATION & MARKET POTENTIAL

Education
NEST Desktop enables teaching computational neuroscience to students without prior coding knowledge in a highly intuitive and interactive manner

Research
NEST Desktop is also used by SNN researchers for early testing and fast prototyping

All tools in one web application
NEST Desktop offers modeling, simulation, analysis and visualisation tools in a single web-based app

Access to high-end simulation technology
NEST Desktop gives easy access to the high-end simulation engine NEST and its underlying scripting code

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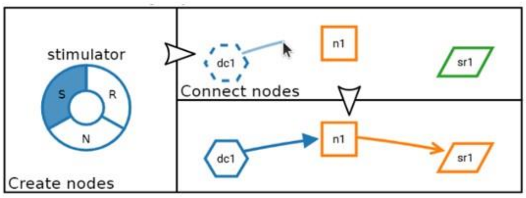
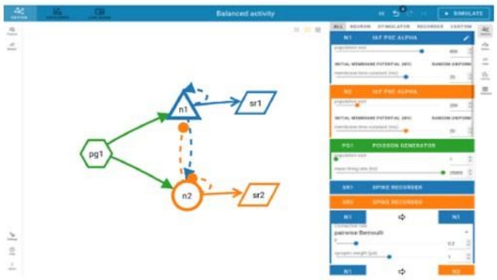
NEST DESKTOP SNAPSHOTS

NETWORK EDITOR

MAIN WORKSPACE TO GRAPHICALLY CONSTRUCT AND PARAMETRISE THE SNN NETWORK.

NETWORK PROPERTIES CAN BE MODIFIED THROUGH THE CONTROLLER PANEL (RIGHT), WHICH PRESENTS THE NODES AND THEIR CONNECTIONS WITH THEIR CORRESPONDING COLOUR-CODED PARAMETERS.





VISUAL NETWORK CONSTRUCTION

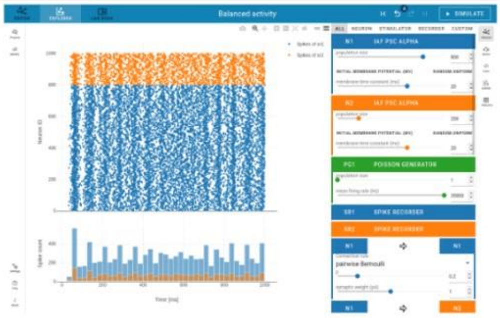
MOUSE RIGHT-CLICKS OPENS CREATION PANEL FOR STIMULATORS (S), NEURONS (N) AND RECORDERS (R).

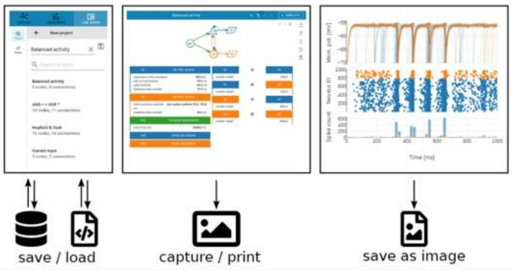
THESE ARE SELECTED FROM THE RANGE OF NEST MODELS AND CAN BE FURTHER PARAMETRISED.

ACTIVITY EXPLORER

SIMULATED ACTIVITY DATA IS VISUALISED TOGETHER WITH THE NETWORK PARAMETERS, ALLOWING TO EXPERIMENT DIRECTLY WITH HOW THE NETWORK PROPERTIES AFFECT THE RESULTS.

SPIKE TIMES AND MEMBRANE POTENTIALS CAN BE DISPLAYED ACROSS TIME WHILST SPIKE COUNTS CAN BE VISUALISED IN 2D AND 3D SPACE.





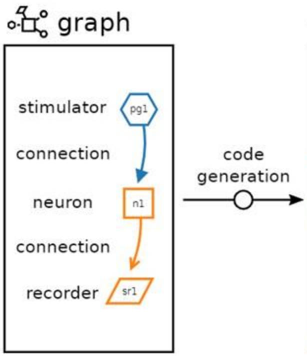
PROJECT ARCHIVING AND EXPORT

THE NEST DESKTOP PROJECT MANAGER ALLOWS USERS TO LOAD PRE-EXISTING NETWORKS OR LOAD SAVED PROJECTS.

NETWORKS CAN BE SCREENSHOT AND ACTIVITY GRAPHS CAN BE EXPORTED AS IMAGES FOR STUDENT SUBMISSIONS AND EVALUATION.

PYNEST CODE GENERATION THROUGH GUI NETWORK CONSTRUCTION.

VISUAL ELEMENTS ARE ASSOCIATED WITH GENERATED CODE LINES, GRANTING THE STUDENTS EXPOSURE TO THE UNDERLYING PROGRAMMING LANGUAGE AND FACILITATING THEIR POTENTIAL TRANSITION TO CODING.



</> code

```
import nest

# Create nodes
pg1 = nest.Create('poisson_generator')
n1 = nest.Create('iaf_psc_alpha')
sr1 = nest.Create('spike_recorder')

# Connect nodes
nest.Connect(pg1, n1)
nest.Connect(n1, sr1)

# Start simulation
nest.Simulate(1000)

# Get activity
sr1.get('events')
```

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COMPETITIVE ADVANTAGES

Various simulators, such as NEST, come with a highly versatile programming interface, which give full control of the simulation to the scientist. However, programming interfaces tend to add an additional barrier when it comes to studying computation neuroscience: basic courses need to first focus on teaching the programming language before students can begin modeling and analysing spiking neural networks.

NEST Desktop reduces this barrier by providing an easy-to-use Graphical User Interface that allows to model, simulate and analyse NEST-driven SNNs, allowing to complement computational neuroscience teaching through experimental learning. It provides over 50 neuron models and 10 synapse models, and students can model simulations from scratch or import existent networks from a large and well-documented repository. The GUI generates a textual script in PyNEST that is fed into the NEST Simulator, granting students direct access to important features of the NEST simulator without knowledge of the simulator control language while also giving them exposure to the underlying Python-based scripts.

INTUITIVE GUI-DRIVEN COMPUTATIONAL NEUROSCIENCE ENTRY-POINT TOOL FOR NOVICE STUDENTS WITHOUT PRIOR PROGRAMMING KNOWLEDGE

SUCCESSFULLY TRIALLED IN VARIOUS COURSES ON COMPUTATIONAL NEUROSCIENCE AT THE UNIVERSITY OF FREIBURG:

- SIMPLE NEURON MODELS (BSC LEVEL)
- BIOPHYSICS OF NEURONS AND NETWORKS (MSC LEVEL)

ITS USE RESULTED IN MORE EFFICIENT LEARNING, IMPROVING STUDENT MOTIVATION AND PERFORMANCE

OPEN-SOURCE, COMMUNITY DRIVEN DEVELOPMENT, DOCKER-RIZED, INTEGRATED INTO THE EBRAINS INFRASTRUCTURE.

SUPPORTED BY EXTENSIVE USER DOCUMENTATION FREELY AVAILABLE IN https://nest-desktop.readthedocs.io/en/latest/

Interested lecturers can find a guide on how NEST Desktop can be integrated into neuroscience courses. It covers course design, structure, modality of teaching and objectives, as well as course protocol preparation.

The guide provides sample assignments for BSc and MSc students, including possible experiments and questions. Some have an embedded video tutorial showcasing how a student would tackle the experiments using NEST Desktop

This is available at:
https://nest-desktop.readthedocs.io/en/latest/lecturer/

In addition, The NEST Desktop team has released a paper detailing:

- The technical details of NEST Desktop (client-server architecture, implementation and installation)
- Its main components and functions
- Two case studies of the tool, portraying its use in the classroom and by SNN researchers

It is available at:
https://www.biorxiv.org/content/10.1101/2021.06.15.444791v2.full

REFERENCES

- EBRAINS Installation: https://ebrains.eu/service/nest-desktop
- Code Repository:https://github.com/nest-desktop/vue-app
- Docker Hub: https://hub.docker.com/r/babsey/nest-desktop

CONTACT

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Brains | Germany
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Figure 8. NEST Desktop showcase page 3. Source: own elaboration, co-designed with the NEST team.

Another action that was used to further showcase the educational potential of NEST Desktop is the addition of lecturer-specific documentation on the tool's online domain, the online "readthedocs.io" documentation. This section works as a guide for lecturers that might be interested in incorporating NEST Desktop into their courses, providing useful suggestions on course design, structure, modality of teaching and learning objectives, as well as on how evaluation and assessment could be done. The section also provides sample assignments at both the BSc and MSc levels drawing on the course scripts used at the University of Freiburg. It covers 7 topics in total, including ones such as Noise current injection into single neurons for the BSc level or Point neuron models with conductance- based synapses for the MSc level.

For each topic, the documentation provides a brief introduction to the underlying theory and then proceeds to describe a series of simulation experiments that can be performed in order to investigate the phenomena, detailing the expected outcomes and implications of the desired results. Once the three demonstration videos were reviewed and approved by the HBP professors, the videos were also uploaded to the lecturer section complementing their corresponding topic documentation. This documentation is thorough and comprehensive and will be very useful in further orientating, informing and engaging with interested lecturers. This section, together with the rest of the documentation, can be found in (Spreizer, 2021).

4.3.2 The European computational neuroscience education landscape

Once the showcase was finalised and accepted, the next step was to identify the institutions and neuroscience programmes that were compatible with NEST Desktop. As such, another one of the main deliverables of the engagement, as discussed in section 4.1.1, is the matching and prioritisation exercise between NEST Desktop and computational neuroscience programmes across Europe in order to identify and characterise the range of institutions that offered courses where the tool could be integrated.

A list of over 200 European neuroscience programmes was produced through on-line search, leveraging specialised directories, neuroscience education associations, conferences and symposiums, and university web pages. In order to narrow down the selection to the most compatible programmes, a series of restrictions were imposed. The main reason to discard a programme was the lack of focus in computational neuroscience, which was common and expected as the field of neuroscience is significantly broad, with many programmes focusing on clinical, social, cognitive, neuro-psychopharmacology, neuroimaging or linguistic neuroscience instead.

Another filter was that the language of instruction must be English, to ensure that the tool and supporting documentation could be readily used by the lecturers and students, as well as to facilitate communications between the institution and the NEST, as English is the quasi-standard language on any type of scientific software. An example of an institution that was discarded for such a reason, even though there was a good degree of curricular fit, was the MSc Fundamental and translational Neuroscience programme at the Universidad Pablo de Olavide.

Once the compatible programmes were narrowed down, the following task was to identify the relevant contact point on the corresponding institution, together with their position and their email, so that the NEST Desktop team can easily distribute their showcase to the courses they wished to engage with. When possible, the lecturer in charge of the specific course where NEST Desktop could be implemented was found, as this would enable the showcase to be directly received by the target lecturer, avoiding going through administrative positions or middlemen and therefore easing the communications and increasing the chances to germinate excitement and catalyse collaboration. The final result was a list of 59 programmes, which for confidentiality purposes with respect to the strategic advantage of NEST Desktop have been removed from the work.

In order to further channel the first efforts of the NEST Desktop team into the most promising institutions, a list of the top 10 computational neuroscience programmes in terms of fit and collaboration potential was produced. There were three main reasons behind the decision to include them in the list: a significant curricular overlap between the relevant courses and the current syllabus being covered by NEST Desktop in Freiburg, as this would allow for the lecturer to clearly perceive the utility of NEST Desktop if applied to his course, incentivise him to collaborate and would make integration readily possible; direct contact to the lecturer (for the aforementioned reasons); and the existence of a link between the institution and the NEST Desktop team such as the HBP network or the Bernstein Centre network. This list is shown in Figure 11.

These programmes could give NEST Desktop the momentum it needs to catapult itself to other geographies and transform awareness into collaboration and impact.

Programme	Country	Institution	Relevant courses	Contact details	Contact email	Reasoning
Master of Life Sciences Engineering with a Specialisation in Neuroscience and Neuroengineering	Switzerland	EPFL	Biological modelling of neural networks; Biophysics: physics of the cell; Biomedical signal processing, Artificial neural networks, Computational cell biology.	Carl Petersen (Responsible for Neuroscience and Neuroengineering specialisation)	carl.petersen@epfl.ch	Good curricular fit (potential overlap with course scripts), Leverage HBP network
International Master Program in Computational Neuroscience	Germany	Technical University of Berlin	Models of Neural Systems; Acquisition and Analysis of Neural Data; Neural Noise and Neural Signals	Elsa Harms (Graduate Programme Coordinator)	elsa.harms (at) bccn-berlin.de / graduateprograms (at) bccn-berlin.de	Leverage connections/proximity through Bernstein Centre network (Freiburg - Berlin)
Joint Master in Neuroscience	France	University of Strasbourg	Computational Neurophysiology	Vincent Lelievre (Head of the Joint Master in Neuroscience program)	lelievre@inci-cnrs.unistra.fr	(imparted in Freiburg - optimal fit if NESTD is not currently being used)
MSc Neuroscience	Spain	University of Santiago de Compostela,	Computational Neuroscience; Biological and computational models of consciousness	Eduardo Sánchez Vila (Lecturer of Computational Neuroscience)	eduardo.sanchez.vila@usc	Good curricular fit (entry-level programming as its directed to students from wide range of disciplines), direct contact to lecturer
MSc Cognitive and Computational Neuroscience	United Kingdom	University of Sheffield	Computational neuroscience 1 (simple 'integrate-and-fire' approximations to full conductance-based compartmental models) optimal fit	Robert Schmidt (Lecturer in Computational Neuroscience 1)	robert.schmidt@sheffield.ac.uk	Good curricular fit (course scripts already tackle I&F networks) direct contact to lecturer
MSc Modeling for Neuronal and Cognitive Systems	France	Université Côte d'Azur	Introduction to modeling in neuroscience and cognition; Dynamical systems in the context of neuron models; Computational Modelling and Simulation	Bruno Cessac (Lecturer in Introduction to modeling in neuroscience and cognition) / Alexandre Muzy (lecturer in Computational modelling and Simulation)	Bruno.CESSAC@univ-cotedazur.fr / alexandre.muzy@cnrs.fr	Good leeway into Strasbourg and Basel, starting from Freiburg, direct contact to lecturer, specialised in SNN modelling
MSc Neuroinformatics	United Kingdom	Newcastle University	An Introduction to Computational Neuroscience and Neuroinformatics (using MatLab); Advanced Computational Neuroscience and Neuroinformatics	Marcus Kaiser (lecturer in Introduction to Computational Neuroscience and Neuroinformatics)	marcus.kaiser@ncl.ac.uk	Good curricular fit (focusing on computation at an introductory level and using MatLab, as in Freiburg previously), direct contact to lecturer
MSc Neurosciences	Germany	Ludwig Maximilians University Munich	Computational Neuroscience course covers Modelling Physiological Processes (Passive membrane, Nernst potential, Hodgin-Huxley model, models of dendrites/cable equations)	Alexander Kaiser (MSc coordinator, implementation of new teaching modules)	Kaiser.Alexander@lmu.de	Good curricular fit, direct contact to lecturer (and responsible for implementation of new teaching initiatives)
MSc Neurobiology	Lithuania	Vilnius University	Biophysics of the neuron	Osvaldas Rukšėnas (Programme Director)	Osvaldas.ruksenas@gf.vu.lt	Course on Biophysics has good degree of synergy with course scripts, expand tool to Balcans
Elite Master of Science in Neuroengineering	Germany	TUM (Technical University of Munich)	Neuroanatomy and Neurophysiology Computational Neuroscience Signal Processing and Dynamic System Modeling Neuro-inspired Systems Engineering	Prof. Dr. Gordon Cheng (Program Director)	gordon@tum.de	Leverage HBP network, Curricular focus in neuro-engineering

Figure 11. Table showing the Top 10 computational neuroscience programmes in terms of fit and collaboration potential

CHAPTER V. CONCLUSIONS

The present work has described the engagement between the HBP Innovation team and the NEST Desktop team, as part of the project's aim to devise effective and efficient innovation management and exploitation strategies for the innovations produced by the HBP. It followed a funnel-like process where the focus of the work was progressively narrowed down into tangible deliverables and insights intended to support and guide the present and future of NEST Desktop.

The engagement started with an analysis of the theoretical framework surrounding simulation EdTech, SNNs and NEST, which served to consolidate the relevant knowledge and guide the investigation design and execution. After performing the internal analysis of NEST Desktop, conducting the interviews and scouting the market, it was concluded that the main barrier preventing the tool from amplifying its impact and expanding internationally was the lack of awareness and market visibility by other Higher Education institutions that could potentially use the tool in their neuroscience curricula. As such, the most effective innovation management and exploitation strategy that will amplify NEST Desktop's scientific and social impact and expand its international footprint was a marketing exercise intended to raise awareness of NEST Desktop amongst other European Higher Education institutions and amplify the tool's impact.

In order to achieve this, one of the main deliverables of the engagement was the NEST Desktop showcase, co-designed with the NEST Desktop team. It consisted of the 3-pager leaflet intended to introduce the tool to other university computational neuroscience lecturers and convey the utility of the tool, and a series of video tutorials demonstrating how the tool can be used to build networks from scratch, parametrise the different elements according to the aim of the experiments, visualise and interpret the resulting simulation, and link it to the implications on the underlying theory.

The online documentation of NEST Desktop was also extended to incorporate a section dedicated for lecturers that might be interested in incorporating NEST Desktop into their courses, providing useful suggestions on course design, structure, modality of teaching, learning objectives, and evaluation. The section also provides sample assignments drawing from the course scripts used at the University of Freiburg, offering a brief introduction to the underlying theory and the corresponding simulation experiments that allow to investigate the phenomena, together with the expected outcomes and implications of the desired results. For three of the topics, the corresponding video demonstration were embedded. This documentation is thorough and comprehensive and will be very useful in further orientating, informing and engaging with interested lecturers.

The second main deliverable of the engagement was the matching and prioritisation exercise between the tool and compatible neuroscience programmes across Europe in order to identify and characterise the target of the marketing strategy: the range of institutions that could be interested in integrating NEST Desktop into their curricula. A list of over 200 European

neuroscience programmes was narrowed down to the most compatible programmes, resulting in a final list of 59 institutions ranked in terms of fit. For each one, the relevant contact points, together with their positions and emails, were identified so that the NEST Desktop team could easily distribute their showcase to the courses they wished to engage with. A list of the top 10 computational neuroscience programmes in terms of fit and collaboration potential was produced to further channel the initial efforts of the NEST Desktop team into the most promising institutions.

The present work is intended to support the NEST Desktop team in their efforts to improve the quality of computational neuroscience education and help catapult Europe to the forefront of neuroscience research.

ACKNOWLEDGEMENTS

I wish to thank the UPM Innovation Team, and specially Gonzalo Leon and Guillermo Velasco, for enabling me to participate in such an enriching opportunity and providing valuable insights every step of the way.

I hope that the Innovation team continues supporting the future endeavours of NEST Desktop, and that it keeps playing an important role within the HBP by fostering and accelerating innovation.

I would also like thank the NEST Desktop team for their transparency and willingness to collaborate and guide the work and hope that my work has added value to their efforts.

Finally, I want to express my sincere gratitude for the friends and family that have supported me throughout this experience and drive me to keep moving forwards.

SUPPORTING DOCUMENTS: EUROPEAN HE LANDSCAPE SCAN

Programme	Country	Institution	Degrees	Relevant courses	Additional Information	Fit	Contact details	Contact email
Athens International Master's Programme in Neurosciences	Greece	NKU Athens	MSc	Cellular and Molecular Neuroscience, Neuroelectrophysiology, Computational Neuroscience	Special focus in Neurodegenerative Disorders and Pathological Aging, Neurogenesis and Development	High	Antonios Stamatakis (Associate Professor of Neuroscience)	astam@nurs.uoa.gr
Bernstein Center for Computational Neuroscience – Munich	Germany	LMU Munich	PhD, MD	Computational neuroscience, Data analysis and software tools, Learning and memory, Neural circuit mechanisms, Neuro-robotics and Neuroprosthetics	Focus in Computational and Theoretical Neuroscience	High	Kay Thurley (Scientific Coordinator) / Andreas Herz (Neurobiology Professor)	thurley@bccn-munich.de / herz@bio.lmu.de
Bilkent University Graduate Program in Neuroscience	Turkey	Bilkent University	MSc, PhD	Mathematical and computational modeling in neuroscience, Neural networks, neuro-engineering. Neuroscience in learning and memory		High	Aydan Ercingoz (Administrativ e Assistant)	aydan@ee.bilkent.edu.tr
Bordeaux Neurocampus Graduate Program	France	University of Bordeaux	MSc, PhD	cell comunication and plasticity, computational neuroscience, functional neuronanatomy		High	DENIS COMBES (Master's supervisor)	master.neurosciences@u-bordeaux.fr
Brain and Cognitive Sciences (Research Master)	The Netherlands	University of Amsterdam	MSc	Neurotransmitters and their receptors,Synaptic plasticity		High	Vincent Tijms (MSc. Programme Coordinator)	V.Tijms@uva.nl
Brain and Mind – Crete	Greece	University of Crete	MSc, PhD	Within biological: neurotransmitters and their receptors, cellular mechanisms of learning and memory. Within computational: neuronal networks, computational vision, biomimetic robotics	3 main domains: biological neurosciences, computational neurosciences and social.cognitive neurosciences	High	Course directory with contact names for each course	http://brain-mind.med.uoc.gr/en/node/19
Cognitive Sciences and Technologies: From Neuron to Cognition	Russia	Higher School of Economics (HSE University).	MSc	Computational neuroscience, computational modelling, psychophysics	focus in linking cognitive neuroscience to neuro-modelling. Taught in close cooperation with the École Normale Supérieure and Aarhus University	High	Vasily Klucharev (Scientific Supervisor)	vasily.klucharev@hse.ru
Computational Neuroscience, Cognition and AI MSc	United Kingdom	University of Nottingham	MSc	Neural Computation, Practial biomedical modelling	Particular focus in how the brain networks of neurons perform computations	High	Marcus Kaiser (Professor of Neuroinformatics)	marcus.kaiser@nottingham.ac.uk
Master of Life Sciences Engineering with a Specialisation in Neuroscience and Neuroengineering	Switzerland	EPFL	MSc	biomedical signal processing, artificial neural networks, biological modelling of neural networks, Biophysics: physiocs of the cell, computational cell biology, In-silico neuroscience	Specialization Neuroscience and Neuroengineering covers disciplines such as experimental neuroscience, computational neuroscience and neurotechnology	High	Carl Petersen (Responsible for Neuroscience and Neuroengineering specialisation)	carl.petersen@epfl.ch
Euromediterranean Master in Neuroscience and Biotechnology	Spain	University of Valencia	MSc	Computational neuroscience and neural networks, Cell comunicatin and plasticity, Cellular and molecular neurobiology, Biophysics.	Study the different levels of neural processing, from the molecular level to the systems level,	High	Enrique Lanuza (Programme Coordinator)	enrique.lanuza@uv.es
Graduate Program in Neuroscience – Crete	Greece	University of Crete	MSc, PhD	Principles of Computational Modeling in Neural Circuits	The Program focuses on Cellular/Molecular/Developmental, Systems, Cognitive, Translational and Clinical Neurosciences	High	Kyriaki Thermos (Director of Studies)	thermos_at_uoc.gr
Graduate Programme in Neuroscience – Oxford	United Kingdom	University of Oxford	MSc, PhD	Computational neuroscience, CNS Development, Plasticity and Repair	Cognition and Neural Network, Neurogenesis and Development	High	Ben Willmore / Timothy Behrens (Lecturer / Professor in the Computational Neuroscience course)	benjamin.willmore@dpag.ox.ac.uk / behrens@fmrib.ox.ac.uk
Graduate School of Neural Information Processing	Germany	Universität Tübingen	MSc, PhD	neural data analysis and models of neural coding and computation, physical and physiological basis of neural recordings and brain imaging, neural network programming	theoretical and computational aspects of neuroscience focusing on biophysics and neural connectivity and signalsynamics	High	Marc Himmelbach (Head of Graduate training Center)	marc.himmelbach@uni-tuebingen.de

Programme	Country	Institution	Degrees	Relevant courses	Additional Information	Fit	Contact details	Contact email
International Master Program in Computational Neuroscience	Germany	Technical University of Berlin	MSc	Models of Neural Systems, Acquisition and Analysis of Neural Data, Neural Noise and Neural Signals	Partnership with the Bernstein Center for Computational Neuroscience Berlin	High	Elsa Harms (Graduate Programme Coordinator)	elsa.harms (at) bccn-berlin.de / graduateprograms (at) bccn-berlin.de
Joint Master in Neuroscience	France	University of Strasbourg	MSc	Computational Neurophysiology (imparted in Freiburg - optimal fit if NESTD is not currently being used)	Jointly imparted between University of Strasbourg (France), Universities of Basel (Switzerland) and Freiburg/Breisgau (Germany),	High	Vincent Lelievre (Head of the Joint Master in Neuroscience program)	lelievre@inci-cnrs.unistra.fr
Master and PhD Neuroscience – Lisbon	Portugal	University of Lisbon	MSc, PhD	Acquisition, archiving and processing of biological signals; Diagnostic Techniques; computational models of functional neuroimaging.	Specialisations in Physical and Engineering Neurosciences and Computational Neurosciences,	High	Alexandra Botelho (Administrative Technician)	balexandra@fm.ul.pt
Master in Brain and Cognition	Spain	Universidad Pompeu Fabra	MSc	Introduction to Computational Neuroscience course touching on Spiking neurons, Dynamic Synapses, Cortical networks, Plasticity/Learning. Very good fit.	Dedicated Centre of Brain and Cognition in the university	High	Gustavo Deco (Professor leading the Computational Neuroscience group and Director of the Center of Brain and Cognition (UPF)	gustavo.deco@upf.edu
Master of Interdisciplinary Neuroscience	Germany	University of Frankfurt	MSc	Subject Area C: Cognitive and computational Neuroscience includes: Computational Moelling of Neuronal Plasticity, Computational neural dynamics, Computational neuroanatomy - quantitative analysis and modelling; and modelling and simulation.	Close contact with Max Planck Institute for Brain Research and the Max Planck Institute for Biophysics as well as the Ernst Strüngmann-Institute for Neuroscience that concentrates on cognitive neuroscience	High	Gabi Lahner (coordinator of MSc programme)	lahner@em.uni-frankfurt.de
Master of Neuroscience	Germany	Carl von Ossietzky University	MSc	Introduction to Neurophysics, Introduction to Computational Neuroscience, Statistical Learning in Computational Neuroscience,	Focus in sensory systems, joint courses with Biology and Psychology	High	Christine Köppl (Professor and Laboratory Head)	master-neuroscience@uni-oldenburg.de
Master of Neuroscience	Spain	University of Santiago de Compostela,	MSc	Computational Neuroscience, Biological and computational models of consciousness	low entry-level for computational neuroscience, since the programme is characterized by being interdisciplinary and covers basic, applied and clinical aspects of neuroscience, as well as training in new technologies such as genomics and bioinformatics.	High	Eduardo Sánchez Vila (Lecturer of Computational Neuroscience)	eduardo.sanchez.vila@usc
Master of Neurosciences	France	University of Bordeaux	MSc	Statistics and Neural Modelling, Neural Networks,	international mobility with Japan, USA, Canada and Europe	High	Denis Combes (Master's supervisor)	master.neurosciences@u-bordeaux.fr
Master's Programme in Neuroscience	Finland	University of Helsinki	MSc	Neuroscience track: introduction to neurobiophysics, synaptic signaling and plasticity,	Two complementary study tracks: Cell and Systems Physiology track and Neuroscience study track	High	Juha Voipio (Programme Director)	juha.voipio@helsinki.fi
MSc Cognitive and Computational Neuroscience	United Kingdom	University of Sheffield	MSc	Computational neuroscience 1 (simple 'integrate-and-fire' approximations to full conductance-based compartmental models) optimal fit	Training computer simulation and mathematical modelling techniques, as well as experimental cognitive psychology and brain imaging	High	Robert Schmidt (Lecturer in Computational Neuroscience 1)	robert.schmidt@sheffield.ac.uk
MSc in Neuroscience – Sussex	United Kingdom	University of Sussex	MSc	Sensory Function and Computation(coding by spike rates and timing);Foundations of Neuroscience; Neuronal Transduction and Transmission	Expertise includes: sensory processing; neural circuits; synapses and ion channels;neurodegeneration	High	Christopher Buckley(senior lecturer in neural computation)	C.L.Buckley@sussex.ac.uk

Programme	Country	Institution	Degrees	Relevant courses	Additional Information	Fit	Contact details	Contact email
MSc in Neurosciences – Bonn	Germany	University of Bonn	MSc	Assembly of Neural Circuits; Principles of Neural information Processing, Synaptic transmission in sensory systems, The Synapse: from molecules to information processing	Special focus in neural signalling and processing; as well as spiking neural network architectures	High	Silke Künzel (MSc coordinator)	neurosciences@uni-bonn.de
MSc Modeling for Neuronal and Cognitive Systems	France	Université Côte d'Azur	MSc	Introduction to modeling in neuroscience and cognition, Dynamical systems in the context of neuron models, Computational Modelling and Simulation	specialised in SNN modelling	High	Bruno cessac (Lecturer in Introduction to modeling in neuroscience and cognition) / Alexandre Muzy (lecturer in Computational modelling and Simulation)	Bruno.CESSAC@univ-cotedazur.fr / alexandre.muzy@cnrs.fr
MSc Neuroinformatics	United Kingdom	Newcastle University	MSc	An Introduction to Computational Neuroscience and Neuroinformatics (using MatLab); Advanced Computational Neuroscience and Neuroinformatics; Computational Analysis of Complex Biological Systems	provides specialist expertise in core neuroinformatics (such as computing and biology) focusing on the development of skills to contribute to biologically realistic simulations of neural activity and developments.	High	Marcus Kaiser (lecturer in Introduction to Computational Neuroscience and Neuroinformatics)	marcus.kaiser@ncl.ac.uk
MSc Neuroscience	United Kingdom	UCL	MSc	Receptors and Synaptic Signalling Systems and Circuits Neuroscience	General Neuroscience course but with greater in neural circuits and signalling	High	Jenni Todd (programme adminisgrator)	j.todd@ucl.ac.uk
MSc Neurosciences	Germany	Ludwig Maximilians University Munich	MSc	Computational Neuroscience course covers Modelling Physiological Processes (Passive membrane, Nernst potential, Hodgin-Huxley model, models of dendrites/cable equations)	Two academic tracks: Systemic-Cellular-Molecular Neuroscience track or a Computational Neuroscience track.	High	Alexander Kaiser(MSc coordinator, implementation of new teaching modiules)	Kaiser.Alexander@lmu.d e
Neurobiology	Lithuania	Vilnius University	MSc	Biophysics of neuron	One course has great fit, university also offers a full MSc Biophysics	High	Osvaldas Rukšėnas (Programme Director)	Osvaldas.ruksenas@gf.v u.lt
Neurocognitive Psychology	Germany	Carl von Ossietzky University Oldenburg	MSc	Computation in Neuroscience	part of the Network of European Neuroscience Schools (NENS).	High	Kerstin Bleichner (Programme coordinator)	kerstin.bleichner@uol.de
UMONS – Master in Biomedicine specialized in Neuroscience	Belgium	University of Mons	MSc	Computational Neuroscience (experimental focus)	interdisciplinary and integrated training approach that covers all major topics of brain research, from normal brain functions to brain disorders.	High	Laurence Ris (Lecturer, head of the department of Neuroscience)	laurence.ris@umons.ac.b e
Elite Master of Science in Neuroengineering	Germany	TUM (Technical University of Munich)	MSc	Relevant areas covered: Neuroanatomy and Neurophysiology Computational Neuroscience Signal Processing and Dynamic System Modeling Mixed Signal Electronics Neuro-inspired Systems Engineering	combines experimental and theoretical neuroscience with profound training in engineering, focusing on neuro-inspired technology	High	Prof. Dr. Gordon Cheng (Program Director)	gordon@tum.de
Behavioral Neuroscience	Italy	Sapienza University	PhD	Within behavioural neurophysiology: characterization of the dynamic properties of neurons in parietal, frontal and prefrontal areas in non-human primates; multi scale analysis of neural signal (local field potentials, single and multiunit activity).	3 main curricula: psychobiology and psychopharmacology, behavioural neurophysiology and cognitive neuropsychology	High (for behavioural neurophysiolo gy track)	Cecilia Guariglia (Course Professor)	behavneurosci-phd@uniroma1.it

Programme	Country	Institution	Degrees	Relevant courses	Additional Information	Fit	Contact details	Contact email
Interdisciplinary Master's in Life Sciences	France	Paris Science and Letters Research University (PSL) ENS (Ecole Normale Supérieure)	MSc	Synapctic foundations of network function, compitational biology, physiology of the neuron	Provides specialization in one offour Master's curricula :Systems biology, genomics and bioinformatics, Neurosciences, Ecology and evolution, and Fundamental biology for health	High (neuroscience specialisation)	Anne Zalmanski (teaching coordinator)	anne.zalmanski@ens.fr
Master and PhD in Cognitive Neuroscience	The Netherlands	Radboud University	MSc, PhD	Within last specialisation, courses include computational neuroscience, Quantitative Brain Networks Advanced computational neuroscience, neural information processing systems	4 specialisations: Language and Communication Perception, Action and Control Plasticity and Memory Neural Computation and Neurotechnology	High (only for last specialisation)	Arno Koning (Programme coordinator)	a.koning@donders.ru.nl
Body and Mind Sciences	Italy	University of Turin	MA	Introduction to computational neuroscience (low-level entry for psychology students where GUI could be very usefu)	Motivation, Emotion and Behaviour, Psychiatric Cognitive Disorders	High (only for this coursel)	Raffaella Ricci and (Associate Professor)	raffaella.ricci@unito.it
Neurobiology	The Netherlands	University of Amsterdam	MSc	Physiology of Synapses and Networks covers Neurophysiology, From Synapse to Network and from Network to behaviour	Positioned at the interface between biology, psychology and philosophy. Four tracks, relevant track is physiology of Synapses and Networks	High (only for this track)	Helmut Kessels (group leader Cellular and Computational Neuroscience)	h.w.h.g.kessels@uva.nl
Doctoral Program Brain & Mind (Finnish Graduate School of Neuroscience)	Finland	University of Helsinki	PhD	Previous projects have built upon concepts surrounding: Cell excitability, Intracellular dynamics, Neural circuit mechanisms.	Open and interdisciplinary, certain focus in computational neuroscience but more supervisor-oriented projects	Medium/High	Katri Wegelius (project coordinator at the Laboratory of Neurobiology)	katri.wegelius@helsinki.fi
Master Neuroscience and Cognition	The Netherlands	University of Utrecht	MSc	Experimental and Clinical Neuroscience track offers training in neuronal connectivity, neuronal plasticity in learning and memory, neuronal signallin	The program is run in association with the University Medical Centre Utrecht (UMCU). Half of the credits are based on an internship, either minor or major.	Medium/High	Geert Ramakers (master's coordinator)	g.m.j.ramakers@umcutre cht.nl
MSc Integrative Neuroscience	Germany	Otto-von-Guericke University	MSc	Theoretical Neuroscience 1(students carry out weekly computational assignments in MatLab) and Theoretical Neuroscience 2 (neural networks activity and dynamic states, and learning through activity-dependent plasticity.)	Wide range of topics covered but increasingly paying attention to neural modelling and quantitative analysis	Medium/High	Nicole Zenker (Programme Coordinator)	neurosci@ovgu.de
Behavioral and Cognitive Neurosciences	The Netherlands	University of Groningen	MSc, PhD	Cognitive Neuroscience and Cognitive Modelling (C-track) (specialization)	3 distinct specialisation tracks: Animal and Human Behavioural Neurosciences; Molecular and Clinical Neuroscience; Cognitive Neuroscience and Cognitive Modelling	Medium	Eva Teuling (Master coordinator)	e.teuling@rug.nl
BIGS Neuroscience PhD programme	Germany	University of Bonn and Rheinische Friedrich-Wilhelms University of Bonn,	PhD	Relevant research groups include: Biophysics of Neurons and Glia, Circuits and Behavior, Molecular Signaling in Neurons and Glia, Sensory Processing	Cognition and Neural Network, Neurogenesis and Development	Medium	Natalie Katzmarski (Responsible for Modules and Courses) / Anne Boehlen (Responsible for PI Recriot,ent and management, and lectures and seminars)	info@bigs-neuroscience.de / office.org@bigs-neuroscience.de
International Masters' Degree in Neuroscience	Italy	University of Trieste	MSc	Neurophysiology of Sensory Systems	multidisciplinary training in both basic and applied neurobiology, spanning from single molecules to whole organisms in normal or pathological conditions.	Medium	Claudia Lodovichi (Neurophysiology of Sensory Systems lecturer)	claudia.lodovichi@unipd.i t
Master Cognitive Neuroscience Berlin (MCNB)	Germany	Freie Universität Berlin	MSc	Introduction to Programming Computational Cognitive Neuroscience, Introduction to programming	Heavier focus in cognitive neuroscience than computational	Medium	Mirjam Bartscherer (Programme administrator)	studium-psy@fu-berlin.de

Programme	Country	Institution	Degrees	Relevant courses	Additional Information	Fit	Contact details	Contact email
Master in Biomedical Sciences, specialisation Neurosciences	Belgium	University of Antwerp	MSc	Excitation, plasticity and the connectivity of neurons	The biomedical sciences programme is a multidisciplinary programme taught by lecturers from the faculties of Pharmaceutical, Biomedical, Veterinary and Medical Sciences	Medium	Sebastiaan Engelborghs (professor of neurology and neurosciences)	sebastiaan.engelborghs @ua.ac.be
Master in Cognitive Science – Trento	Italy	University of Trento	MSc	Introduction to Computer Programming, Neural Foundations of Human Behaviour (neuronal function, synaptic transmission, sensory processing, movement, sleep and neural plasticity)	Students choose between two tracks: Cognitive Neuroscience (CN) Language and Multimodal Interaction (LMI)	Medium	Manuela Piazza (Full professor Department of Psychology and Cognitive Science)	manuela.piazza@unitn.it
Master in Neuroscience	Switzerland	University of Geneva	MSc	Principles of neurobiology (action potentials and plasticity), Trends in computational neuroscience	The program is strongly research-oriented offering courses from three faculties : Medicine, Psychology and Educational Sciences and Science.	Medium	Delphine Jochaut-Roussillon (Master Coordinator) / Daniel Huber (Associate Professor, lecturer of principles of Neurobiology)	Delphine.Jochaut@unige.ch
Master in Neurosciences	Spain	University San Juan de Alicante	MSc	Cell communication; Synaptic transmission and plasticity. Processing of sensory information; From ionic channels to information processing in the Nervous System: a functional approach	Official Master of the Instituto de Neurociencias, and part of the Spanish National Research Council (CSIC)	Medium	Emilio Geijo Barrientos (Director of Master)	emilio.geijo@umh.es

ANNEX: BIBLIOGRAPHY

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