SP10 Neurorobotics Platform - Results for SGA2 Year 1 (D10.5.1 – SGA2)

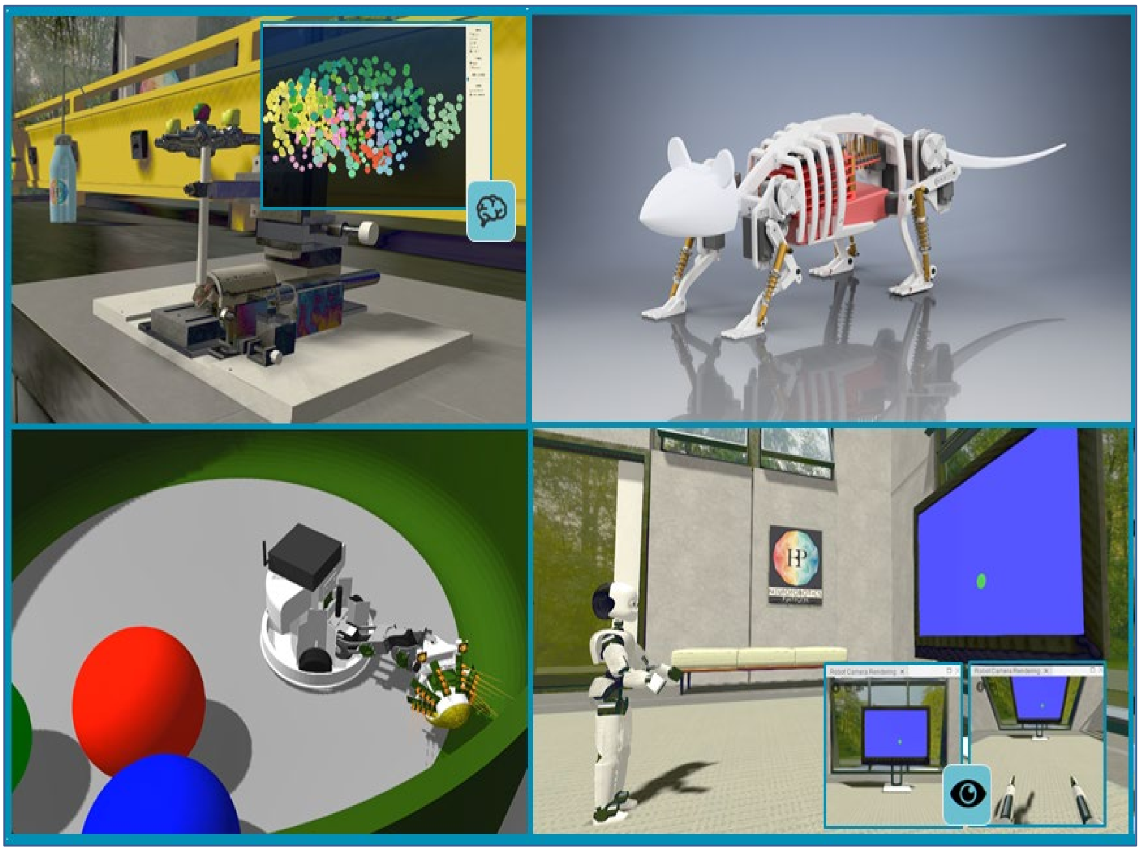

Figure 1: The Neurorobotics Platform

The Neurorobotics Platform supports *in silico* exploration of multiple scientific questions in both neuroscience and robotics, such as synergies between musculoskeletal system and motor control, visuomotor processing with spiking neural networks, navigation, and transfer learning to robotic platforms.

Project Number:	785907	Project Title:	Human Brain Project SGA2

Document Title:	SP10 Neurorobotics Platform - Results for SGA2 Year 1
Document Filename:	D10.5.1 (D67.1 D28) SGA2 M12 ACCEPTED 190723
Deliverable Number:	SGA2 D10.5.1 (D67.1, D28)
Deliverable Type:	Report
Work Package(s):	WP10.1, WP10.2, WP10.3, WP10.4
Dissemination Level:	PU = Public
Planned Delivery Date:	SGA2 M12 / 31 Mar 2019
Actual Delivery Date:	SGA2 M12 / 29 Mar 2019; ACCEPTED 23 Jul 2019
Authors:	Alois KNOLL, TUM (P56), Egidio FALOTICO, SSSA (P49)
Compiling Editors:	Fabrice MORIN, TUM (P56); Bianca SCHMIEDLE, EPFL (P1)
Contributors:	Egidio FALOTICO, SSSA (P49), KR10.1 Jörg CONRADT, KTH (P39), KR10.5 Fabrice MORIN, TUM (P56), KR10.2, KR10.3 Axel VON ARNIM, FORTISS (P21), KR10.4
SciTechCoord Review:	
Editorial Review:	Annemieke MICHELS, EPFL (P1), Guy WILLIS, EPFL (P1)
Description in GA:	WPs involved: WP10.1, WP10.2, WP10.3, WP10.4 & WP10.5 Summary of SP Results for M1-12, broken down by Task: o Actual vs. planned results (due & done/due & not done) o Results passed to another Task, WP or SP (due & done/due & not done) o Milestones due and achieved, how validated, by whom. o Milestones due but not achieved, why, impact, corrective action o Publications o SP Roadmap for SGA3 *For consistent presentation of HBP results, SGA2 M12 Deliverables describing the accomplishments of an entire SP or CDP have been prepared according to a standard template, which focuses on Key Results and the outputs that contribute to them. Project management elements such as Milestones and Risks will be covered, as per normal practice, in the SGA2 Year 1 Report.*
Abstract:	This deliverable is the annual compound of HBP deliveries and results (outputs and outcomes) from Sub-Project SP10 – Neurorobotics Platform (NRP). The main technical and scientific deliveries from April-2018 to March-2019 for SP10 were: • *In silico* experiments with realistic neuromusculoskeletal rodent model as co-design drivers (KR10.1). • Two new releases of the robot rodent and the specifications of the final release to be released in the second half of SGA2 (KR10.2). • Multiple individual building blocks (visual system in particular) of what will become the Integrated Behavioural Architecture (KR10.3). • A series of new functional features and improvements to the NRP delivered in releases 2.1 and 2.2 (KRP10.4).

	• The continued development of compliant robotics and demonstration of what the NRP can offer in terms of knowledge transfer to such physical robots
Keywords:	Neurorobotics, Virtual Robotics, *in silico* experiments
Target Users/Readers:	Computational neuroscientists, neuroroboticists, consortium members, funders

Table of Contents

Table of Tables

Table of Figures

1. Overview

Neurorobotics is an emerging research field where key concepts and technologies from both brain science and robotics are fused in order to: 1) provide new experimental paradigms in brain simulation; and 2) produce new technological solutions in artificial intelligence and robotics. The first objective relies on the concept of embodiment (i.e. placing the brain inside a body and simulating them both) for implementing closed-loop experiments, where brain activity is driven by streams of sensory stimuli and interactions with the environment. The second objective relies on identifying features of the brain as an information-processing system that would provide digital systems (including robots) with functional capabilities that are currently beyond the state of the art (situational awareness, decisional ability, etc.).

HBP Subproject 10 (SP10) aims to establish the HBP as a trailblazer for global neurorobotics development and the establishment of a global neurorobotics community. The primary strategy of SP10 is to provide tools and workflows that capitalise on state-of-the-art approaches and technologies for defining, simulating and visualising models of brains, robots and physically realistic environments. Concretely, SP10 is building and operating the Neurorobotics Platform (NRP) as a reliable research infrastructure where researchers from within and outside the HBP can define, run and share experiments and simulations.

Via the NRP, SP10 thus offers researchers (ranging from neuroscientists to roboticists) a unique tool that serves as common ground on which they can evaluate models ranging from simple sensorimotor models to large-scale behavioural architectures, controlling complex robot bodies with many degrees of freedom. Through co-design activities linking research in neuroscience and software development, SP10 also strives to establish scaffold (framework) models that provide the research community with tools that support continuous integration of new data and models in a standardised and collaborative manner. Finally, a long-term objective of SP10 is to leverage lessons from neuroscience to endow robots with some abilities that are currently beyond the state of the art (e.g. situational awareness, adaptability to unforeseen changes in task parameters, etc.).

The present document provides a high-level summary of the Key Results (as defined in the Grant Agreement) from SP10.

2. Introduction

The present document provides a high-level summary of the scientific and technical activities carried out by the SP10 Partners in the first year of SGA2. It is structured around the Key Results defined in the Grant Agreement, and frames the developments in terms of their contribution to the overarching objectives of both the HBP and SP10. The Key Results exemplify the collaboration and synergy between researchers inside and outside SP10 and, most importantly, introduce the various experimental setups that are intended to become a long-term frame of reference for model testing within the HBP.

The first Key Result is the continued development and expanded use of the virtual rodent model for *in silico* behavioural experiments (KR10.1). This uniquely detailed body model is available on the NRP. It is based upon a realistic musculoskeletal mode and enables implementation of high-resolution tactile signals (e.g. from skin and whiskers) required for locomotion and other behavioural tasks, and supports research on sensory integration as well. It is leveraged in three different experiments and demonstrators. The first two demonstrators focus on motor control in rodents, in the context of reaching and grasping tasks. Both experiments use the same rodent and spinal cord models, and both experiments were originally conceived to study motor learning before and after a topical stroke in the motor cortex. The third experiment focuses on modelling locomotion in rodents (and humans) in the context of spinal cord injury treatment. Several high-profile papers were published last year, illustrating the success of our modelling approach (e.g. Formento *et al*. (2018), Nature Neuroscience, 21, 1728–1741.).

The second Key Result is the rodent robot, a lightweight technology platform which uses mechanically compliant structural elements and is designed to approximate rodent locomotion patterns. It is intended to be cheap enough to be shared between HBP Partners as a means to transfer neuronal models into a common physical embodiment controlled with neuromorphic hardware. Several versions of this rodent robot were released in the first six months of SGA2, providing additional functionalities (e.g. flexibility of the spine) and new technical features (sensors in particular).

The third Key Result regroups the various steps towards establishing the Integrated Behavioural Architecture (IBA). This is a modular, expandable scaffold framework on the NRP; it will allow integration of heterogeneous pieces of code, each modelling specific brain areas, into a single functional architecture that can run on the NRP. The IBA will be implemented through an API that enables individual scientists to easily plug-in their own code and leverage resources already present on the NRP, in order to perform experiments based on complex cognitive tasks. The IBA is still under development, and the present report therefore focuses on the different sub-components that are its co-design drivers, the establishment of testing setups of adequate complexity, as well as on the integration of one complete cognitive architecture developed by our colleagues in SP3, which we used as a starting point for the IBA.

The fourth Key Result is the improved NRP itself. In the first year of SGA2, we focused essentially on improving usability and reliability. The various new features introduced are described, as well as the rationale for their implementation.

Finally, the fifth and last Key Result is modular control for physical robots under real-time constraints. While simulation can indeed guide robotic development, especially when combined with learning processes (inspired by either biology or AI), the intrinsic limitations of the physics engines available in the NRP create an unavoidable reality gap that needs to be characterised. We thus address manipulation of objects with complex inertial properties (e.g. a half-full water bottle) with a compliant / soft robot as a test case for motor learning and adaptation, comparing simulations on the NRP to “real-world” experimental results.

3. Key Result KR10.1: Virtual rodent model for *in silico* behaviour experiments

3.1 Outputs

3.1.1 Overview of Outputs

The virtual rodent model, comprising of both biomechanical and neural models, aims to provide neuroscientists with a comprehensive platform for the simulation of realistic behavioural experiments. Different musculoskeletal models of mice and rats are thus developed and integrated alongside biologically-inspired neural networks, starting from essential, low-level, reusable components such as the spinal cord circuitry (Outputs 1 and 3). Finally, models capable of translating information between the physical and neural simulation in a biologically realistic manner are also developed and integrated (Output 2). Currently, the experimental setups considered are the post-stroke rehabilitation experiment with the robotic M-platform and a locomotion scenario. All experiments and models are being integrated in the NRP.

3.1.2 Output 1: Spinal cord model and parameters tuning for in silico stroke rehabilitation on rodents

This work relates to Components SGA2-C2599, SGA2-C2600, SGA2-C2614, SGA2-C2615.

In order to fully simulate the stroke rehabilitation procedure, performed with the M-platform on post-stroke mice, several important steps have to be undertaken. A basic component in the simulation is the lower-level neural circuit, the spinal cord circuitry, that directly connects with the simulated embodiment. In order to produce realistic outputs, such a network has to be developed by integrating biologically accurate models of its neural populations. For this reason, we developed a functional spinal cord circuitry that includes a model for integration of muscle fibre twitches. This is connected to a population of motoneurons, whose membrane parameters are able to implement a specific recruitment order, and to interneural populations and excitatory/inhibitory connections that can reproduce monosynaptic and disynaptic stretch/inhibition reflexes (see Figure 2).

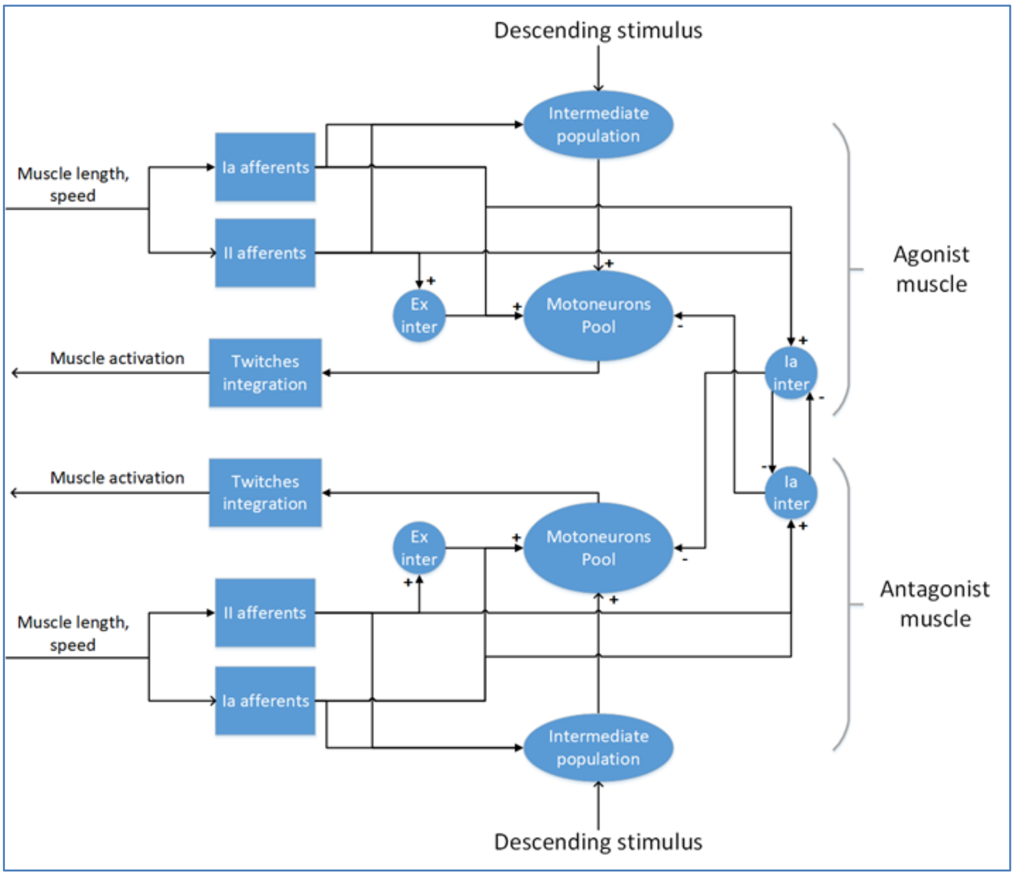

Figure 2: Spinal cord network model.

In order to validate the developed spinal cord model, and tune some of its parameters for the generation of appropriate motor commands, we devised a validation procedure in which we reproduce a real experiment in the NRP; we employ the model on the musculoskeletal mouse embodiment, connected to the M-platform, with the aim of replicating the kinematic movement of the slide actuated by the mouse (see Figure 3). The stimulus to the spinal circuitry is provided by recorded neural activity of relevant neurons of the motor cortex of healthy mice whose slide motion is also recorded. Using this data, we can tune the spinal cord model so that the simulated mouse can perform the pulling as close as possible to its real counterpart.

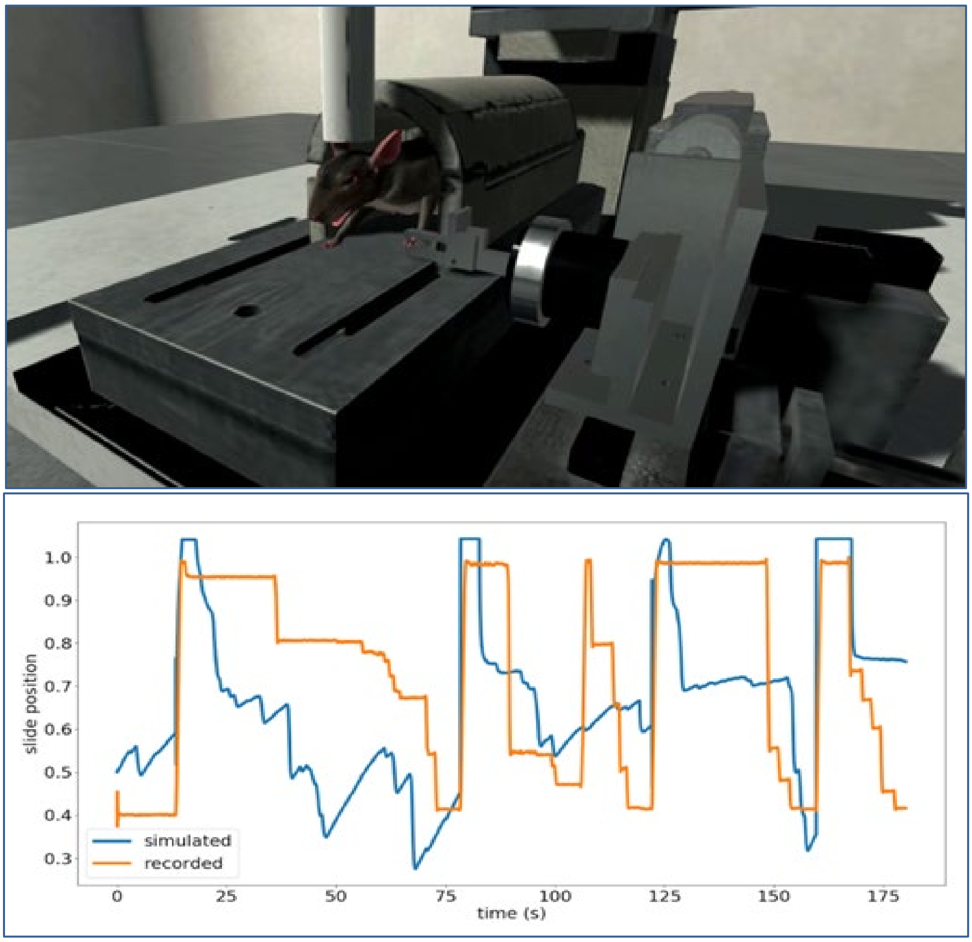

Figure 3: Spinal cord model validation

Simulation of the virtual mouse and the M-platform in the NRP (above). Comparison between slide position recorded during the *in-vivo* experiment and the simulated one (below).

Reproduction of the movement is not yet accurate (see Figure 3 below), but we identified a possible cause in the variability of firing rates of the recorded neurons. We are working on a normalisation procedure that can overcome this, by employing multi-unit instead of single-unit activity. In particular, intracortical voltage signals (sampled at 24 kHz) are computed band-passing recordings in the 300 – 6,000 Hz range. The multi-unit activity is then calculated from the neural signal crossing a threshold value, defined as three times the standard deviation for each channel. The kinematic signals are then oversampled and synchronised with the neural activity (see Figure 4).

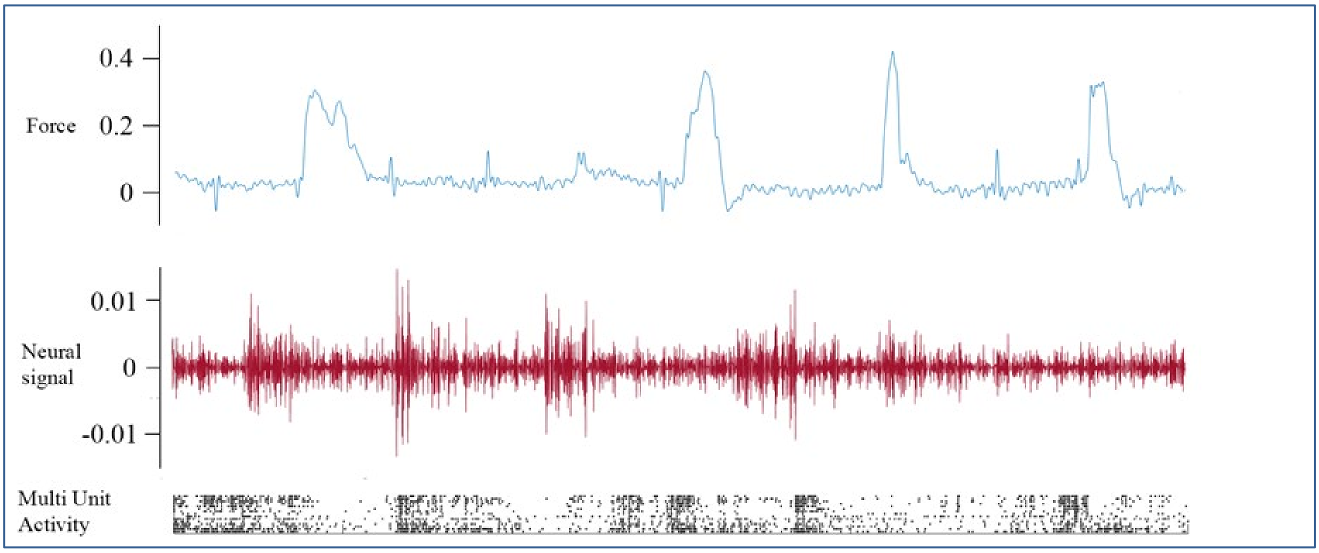

Figure 4: Synchronised neural and kinematic signals.

3.1.3 Output 2: Neuromorphic model of vestibular afferents

This work relates to Components SGA2-C2601, SGA2-C2603.

When connecting physical and neural simulations, it is crucial to translate analogue signals into an event-based coding scheme. In particular, to preserve the realism of the overall simulation, biologically plausible translation mechanisms should be developed and implemented. For this reason, we designed a neuromorphic model of the mouse vestibular system that is capable of translating sensory information coming from artificial sensors, such as inertial measurement units, into a neural activity that closely matches the one recorded from the real semi-circular canals. Concretely, we tuned the parameters of an existing computational model of the semi-circular canals to produce an output that matched neurophysiological recordings. The resulting model used the rotational velocity on an axis of rotation as input and produced the corresponding spiking activity for that particular canal, including both regular and irregular afferents (Figure 5). The tuned model was then implemented as a new neural model for the spiking neural network simulator NEST.

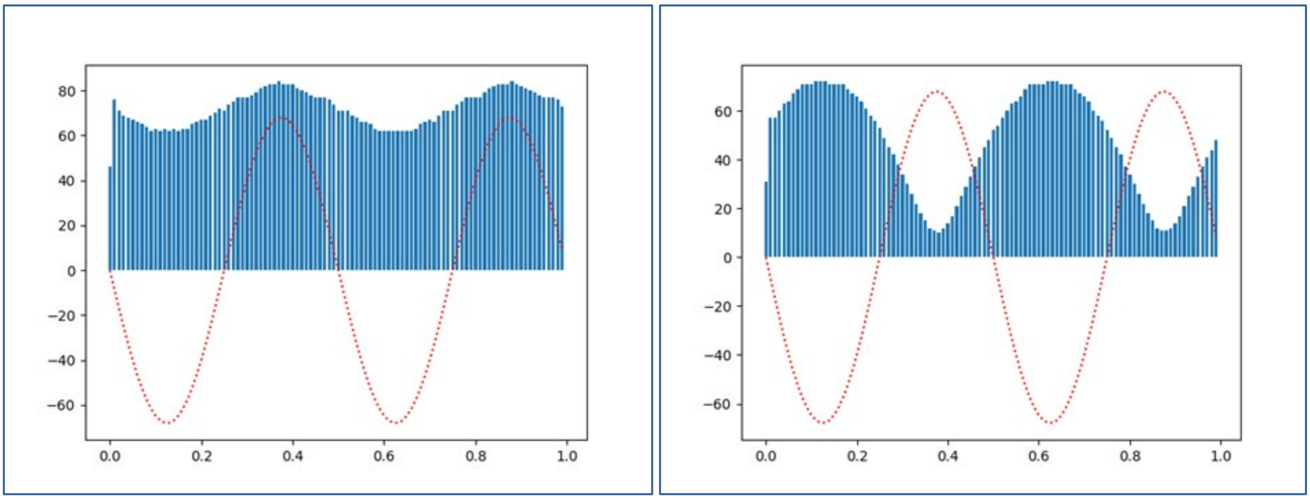

Figure 5: Average firing rate of the regular (left) and irregular (right) afferents in response to a rotation of the head.

To test the translation, a complete circuit for the generation of motor commands for the eye muscles, through the vestibulo-ocular reflex (VOR), was implemented for the virtual mouse in the NRP. The circuit used the aforementioned vestibular afferents as inputs, and the motoneuron pools and twitch integration models already developed for the spinal cord circuitry. The VOR model was tested in the NRP, where we showed the circuitry's ability to produce corrective eye motions in response to head rotations (see Figure 6).

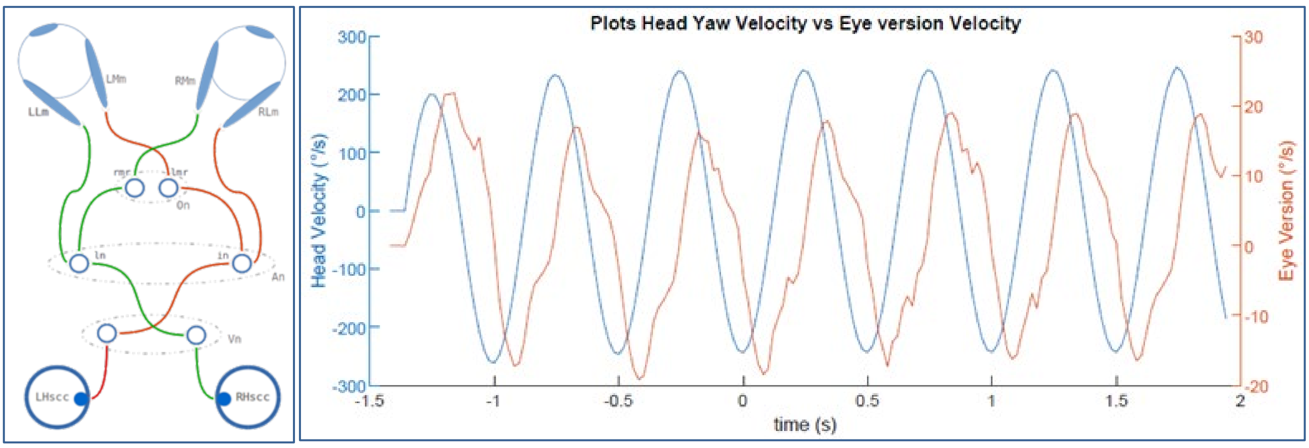

Figure 6: VOR circuit & eye compensation for a sinusoidal head rotation with a frequency of 2Hz

3.1.4 *Output 3: Models of locomotion and recovery of the spinal cord injuries: from rodents to humans*

This work contributes to Components: SGA2-C2596, SGA2-C2597, SGA2-C2602, SGA2-C2604, SGA2-C2606, SGA2-C2607, SGA2-C2608, SGA2-C2609, SGA2-C2610

In order to improve the biomechanical model of the mouse, a pipeline was established to rapidly generate musculoskeletal models of mice with different parameter options (Figure 7). This allows better validation of simulation models, by allowing them to be compared much more closely with experimental results.

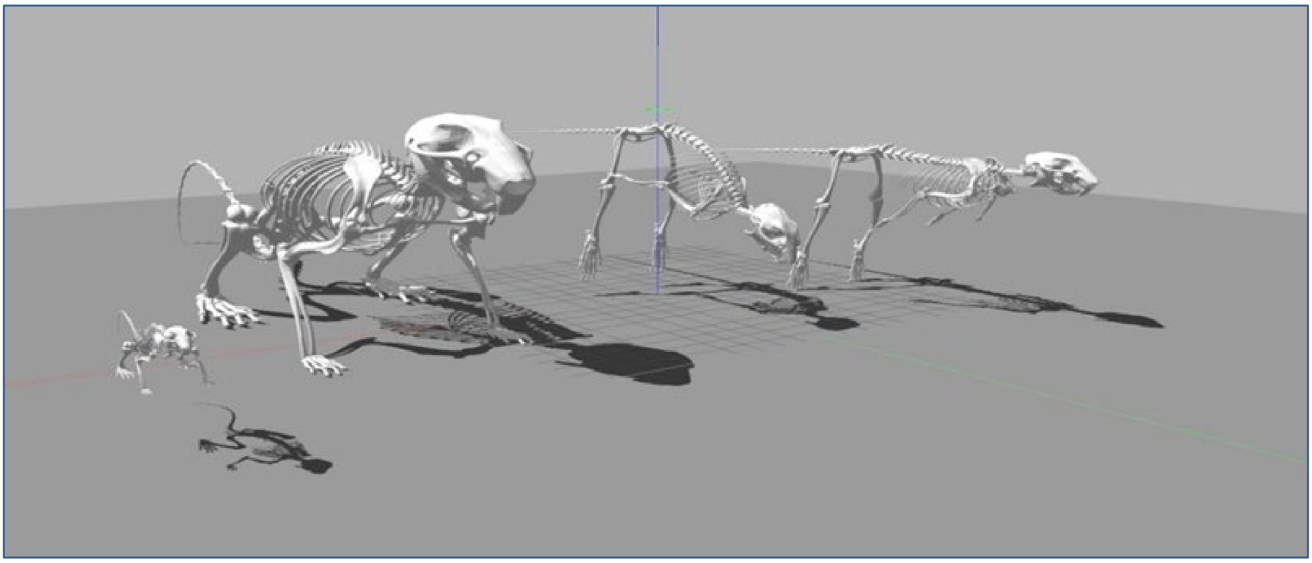

Figure 7: Examples of mouse skeletal systems, generated with different parameters.

A neural framework was also developed to incorporate various neuron model abstractions in closed loop experiments (Figure 8). This framework is highly configurable to enable proper representations of biologically realistic, spinal sensorimotor circuits to be found. For example, a subset of possible connectivity models can be pre-selected, or different neuron model abstractions implemented easily in closed loop experiments.

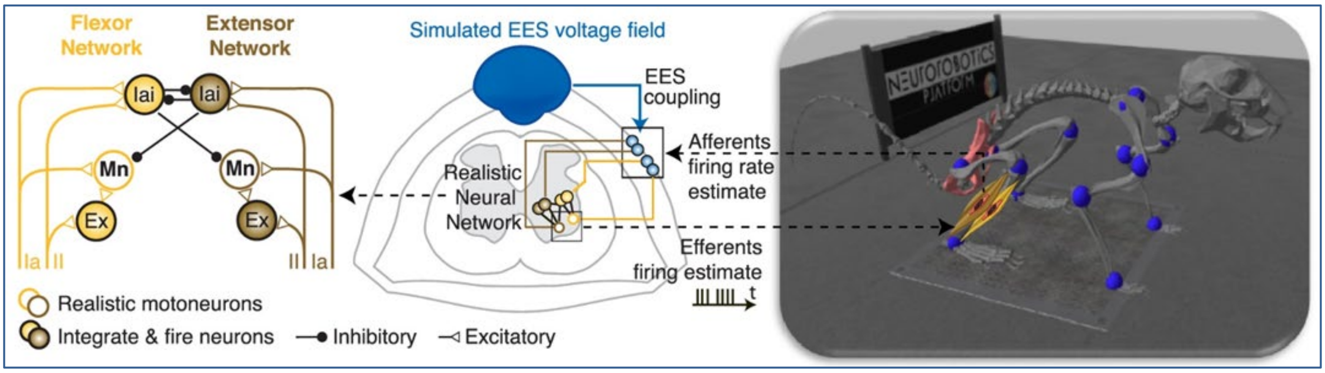

Figure 8: Sketch of the closed-loop framework for rodent locomotion.

This modelling underpinned our work to understand the mechanism of action of epidural electrical stimulation (EES) of the lumbar spinal cord in restoring locomotion in rodents and humans. Computer simulations suggested that, in humans, continuous EES blocks the proprioceptive signals travelling along the recruited fibres. To corroborate this prediction, we performed experiments in rats and humans with spinal cord injury (SCI) (Figure 9). Results showed that EES disrupts both the conscious perception of leg movements and the afferent modulation of sensorimotor circuits in humans, but not in rats. Combining simulation and behavioural experiments, we then provided evidence that, because of this phenomenon, continuous EES in humans can only facilitate locomotion to a limited extent, which was insufficient to provide clinically-relevant improvements. Finally, we proposed two sensory-compliant stimulation strategies and showed that these strategies lead to significant improvements in locomotor functions, with two subjects (out of three) regaining the ability to transition from sitting to standing and walking with crutches.

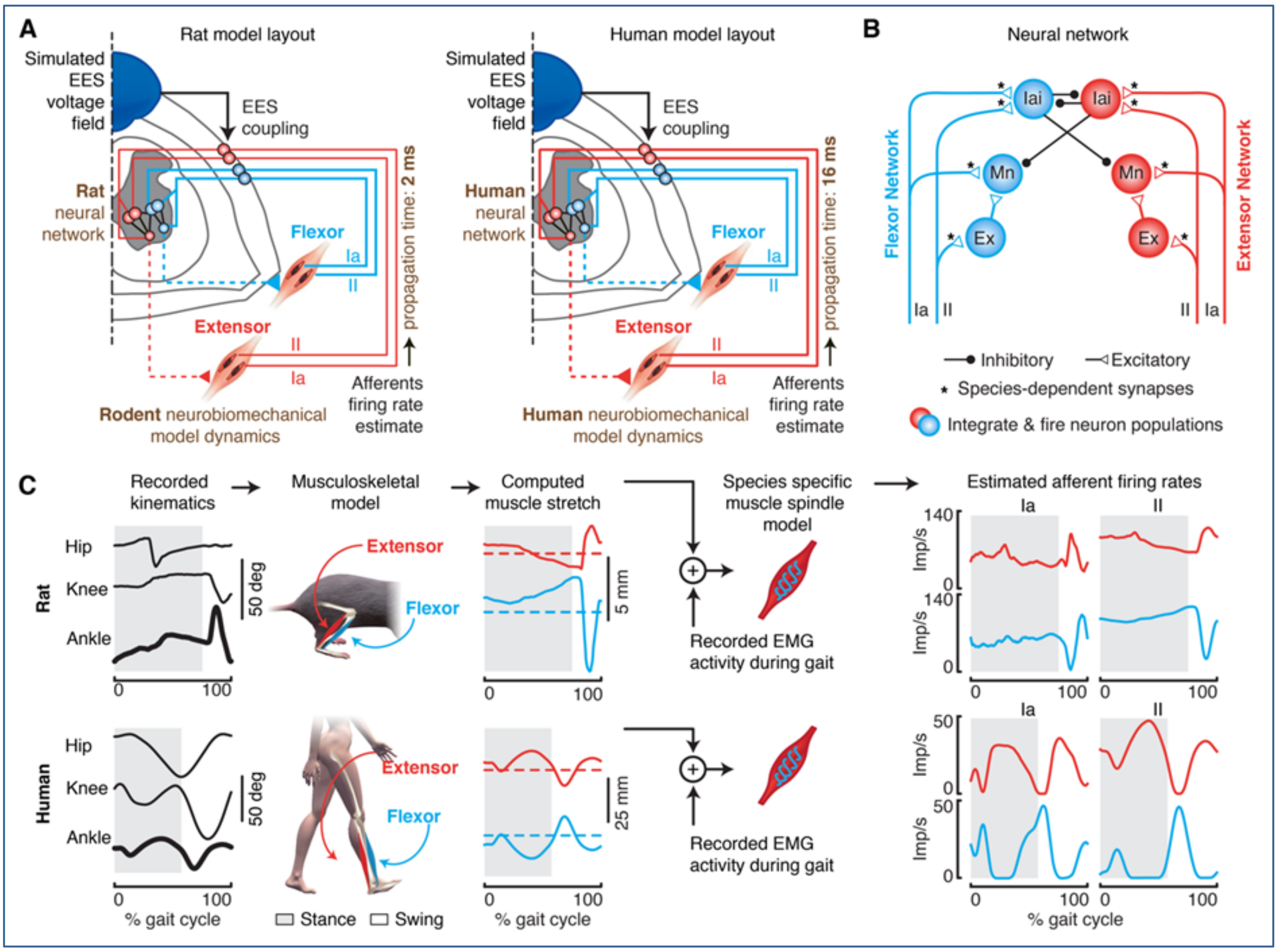

Figure 9: Computational model of rat & human muscle spindle circuitries during locomotion.

A: Layout of the computational models built for rats and humans. The components highlighted in brown are tuned to match the anatomical and physiological features of rats versus humans. B: Spiking neural network model of muscle spindle feedback circuits for a pair of antagonist muscles. Mn, motoneuron. Ex, excitatory interneurons. Iai, Ia-inhibitory interneurons. The synapses highlighted with an asterisk (*) are tuned to match the known properties of humans and rats. C: Estimated stretch profiles and afferent firing rates of ankle flexor and extensor muscles over an entire gait cycle in rats (top) and humans (bottom).

3.2 Validation and Impact

3.2.1 *Actual Use of Output(s) / Exploitation*

The outputs of this work are being used in the strategic experiments of SP10 and CDP1.

3.2.2 *Potential Use of Output(s)*

These biologically realistic models will advance our knowledge of sensorimotor integration by testing neuroscientific theories through embodiment in closed loop simulations. Experimenters will also benefit from the simulations by being able to test different experimental conditions before performing a real experiment, thus saving time in the experimentation process.

3.2.3 Publications

The main publications for this Key Result are:

- E. Formento, K. Minassian, F. Wagner, JB. Mignardot, C.G. Le Goff, A. Rowald, J. Bloch, S. Micera*, M. Capogrosso* and G. Courtine*. Electrical spinal cord stimulation must preserve proprioception to enable locomotion in humans with spinal cord injury. Nature Neuroscience, 21.12: 1728, 2018.
    - This publication provides insights on how to employ epidural electrical stimulation techniques developed on rodents, for human rehabilitation (Output 3).
- Wagner, F. B., Mignardot, J., Le Goff-Mignardot, C. G., Demesmaeker, R., Komi, S., Capogrosso, M., … Courtine, G. Targeted neurotechnology restores walking in humans with spinal cord injury. Nature, 563(7729), 65–71, 2018.
    - This publication reports a successful case of restoring walking after spinal cord injury in human subjects (Output 3).
- Salimi-Nezhad N., Amiri M., Falotico E., Laschi C., A Digital Hardware Realization for Spiking Model of Cutaneous Mechanoreceptor, Front. Neurosci., 2018, https://doi.org/10.3389/fnins.2018.00322

3.2.4 Measures to Increase Impact of Output(s): disseminations

The main dissemination measures for this Key Result were:

- Press release in the New York Times: https://www.nytimes.com/2018/10/31/health/spine-surgery-paralysis.html?action=click&module=Top%20Stories&pgtype=Homepage
- Appearance on BBC news: https://www.bbc.com/news/health-46043924
- Press release from National Geographic: https://www.nationalgeographic.com/science/2018/10/news-spinal-cord-injuries-walk-again-electrical-stimulation-health/

4. Key Result KR10.2: Rodent robot

4.1 Outputs

4.1.1 Overview of Outputs

The NRP_Mouse strives to be the first lightweight robotic platform combining naturalistic movement, mechanical compliance and neural control. The first output of this Key Result is comprised of the various robot mouse versions made available over the past year; these provide the first demonstrations of a life-sized robot rodent with an actuated flexible spine. The second output is the specification set for the 4th and final version, to be delivered at the end of April 2019, with advanced sensing capabilities paving the way for closed-loop control.

4.1.2 Output 1: New versions of the rodent robot produced

This work relates to Components SGA2-C10.3.4.1, SGA2-C10.3.4.2 and SGA2-C10.3.4.3.

For convenience, the differences between versions are summarised in Table 1:

Table 1: NRP_Mouse versions

	V1 (SGA1)	V2	V2.1	V3	V4
Build	May 2017	April 2018	May 2018	October 2018	In Progress; est. April 2019
DOF	8	10	10	11	13
Size [mm]	316 x 85 x 72	340 x 85 x 71	340 x 85 x 71	310 x 81 x 85	402 x 91 x 90
Weight [g]	225	200,3	148,5	181,4	?
Processor	Intel® Edison	Teensy 3.6	Teensy 3.1	Teensy 3.1	Raspberry Zero W
Approx. Cost [€]	480	400	350	400	?

4.1.2.1 Version 2:

The second version (Figure 10) of the NRP_Mouse implemented lateral spinal flexion. The additional 2 Degrees of Freedom (DOF) allowed lateral flexion of the lower lumbar spine and the complete tail. The spring system was improved, using machined parts for the hind legs and an equivalent direct spring attachment for the forelegs. Micro position sensors were introduced within the knees and elbows to measure the leg state.

Finally, due to the discontinuation of the Intel® Edison, a Teensy 3.6 Microcontroller was used as computational platform, together with a Bluetooth module, to allow direct control via a connected laptop running ROS and the NRP. Locomotion-controlled central pattern generators from within the NRP were demonstrated.

4.1.2.2 Version 2.1

Version 2.1 (Figure 10) introduced a single-piece 3D-printed leg in order to explore a reduction in complexity of the leg design from 26 parts to one. The leg design was based on flexible hinges, a flexural mechanism from a surgical arm manipulator robot developed by Prof. Tim LUETH within the framework of a collaboration with TUM. This required material tests on the flexibility and elasticity of the printed material, which were done using force gauges and camera imaging to define the necessary thickness and curvature for the hinges.

We showed that simplification of the legs is possible, with some caveats. In particular, the pantograph design of the jointed legs could not be implemented properly within a single-piece design, leading to collisions between the toes and the ground during the swing phase of the leg. Moreover, the material properties of the legs were not consistent due to limitations of the printing technology used.

4.1.2.3 Version 3

The third version (Figure 10) of the mouse implemented an additional DOF for the lumbar flexion of the spine. This is realised by introducing dental rubber bands as flexors on the ventral side of the spine and a servo-pulled tendon on the dorsal side. This robot was used to test the influence of spinal flexion on the gait. However, the design proved too flexible and the control of one single axis (lateral flexion or lumbar flexion) was impossible. A redesign of the spine improved stability but limited the motion range.

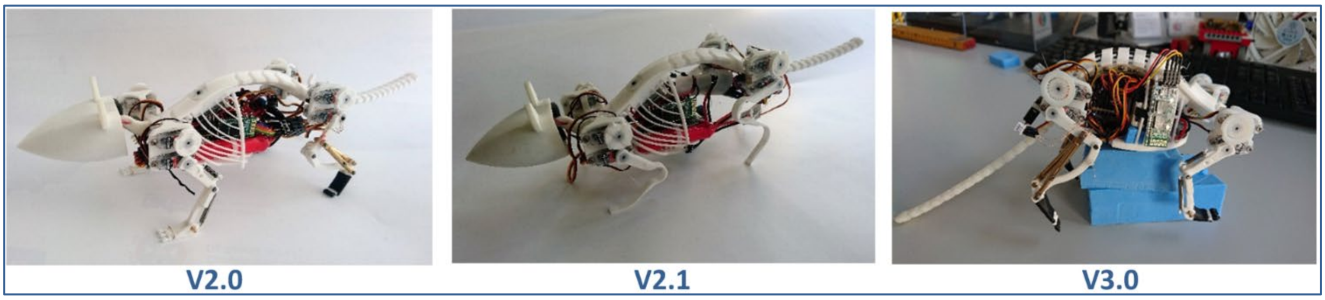

Figure 10: NRP_Mouse versions released between SGA2 M1 and M12

4.1.3 Output 2: Specifications of v4 of the rodent robot

This work mostly relates to Component SGA2-C10.3.4.1.

4.1.3.1 New leg design and testing

The pantograph of the v2.1 leg design was improved. A third flexible hinge between the knee and the heel was introduced, as well as a connection between the femur and the tibia which can be "clipped" into position, allowing for rotational movement at both endpoints. To find the optimal configuration, a test leg was built, allowing 42 different configurations, which were assessed manually for their angular inclination of the foot while flexing the leg. Stress testing of the 3D-printed materials was carried out using a custom test setup where the leg with a flexible hinge repeatedly pushed a switch. After over 70,000 cycles, no significant wear and tear on the material could be observed.

The new design now consists of three parts, including a toe, as was used in the more complex leg setups for stability in the most backward leg position. Additionally, a printed circuit board (PCB) can be fixed to the inside of the leg, allowing the attachment of a rotational sensor in the knee joint and a pressure sensor in the foot.

4.1.3.2 New core body design

The core body model was entirely redesigned to be sturdier, especially the spine, with motion defined through hinges specifically designed for lumbar or lateral flexion. Maximal motion was limited by fixed end stops, to prevent over-flexing of the hinges. The battery mounting was adapted, allowing a quick change when the battery is empty. Two new DOFs were introduced to allow for a pan/tilt of the head, with one servo in the body and one in the head. The head was redone as well to allow space for the servo and two USB cameras, to make binocular vision possible. The space in the neck was extended for accommodate two more DOFs, to possibly allow closing of the forelimbs in the future. All servo mounts (including the critically important hip and shoulder mounts) were changed to be more robust and accommodate the new servos. The tail was redone as well, to fit the biological model in length and shape, with a tapered end. The wiring was also revised, so it could be fixed more easily and guided more precisely through the robot. In particular, this helped to prevent slippage of the wire coils at the shoulder/hip, which sometimes occurred when the legs were lifted for the swing phase.

4.1.3.3 Electronics

The servos will be fitted with custom PCBs, allowing full control over motor position and (indirectly) applied force. Similarly, PCBs for new position and pressure sensors will be fitted in the legs. For additional computing power, the main computer will be a "Raspberry Zero W" with WLAN and Bluetooth accessibility, as well as a direct camera interface. For this, a custom PCB will be made, acting as an interface to the real-time computation needed for the legs, other servos and sensors, as well as power management.

4.2 Validation and Impact

4.2.1 Actual Use of Output(s)

A collaborative experiment with Prof. Oota at RIKEN (Japan) is planned for the second half of SGA2, to compare gait parameters of biological rodents and of the NRP_Mouse robot.

4.2.2 Potential Use of Output(s)

Given its low price tag and ease of use, the robot rodent v4 is suitable for use as an educational robot in practical courses. It is also a convenient platform to study transfer of learning from the NRP to real robots.

4.2.3 Publications

The main publication for this Key Result is:

- P. Lucas, F. Walter and A. Knoll, "Design of a Biomimetic Rodent Robot", Technische Universität München, Institut für Informatik, 2018, TUM-I1870, doi: http://doi.org/10.14459/2018md1464578; PLUS ID: 1574
    - This publication details the design considerations for version 2 of the NRP_Mouse, which have had an essential impact on the future iterations, up to and including the upcoming v4.0, and will be used in from the second half of SGA2 in scientific experiments.

4.2.4 Measures to Increase Impact of Output(s): disseminations

The main dissemination measures for this Key Result were:

- Television appearance (23.05.2018 – ARD-alpha): “Von der Maus zum Menschen”: https://www.br.de/fernsehen/ard-alpha/sendungen/campus/robotermaus-tu-muenchen-robotik-kuenstliche-intelligenz-forschung-campus-magazin-114.html
- Booth at Cebit – Europe’s Leading Business Festival for Innovation and Digitization (13.-15.06.2018)
- Press Release: “Cebit: Die Roboterhunde kommen” (15/06/2018 – Spiegel Online) http://www.spiegel.de/fotostrecke/roboter-der-zukunft-helfer-im-alltag-fotostrecke-161598-7.html

5. Key Result KR10.3: Integrated Behavioural Architecture

5.1 Outputs

5.1.1 Overview of Outputs

The Integrated Behavioural Architecture (IBA) is a software framework through which neuro-computational components can be integrated into the NRP as part of a modular, expandable cognitive architecture, in order to evaluate their functional performance through embodied simulation. An essential objective of the IBA is to enable users to plug their own code into such a cognitive architecture in the NRP with minimal effort, thus enabling them to run behavioural experiments without having to write every component that is required for this purpose themselves. No such system currently exists, which impedes the use of simulation as a widespread tool in cognitive/behavioural neuroscience. However, to deliver its full potential, the IBA must: 1) implement a basic cognitive architecture, comprising modules which can be easily swapped for user-produced code, and that can be easily expanded; 2) rely on a library of modules (functional or data-driven) available for off-the-shelf use. The outputs below describe our progress towards those two objectives.

5.1.2 Output 1: Importation of the Whiskeye robot in the NRP and ongoing development of new visuo-tactile algorithm

This work relates to Component SGA2-C2301, SGA2-C2527, SGA2-C2943.

As a starting point for the IBA, the cognitive architecture developed in the HBP's SP3 (Systems and Cognitive Neuroscience) was implemented on the NRP together with the Whiskeye robot model. It consists in a set of Python modules communicating with the NRP through a ROS-based overseer. Some communication features of this software architecture will be reused by the IBA (see Figure 11).

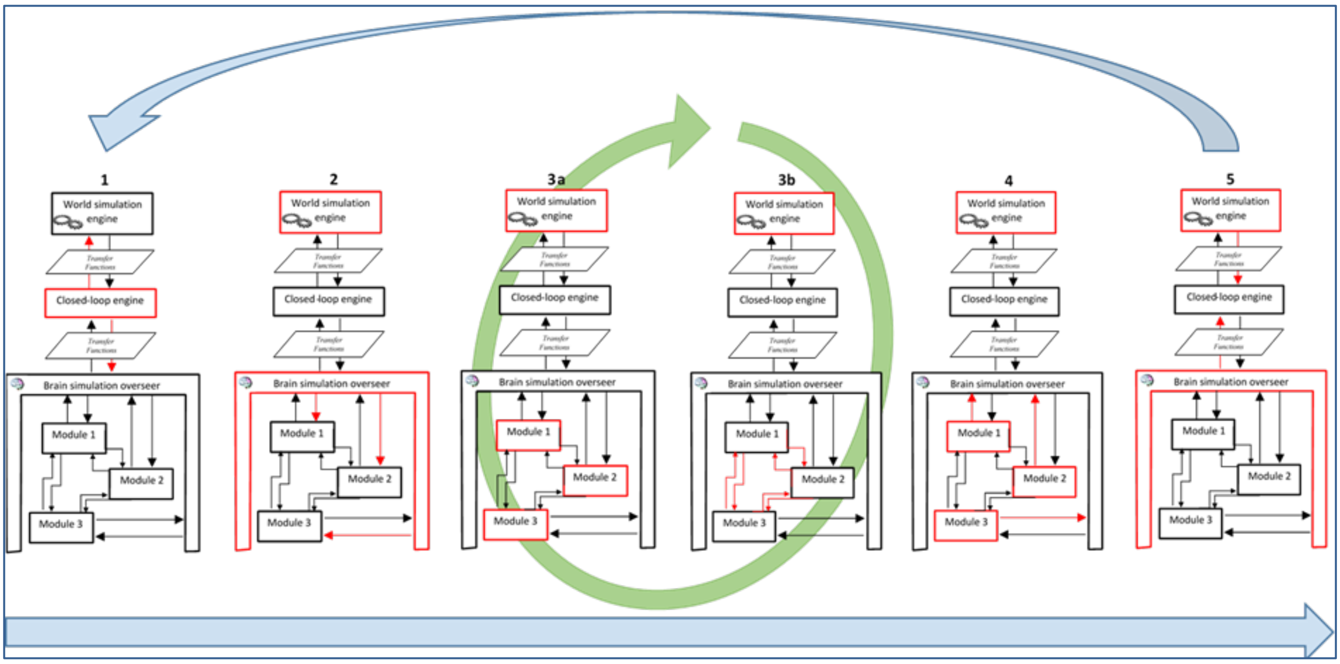

Figure 11: Functional structure of the Integrated Behavioural Architecture (IBA).

This functional structure is inspired by the reference architecture that drives the Whiskeye robot. The red colour indicates where computations happen at each stage. The outer loop (blue arrows) represents the time step of the IBA as a whole, whereas the inner loop (green arrow) represents the individual time steps of the world simulation engine on the one hand and of the modules of the brain model on the other.

The cognitive architecture is used inside the NRP with a Whiskeye model to develop a novel visuotactile self-localisation and mapping (SLAM) algorithm that we call ViTa-SLAM. With the latter, our ambition is to go beyond the state of the art (e.g. the RatSLAM model), by accounting for additional sensory modalities on top of the visual one. We used the NRP to study how sensing information accrued from long- and short-range sensing can be utilised to perform optimally. We confirmed that we could reproduce the shortcomings of the vanilla RatSLAM in the NRP (for example, visual ambiguity led to ambiguity in actual pose estimation, which in turn led to incorrect loop closure and misaligned experience map), thus providing a baseline against which ViTa-SLAM could be compared.

5.1.3 Output 2: Development of multi-component integrated visual model

This work relates to Component SGA2-C2526.

We used the NRP to connect and simulate several models for different functions of human vision into a coherently running system (Figure 12: a segmentation model, a retina model and a saliency model) and to explain advanced results in visual perception, namely visual crowding. We used the NRP to reproduce the visual stimuli involved in representative crowding paradigms and to observe the models' responses. The results produced by the NRP simulation showed that our segmentation model not only explained crowding better than the traditional models (Doerig *et al.*, PLoS Comp. Biology 2019), but that it was also able to produce inward-outward anisotropy (a well-known feature of crowding that is not explained by any traditional model, see Figure 13), provided it was incorporated into a more realistic visual system.

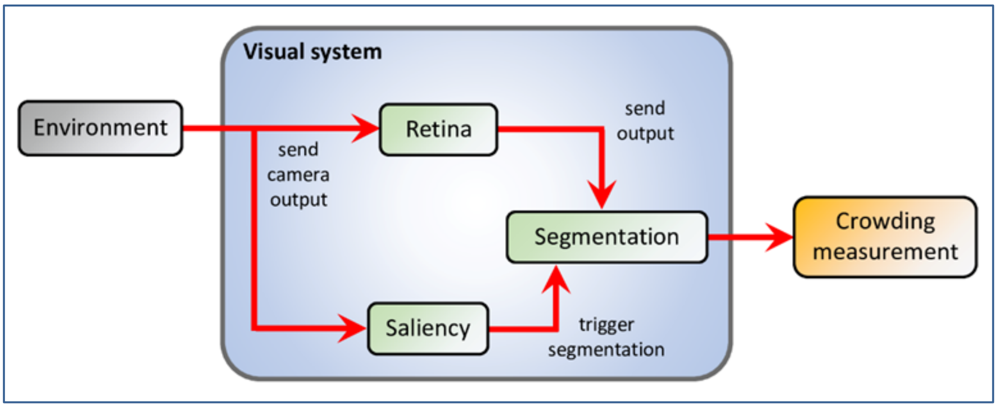

Figure 12: Schematic representation of the visual system implemented on the NRP

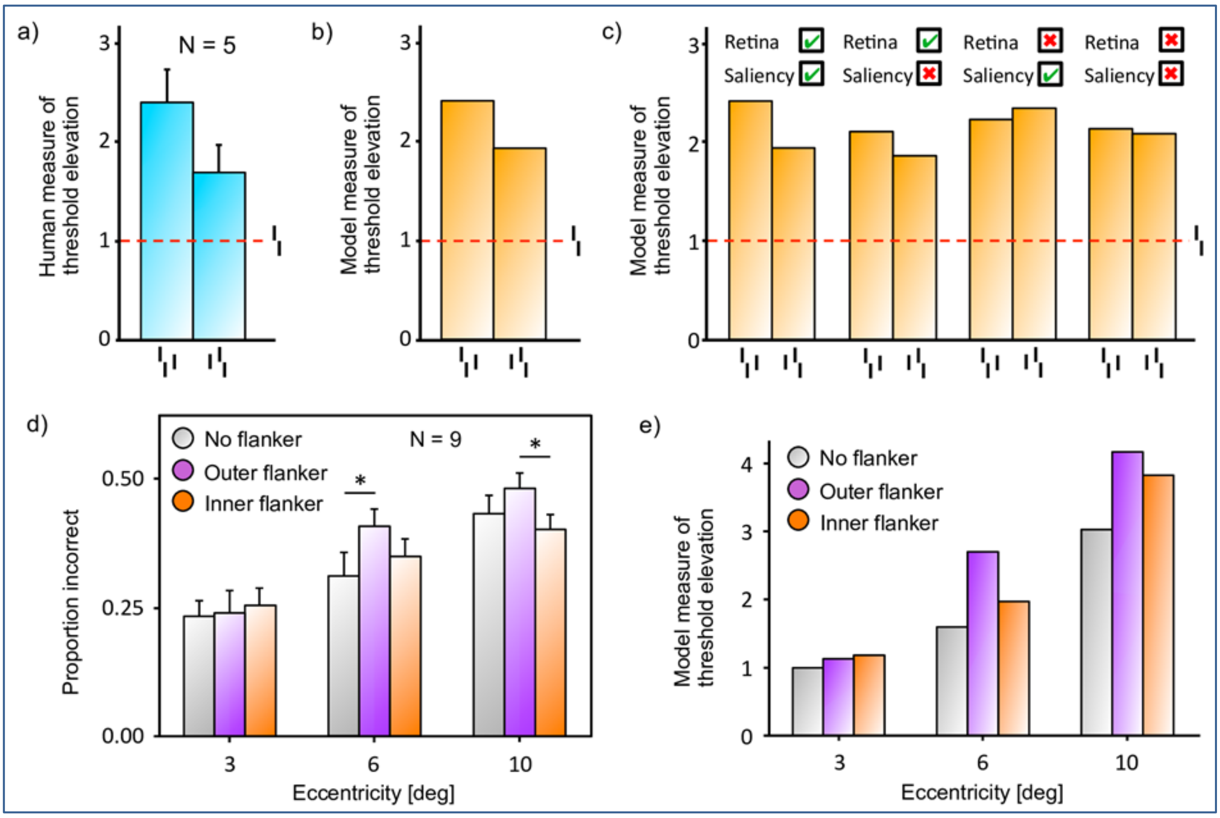

Figure 13: Comparison of results from simulation and experiments

a) Behavioural data from experiment 1b in Manassi *et al*. (2012), measuring inward-outward anisotropy in a Vernier discrimination task. b) Simulation results obtained with the full visual system (retina, saliency and segmentation), reproducing all conditions of the original experiment of a) on the NRP. The model fits the human data well. c) Comparison of the simulation results with and without the activation of the different modules of the visual system. The best fit comes from the full visual system. The NRP supports this kind of very useful comparison, as it allows de-activating a module simply by commenting one single line of code. d) Data from experiment 5 of Farzin *et al*. (2009), measuring inward-outward anisotropy in a Mooney face discrimination task. e) Simulation results obtained with the full visual system. The model fits the data well.

Additionally, by simulating the same visual system on the NRP, we were able to provide a new explanation for a different feature of crowding (uncrowding). On the basis of these simulation results, we made predictions for new uncrowding paradigms involving attention that we are currently testing on humans in our laboratory.

5.1.4 Output 3: Force control of complex motions with the cerebellum

This work relates to SGA2-C2942.

We compared plausible control architectures, in which spiking cerebellar inverse model (for force control) and forward model (for state prediction) are combined together as a hybrid force feedback architecture [9], for simple robotic control tasks involving force control (see Figure 14.a). A spiking cerebellar model (developed by the HBP's SP6 and the Cerebnest Partnering Project) was simplified in terms of size of the neural populations and number of plastic synapses, and integrated into NRP. The NRP enabled us to drive the model with sensory input-carrying information about the robot state instead of using random spike trains. This model was topologically adapted to deal with task-relevant higher-dimensional inputs, and we also modified signal transmission at the level of the inferior olive in order to optimise the angular position error during movement execution.

The robotic task consisted of performing an eight-shape figure with the end-effector of the Fable robot module. A weakly-tuned feedback controller was used to maintain the initial stability of the system. The cerebellar-like adaptive controller was tasked with adding corrections to complement the weakly-tuned static controller. The system performance was recorded and saved with the NRP toolchain. Results show that the cerebellar control led to a reduction of errors by up to 30% (Figure 14c). This suggest that cerebellar computations on both forward and inverse kinematics may enhance closed-loop performance of less precise control schemes.

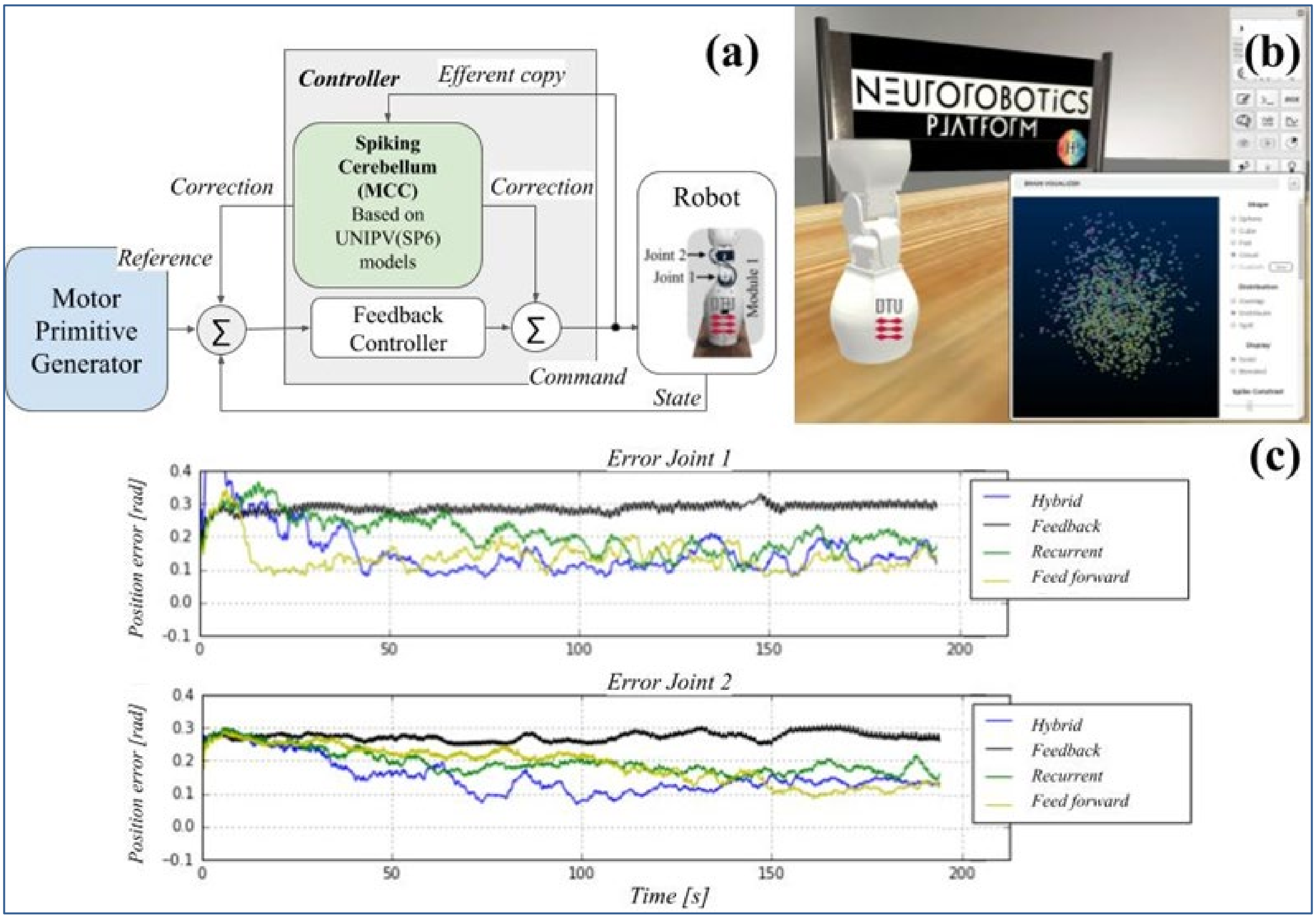

Figure 14: Control architecture and experimental results

a) Hybrid control architecture including the spiking cerebellar-like component. b) Fable robot simulated in the NRP. c) Comparison of experimental results of 4 different architectures: Feedback (includes only the feedback controller); Feed forward (includes the feedback and the feed forward cerebellar-like controller contributions); Recurrent (includes the feedback and the recurrent cerebellar-like controller contributions); Hybrid (merges the recurrent and feed forward configuration of the cerebellar-like controller together with the feedback action (see a)).

5.1.5 Output 4: Target reaching with spiking neural networks

This work relates to Component SGA2-C2582.

We developed a spiking network that controls a robot arm to go to different targets using motor primitives. We avoided the complexity of calculating the inverse kinematics and doing motion planning, and instead used a combination of motor primitives. Our novel bio-inspired architecture was able to perform target reaching with a robot arm without planning, and it did so with spiking neural networks, which is original. The spiking networks provided a representation of motions in a hierarchy of motor primitives (Figure 15). Different correction primitives were combined using an error signal. We carried out virtual experiments with a robot arm to cover the working space extensively by going to different points and returning to the start point. We also carried out experiments to test extreme targets and random points in sequence.

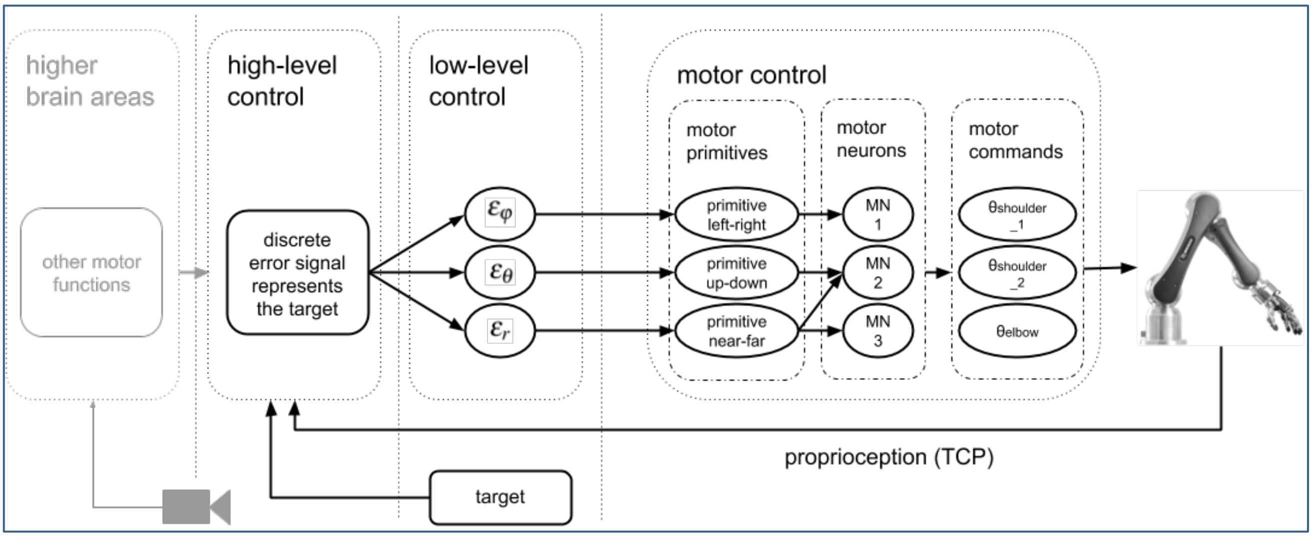

Figure 15: Control architecture with spiking neural networks

Details of the control SNN with all layers and populations in the closed-loop scenario. A motor control hierarchy is used to represent the motions and the activation. The robot receives commands from the motor control layer, where the primitives and output populations for each joint are. The different motor primitives — left–right, up–down and far–near — are activated form the low-level control layer, where populations represent the discrete error signals that drive the primitives.

5.2 Validation and Impact

5.2.1 *Actual Use of Output(s)*

The outputs of this work are being used in the strategic experiments of SP10 (summarised in an additional Deliverable "SP10 strategic experiments SGA2", not yet added to SGA2 GA) to provide virtual agents simulated on the NRP with advanced cognitive abilities (navigation, situational awareness, anticipation, etc.). They provide important input to the current discussions inside the HBP about planning the next phase of the Project.

5.2.2 *Potential Use of Output(s)*

The aim of this work is to provide the tools required to understand how interactions between various brain areas enable human cognitive functions, by emulating the architecture and operation of the brain, and by investigating the significance of the underlying mechanisms as the brain performs cognitive tasks. The modular nature of the proposed IBA will therefore enable neuroscientists to compare models of a given area or function by swapping them inside the IBA and running comparative simulations of well-defined virtual tasks. We have already designed experimental setups that address navigation, as well as reaching and grasping tasks, and we believe these should be of interest to a large community in neuroscience (see additional Deliverable "SP10 strategic experiments SGA2").

Furthermore, the insights derived from this approach will be applied to address open challenges in robotics for which robots currently lack the required cognitive abilities (e.g. situational awareness for cobots, adaptability to unforeseen changes in operational task parameters for unmanned vehicles, etc.). The IBA will be used to benchmark possible solutions in simulation, before transferring these results to physical robots. Here also, the experimental setups that we have already established are highly relevant and should be of interest to a large community in robotics.

5.2.3 *Publications*

The main publications for this Key Result are:

- Doerig, A., Bornet, A., Rosenholtz, R., Francis, G., Clarke, A. M., and Herzog, M. H. (2019). Beyond Bouma's Window: How to explain global effects of crowding? PLOS Comp. Biology. (Accepted)
    - This publication integrates many of the results obtained with the NRP during SAG1 and SGA2 on the phenomenon of crowding (Output 2). This will provide a visual module for the IBA that should be of interest for the future implementation of cognitive tasks where visual clutter plays a role.
- S.Tolu, M. C. Capolei, Learn, predict, adapt: the combination of forward model-based control and cerebellar recurrent theory. Neural Control of Movement (NCM) annual meeting at the Toyama International Conference Centre, 23rd - 27th of April 2019 (Accepted).
    - This publication summarises a novel theory of cerebellar function (Output 3), the investigation of which was made possible by the NRP. This will provide a module for the IBA that should be of interest to a large number of researchers.
- Tieck, J. C. V., Steffen, L., Kaiser, J., Reichard, D., Roennau, A., & Dillmann, R. (2018). Controlling a robot arm for target reaching without planning using spiking neurons. In 2018 IEEE 17th International Conference on Cognitive Informatics & Cognitive Computing (ICCI* CC). DOI: https://doi.org/10.1109/ICCI-CC.2018.8482049 (PLUS ID: P1504).
    - This publication demonstrates the use of spiking neural networks to achieve target reaching through composition of motor primitives (Output 4), which is a promising avenue for applications in robotics due to its simplicity of implementation. This publication received the best paper award at the conference at which it was presented.

6. Key Result KR10.4: Improved NRP

6.1 Outputs

6.1.1 Overview of Outputs

The Neurorobotics Platform had two version releases in this first year of SGA2, called 2.1 and 2.2. Each came with different types of improvements.

The 2.1 release (November 2018) came with high-value new features, such as support for the Nengo brain simulator (output 1), easy Docker-based installation (Output 2) and a new web cockpit design (Output 3).

The 2.2 release (March 2019) had less new features, but offered progress on very important topics like the Joint Platform-related convergence with the large SP7 HPC cluster Piz Daint (Output 4), or the Joint Platform-related convergence with SP5's Knowledge Graph and SP6's Brain Simulation Platform (Output 5).

Aside from the releases, interesting research results have been achieved on the field of virtual reality, via the porting of the NRP into University Weimar's immersive VR system and the resulting ability of users to embed themselves into the experiment and interact with objects and robot (Output 6).

6.1.2 Output 1: Nengo simulator support

Related Components: SGA2-C10.4.2.2

The Neurorobotics Platform supports Nengo as a brain simulator, as shown in Figure 16. The Husky robot controlled by a Nengo brain Nengo is a population-based spiking neural simulator that has many advantages over more detailed simulators. It is faster, its user API is more concise and easier to grasp and it provides many examples and tutorials. The benefit for the NRP is the potential inclusion of a large Nengo user community and the new, less fine grained, types of experiments, that are possible with this simulator.

Another significant benefit is that Nengo supports the Intel Loihi neuromorphic hardware natively. Thus, the porting of NRP to Loihi will be possible very soon, which should have a high impact in terms of visibility.

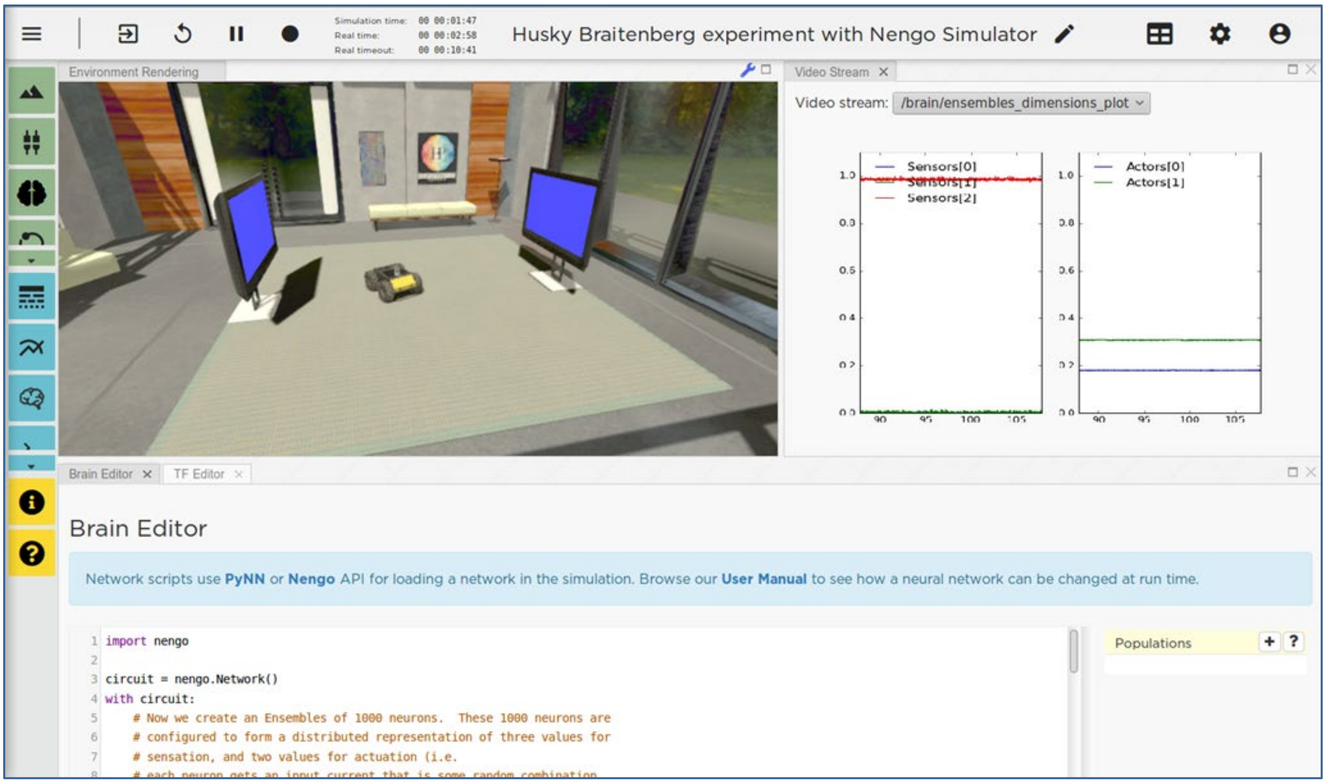

Figure 16: The Husky robot controlled by a Nengo brain

6.1.3 Output 2: Easier NRP installation

Since Version 2.1, users can use the NRP in four different ways. The online Platform or three different brands of local installations:

- Installation from source (tedious)
- Installation or boot from live USB image
- New Docker installation

All installation types are described on our website and in Table 2.

The last type has been introduced in Version 2.1 and allows for a 5~10-minute installation on users' computers with one command, assuming that they have Docker installed (straightforward). This new installation type has increased our user base, as NRP statistics report 115 new Docker installations between 20 December 2018 and 13 February 2019 (i.e. in less than two months).

The new Docker installation is auto-updated and reports statistics about user installs and updates.

Table 2: Comparison of the various available versions of the NRP

	Online demo	Online platform	Local install (docker)	Source install	Live USB image
Pros	• Online, no installation • Public, no account • Interactive • Totally automated, no prior knowledge needed • Commented, self-explanatory	• Online, no installation • Always up-to-date, no maintenance • Decent number of template experiments • Servers available 24/7	• Easy installation • No software dependencies • Works on Linux, Windows and Mac • Isolated from your other software • Runs 100% on your computer • Auto-updatable • Access to lower-level tools still possible by accessing containers	• Full flexibility • Completely extendable and tunable • Easily updatable	• Works on all USB bpptable computers • No installation required • Customizable and persistent on USB storage • Easily updatable
Cons	• Restricted to a few demo experiments • Usable only for demo and discovery purposes	• Impossible to add additional python packages for use in transfer functions • Impossible to upload custom Gazebo plugins (yet)	• Changes in containers are lost on updates (not in Models or Experiments folders though) • Update might fail if Models or Experiments have been too much hacked • Customization is possible but tedious inside container	• Tedious installation, many dependencies • Works only on Linux Ubuntu • Might conflict with existing software • Has to be kept up-to-date manually	• Image is updated only on major releases • Discontinued from 2.2 • Does not work on all computers • Keyboard and Wifi support are random • Slow startup, deüending on USB hardware
Installation time	0	0	5-10 min	3 hours	15 min
Recommended for	Presentations, discovery	Seminars, courses, prototyping	Most users with a powerful computer	Code contributors	Demos, courses

6.1.4 Output 3: New web cockpit design

As of Version 2.1, the Web Cockpit design has been changed according to the design proposal made in SGA1. The new design features a flexible view management system and a comprehensive vertical toolbar with buttons grouped by categories, as shown in Figure 17. The views can now be arranged as wished without hiding each other; they can also be distributed over multiple tabs, made full-screen or minimised, and they can support contextual features. Arrangements can be saved.

In addition, most “save” buttons disappeared and all user code or changes were made persistent, to conform with modern web application design practice.

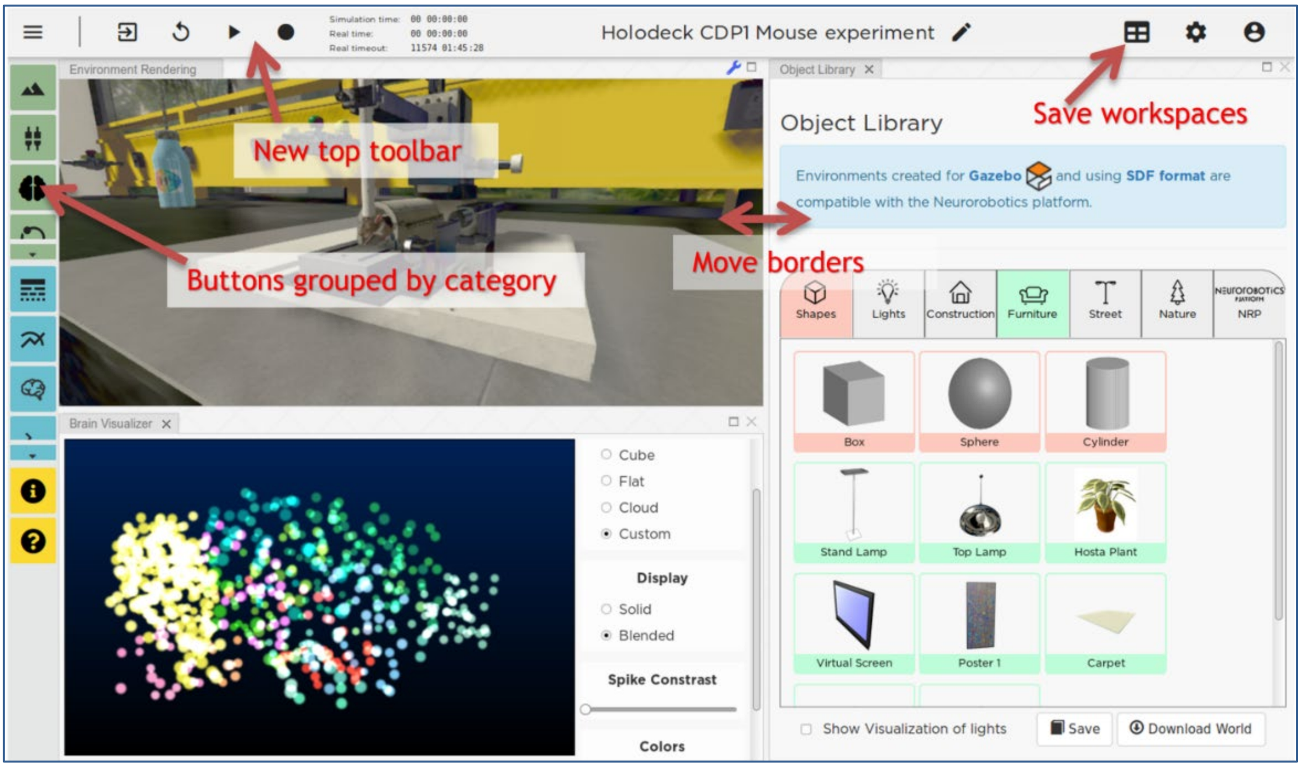

Figure 17: New design of the web cockpit

6.1.5 Output 4: Joint Platform NRP on Piz Daint cluster

The porting of the NRP onto SP7's huge CSCS Piz Daint cluster started in SGA1 but was initially rather unsuccessful. In SGA2, because it is now a more concrete Joint Platform objective, progress is much better controlled and measurable. We have a comprehensive road map that covers the whole of SGA2 and ends with the complete dynamic spawning of NRP back ends in Piz Daint and the parallel execution of NEST on multiple Piz Daint nodes. This final objective is called "Step 4" in our jargon.

In Version 2.1, we reached "Step 1" which was about being able to spawn a single backend on a Piz Daint node from a single frontend virtual machine. This was achieved, despite very difficult networking and security issues. We now have a frozen stable prototype for this use case.

In Version 2.2, "Step 2" will be reached, which will allow NEST to be run in parallel (multi-process) using the same standard MPI library that runs on Piz Daint, inside the "Step 1" single backend node.

Future releases will focus on opening external nodes to NEST processes and scaling up.

6.1.6 Output 5: Joint Platform NRP-BSP-NIP convergence

The first year of SGA2 has seen the start of convergence between the Neurorobotics Platform, the Neuroinformatics Platform (NIP) and the Brain Simulation Platform (BSP). Version 2.2's goal is to create a basic prototype showing how a simplified (NEST) model from the BSP can be referenced into the NIP's Knowledge Graph and from there be browsed from within the NRP and connected to robots. It should be possible to reference results of the simulation back in the NIP's Knowledge Graph and make them available to BSP users.

The first significant results of this work is a specification for data exchange between the platforms and a detailed use case work flow, as shown in Figure 18.

- NRPJP-54 Find a suitable demo simplified model
- NRPJP-52 NIP: Integrate models and NRP experiments in search UI
- NRPJP-50 BSP: browse NRP logs by detailed circuit
- NRPJP-49 NRP: Create a spike CSV log KG instance and register
- NRPJP-48 NRP: Create a KG schema for NRP simulation results
- NRPJP-51 NRP: Investigate a relevant demo experiment
- NRPJP-47 NRP: dynamically copy the hyppocampus
- NRPJP-46 NRP: select a precopied simplified model
- NRPJP-45 NRP: From the brain library, display available KG brain models
- NRPJP-53 BSP: Create the schema for simplified models
- NRPJP-44 BSP: Register simplified model in the knowledge graph
- NRPJP-31 Write a higher level basic use case including NIP
- NRPJP-30 Play with Nexus
- NRPJP-32 Provide Nexus schema for our brain files

Figure 18: List of user stories in the NRP-BSP-NIP epic

The blue tick boxes indicate that the user story has been completed.

6.1.7 Output 6: Collaborative immersive virtual reality

It is now possible to run the NRP on the high-fidelity immersive system at Bauhaus-Universität Weimar and to interact with objects and robots while being in the 3D scene and seeing other users from remote locations. The avatars are the reconstructed bodies of the real users, so they can recognise each other immediately. The interactions are done through hardware devices like a navigation sphere and virtual "laser" pointers that can move objects around which the simulated robots react to, as shown in Figure 19. In our next step, we will enable simulated robots to react directly, in real-time, with the reconstructed user bodies in their environment.

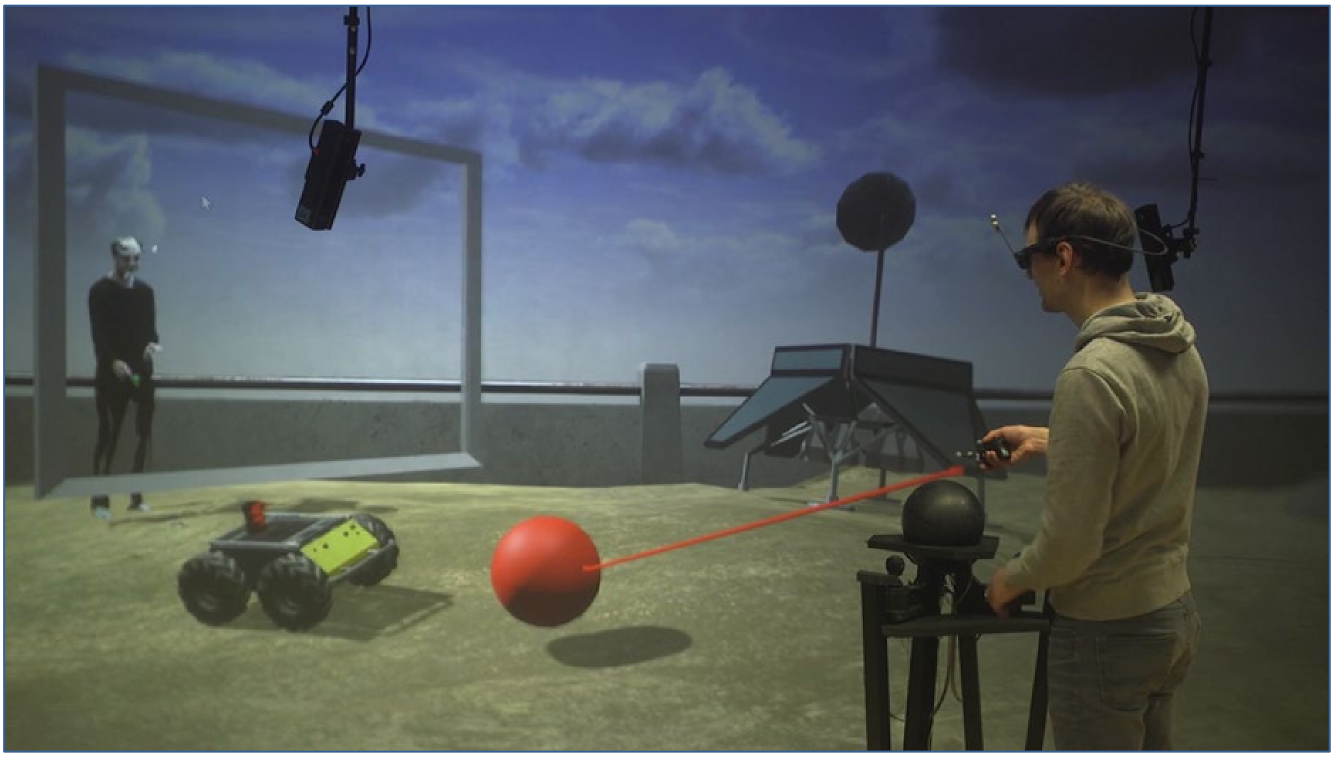

Figure 19: A local and a remote user immersed in the NRP

6.2 Validation and Impact

6.2.1 Actual Use of Output(s)

The easier installation has definitely increased our user base, as 115 installations were reported in just two months. The new web cockpit design has many advantages, including the ability to save custom view layouts and providing a cleaner management of views that enables the user to focus more closely on the actual simulation control. The Piz Daint NRP prototype ("Step 1") is an important step forward after the delays accumulated in SGA1, which raises hopes of being able to offer a fully distributed Platform by the end of SGA2.

The initial specification of the NRP-BSP-NIP convergence serves today as a reference for the three Subprojects concerned (SP5, SP6 and SP10) to implement their Joint Platform efforts on a common basis.

6.2.2 Potential Use of Output(s)

Providing support for Nengo is most certainly opening the NRP up to a whole new community of users who prefer coarser-grained brain models than NEST and PyNN users. Secondly, support for Nengo opens the door to support for Intel's Loihi neuromophic chip (since the latter can be programmed using a Nengo backend), which has the potential to dramatically increase the HBP's visibility and impact.

The immersive high-fidelity system should have a very important impact. When completed, it will enable users to influence a simulation via intuitive human interaction and, thus, allow exploration of human-robot interaction and learning.

6.2.3 Publications

The main publication for this Key Result is:

- "The Collaborative Virtual Reality Neurorobotics Lab", Carl Matthes *et al.*, IEEE VR 2019 proceedings
    - Linked to output 6, this publication introduces the NRP and its new VR capabilities to a large audience at a major conference for the VR community.

6.2.4 Measures to Increase Impact of Output(s): disseminations

The main dissemination measures for this Key Result were:

- Fortiss open day on October 9th, 2018: presentation of University Ghent's Tigrillo robot with gait learning in the NRP.
- Press article in Germany's Welt generalist newspaper: "*Bayerisches Zentrum für Künstliche Intelligenz eröffnet*", 9 October 2018.
- User workshop at University Ghent on 8 February 2019: small hands-on session with the NRP with master students

7. Key Result KR10.5: Modular neural motor control for robots under real-time constraints

7.1 Outputs

7.1.1 Overview of Outputs

Research into neuronal motor control for robots explores real-time capable distributed neuronal methods to control intricate robotic actuators, such as typically found in compliant systems or soft robotics. The overarching goal of the involved research groups is to provide the complete set of expertise and tools required to accurately actuate such novel robots, for long-term use in human-safe interactions and/or in neuro-prosthetic devices. In pursuit of this goal, we report on real-time execution of large-scale neuronal models on neuromorphic hardware (Output 1, Section 7.1.2); dynamic control of soft actuators (Output 2, Section 7.1.3); and self-adaptation and modular control of compliant actuators (Output 3, Section 7.1.4). All efforts are directed towards a common demonstrator (SP10 Demonstrator #7), to be presented by the end of SGA2 (see Section 8).

7.1.2 Output 1: Neuromorphic Computing for Compliant Robots

This work relates to Components SGA2-C2559, SGA2-C2561, SGA2-C2536

This work employs SP9's SpiNNaker neuromorphic computing platform to control physically compliant robotic manipulators composed of myo-muscles, both in simulation in the NRP and as a real-world real-time system with environmental interactions. The myo-muscular system has been modelled in the NRP, ranging from individual muscles to complex multi degree-of-freedom robotic arms (e.g. a shoulder and elbow combination with a total of 13 DOF), which will be made public in a future release of the NRP in SGA2. Regarding the integration of neuromorphic computing hardware, the SpiNNaker interface board developed in SGA1 now seamlessly provides sensor data at >= 1M Event-packet per second from the physical robot into a real-time network execution on SpiNNaker, and propagates motor commands to the multi-DOF robot arm. Significant hardware and software updates in both, the board's firmware and in the SpiNNaker programming environment have been undertaken to increase the bandwidth and ease of configuring the system. Multiple revised boards have been shipped to partners within and outside of HBP. The developed neurocomputing/neurorobotics environment will be applied in the upcoming SpiNNaker workshop on "Neurorobotics on SpiNNaker", to be held in Manchester, 9-13 September 2019.

7.1.3 Output 2: Cerebellar principles for saccade generation

This work relates to Components SGA2-C2566.

A mathematical model (Figure 20) was previously constructed to decode the role of cerebellar plasticity in preserving the optimality of fast eye movements, called saccades. On this basis, we developed a model of multimodal sensory representation for object classification. More details can be found in Kirtay *et al.* (2018).

We modelled the bidirectional plasticity at the parallel fibre to Purkinje cell synapses that can account for fast movement characteristics. We provided a mathematical and a humanoid experimental demonstration of how the equations governing the cerebellar plasticity are determined by the desirability of the behaviour.

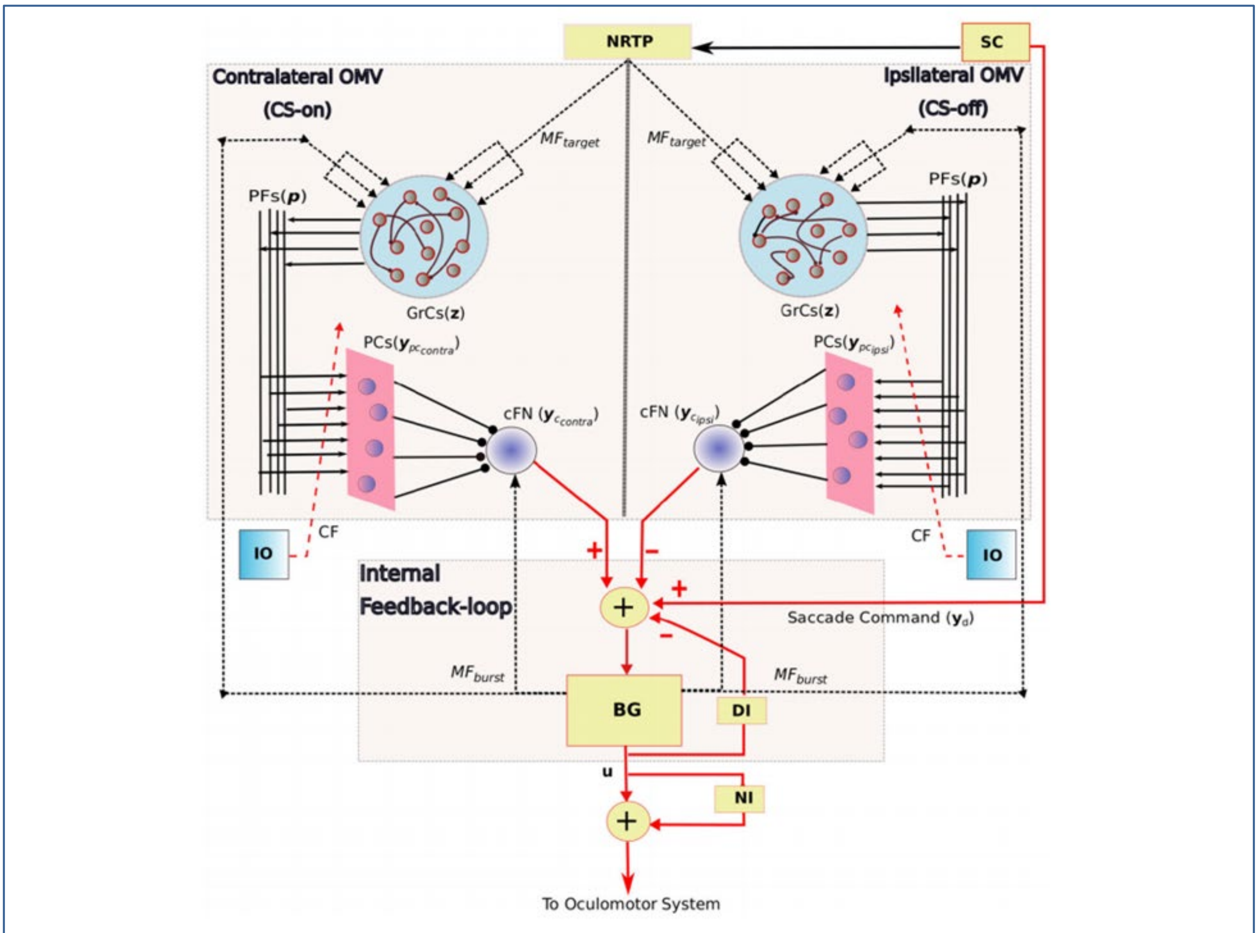

Figure 20: Bilateral organisation of the OMV and its connectivity with the internal feedback loop in saccadic production

In this model, the brain-stem takes motor error during the movement as input and produces a proportional burst as velocity commands to the pre-motor circuitry. The cerebellum modulates the input to the brain-stem. For validation of the proposed cerebellar learning principles, we implemented the saccade adaptation task on a model of biological eye, iCub humanoid robot, and a soft-robot arm simulation.

For the saccade adaptation task, we performed adaptation from scratch, which involved incremental learning in the cerebellar block. We used a target jump paradigm, (Figure 21), to compare model saccade experiments to biological results. Adaptation results on sample test targets in the healthy model system are shown in Figure 22. More details can be found in Kalidindi *et al.* (2019) (reference in Section 7.2.3).

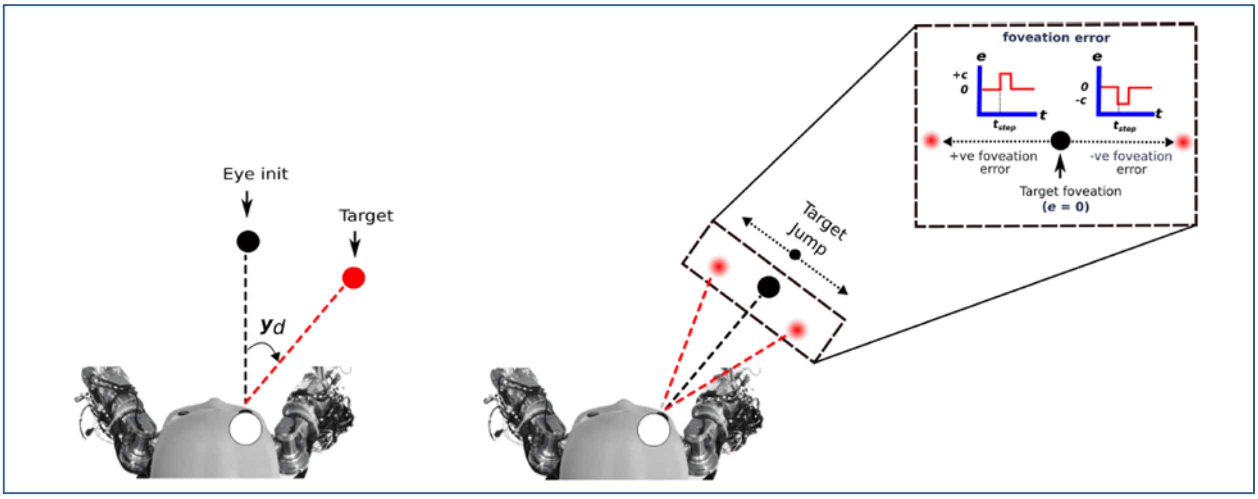

Figure 21: iCub target jump experiment.

The iCub, shown in the left panel, is required to move its eye from initial position (represented as black lines and black circle) to a target location (represented as red lines and red circle), with y_d as desired eye displacement. For details see Khalindi et al. (2019).

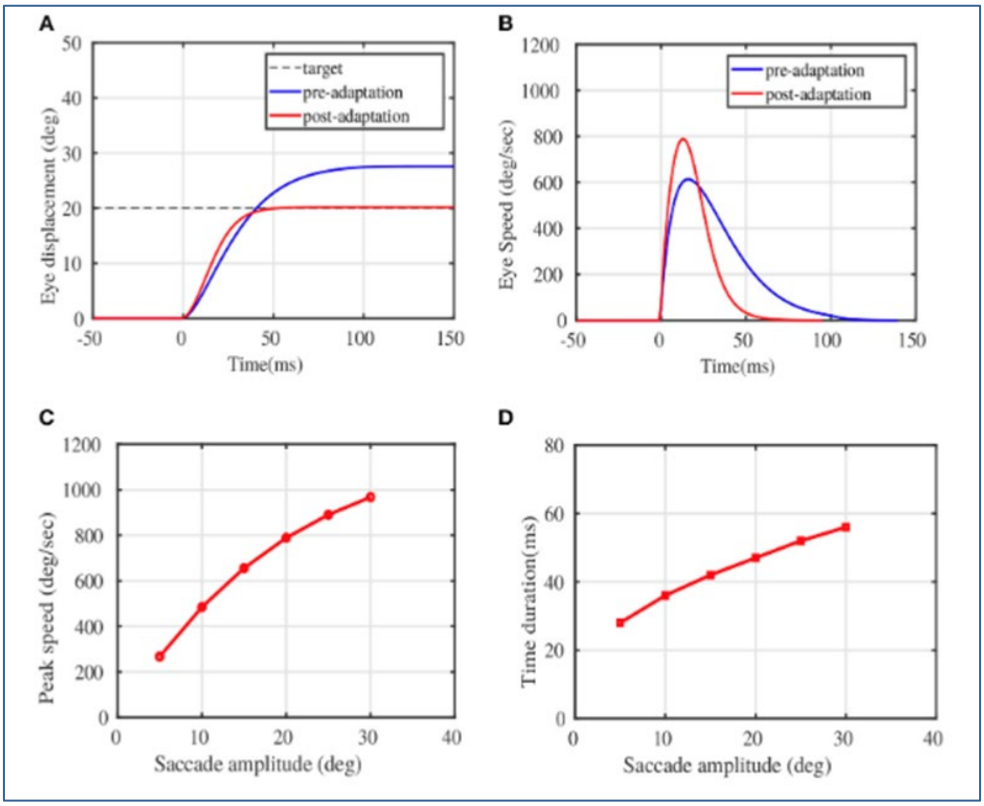

Figure 22: Adaptation results on sample test targets.

(A) The displacement of eye position plotted against the movement time in milliseconds for a given test target of 20 deg. (B) The eye speed trajectory in deg/sec for the same test target of 20 deg. (C) The duration of saccades against magnitude of the target displacements post adaptation. (D) Peak Eye speeds at various simulated target displacements post adaptation.

7.1.4 Output 3: Modular control of compliant actuators

This work relates to Component SGA2-C2563

This investigation focuses on the influence of cerebellum modularity on robotic motor control, particularly in robots that interact with their external environment. We embedded a cerebellum-based control system into a humanoid robot that became capable of handling dynamic external and internal complexity. In particular, we artificially enhanced a canonical cerebellar microcircuit (CCM) with plastic synapses, of the type found on Mossy fibres-Granular cells, Parallel fibres-Purkinje cells, Inferior Olive-Parallel fibres, Purkinje cells-Deep Cerebellar Nuclei, Mossy fibres-Deep Cerebellar Nuclei and Inferior Olive-Deep Cerebellar Nuclei. The synaptic weights in the CCM were adjusted by combining machine learning and computational neuroscience techniques. The CCM was also used as a point of comparison for the spiking cerebellar model (see Section 5.1.4).

Different CCMs were combined to form the modular cerebellar circuit (MCC). The neural connections and the sensorimotor signals processing among CCMs was investigated with the aim of getting insights about the modularity of the cerebellum. The overall design of the neural control system (Figure 23-a) consisted of a static weakly tuned controller, to keep the system marginally stable initially, and of the MCC, representing the adaptive bio-mimetic component. The control system was tested on the humanoid robot iCub simulated in the Neurorobotic Platform (NRP) (Figure 23-b) with a standard robotic task.

During the experiment, the robot was requested to follow a reference movement planned by the motor primitive generator; the three controlled joint of the right arm was actuated with torque commands. The robot had a board attached to the right hand, and during the simulation a ball was launched on the board and left free to move. The robot was supposed to simultaneously control the external objects dynamics and the force exerted by the robot arm to follow the requested trajectory. The purpose of considering such heterogeneous stochastic dynamical stimuli was to test and examine the activation of incremental learning and adaptation of the MCC controller and at the same time to confirm its coupling with the feedback action.

The control system was analysed in four different test cases: with (without) cerebellum, with (without) perturbations; with (without) cerebellum, with (without) perturbations. The results concerning the three controlled joints proved that the cerebellum-like controller boosted reactiveness and robustness to stochastic perturbation of the system. In Figure 23-c, the mean absolute angular position error (MAE) dropped drastically when the MCC correction was active. The experimental results showed that the performance of the overall neural controller was significantly affected by the specialisation of each CCM and the connections among them.

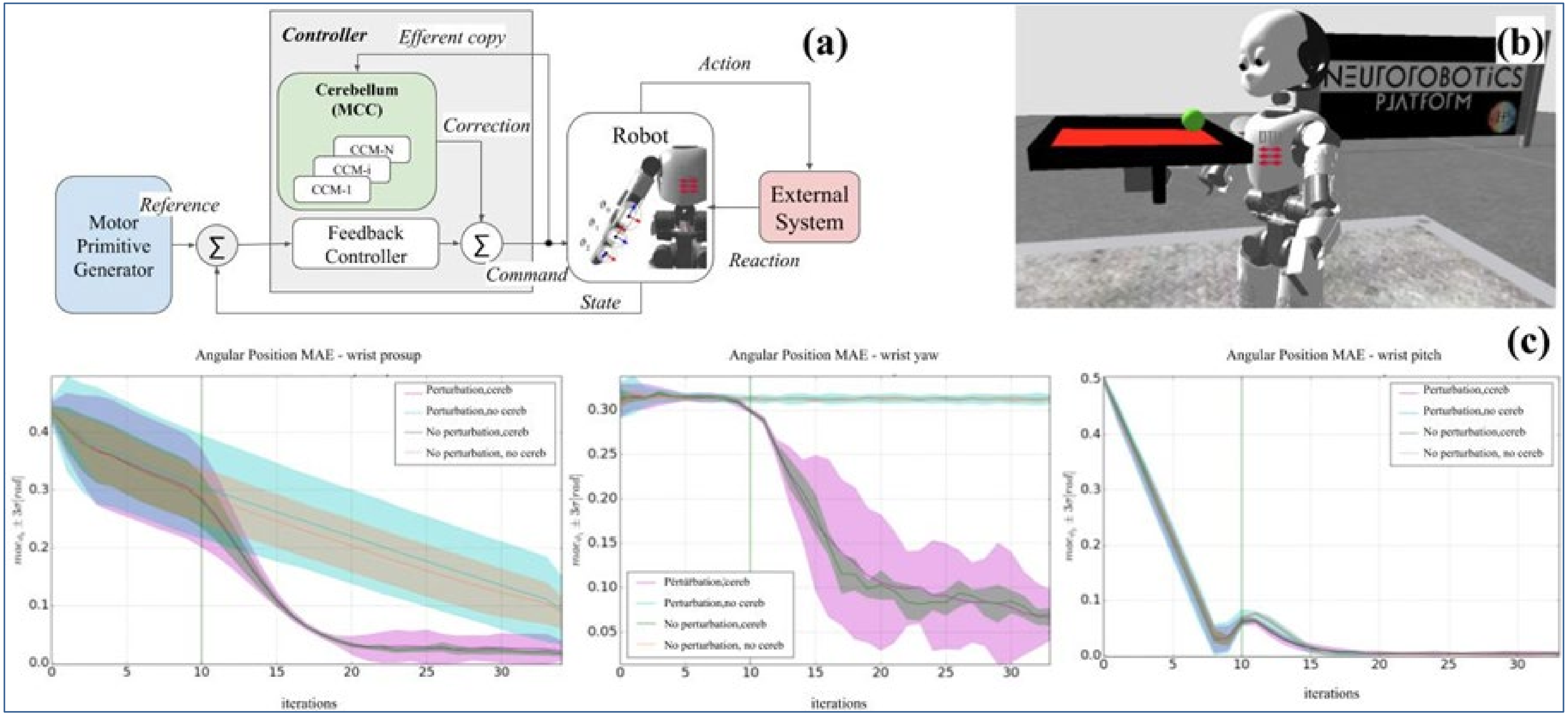

Figure 23: Control architecture, implementation and results

a) Cerebellum-based modular control. b) The virtual humanoid robot in the Neuro-robotic Platform. c) Mean absolute angular position error of the three controlled joints during the 4 test cases.

7.2 Validation and Impact

7.2.1 Actual Use of Output(s)

The SpiNNaker IO board is widely used within HBP (SP9 and SP10), and by selected external partners. It is a key component for real-time high-bandwidth data exchange between SpiNNaker and robotic systems.

The models from KR10.5 Output 2 and 3 are in use for the respective robots and have been used during workshops, summer-schools and scientific meetings. This enables us to provide colleagues working on modelling with concrete feedback regarding functional performance, and is an essential activity to drive adoption of neuromorphic hardware for embedded applications on real robots.

7.2.2 Potential Use of Output(s)

The SpiNNaker IO board will be used for educational purposes (e.g. during the Workshop on neurorobotics on SpiNNaker, Manchester, September 9-13, 2019).

Controllers based on motor feedback have much potential for use in future (industry) robotic settings, where modular and compliant robot control will be key to allowing safe human-robot interactions, e.g. in on-demand industry production (industry 4.0), right up to exoskeletons and/or neuro-prosthetic devices.

7.2.3 Publications

The main publications of this Key Result are:

- Kirtay, M., Vannucci, L., Albanese, U., Falotico, E. and Laschi, C., Multimodal sensory representation for object classification via Neo-cortically inspired Algorithm. International Conference on Development and Learning and Epigenetic Robotics (ICDL-EpiRob 2018).
    - Linked to Output 2, this publication presents results on multimodal object recognition that can be re-used in many visuo-guided manipulation tasks (see Kalidindi *et al*. below).
- Capolei M, Falotico E, Hautop Lund H, and Tolu S., Distributed and Modular Bio-Inspired Architecture for Adaptive Motor Learning and Control. Conference Abstract: School of Brain Cells and Circuits" Camillo Golgi" — Ettore Majorana Foundation and Centre for Scientific Culture, Erice (Italy), Dec. 2018. Abstract accepted for publication in Frontiers Computational Neuroscience.
    - Linked to Output 3, this publication demonstrates that the performance of a distributed neural controller is largely affected by the specialisation of each canonical cerebellar microcircuit (CCM) and the connections among them. Therefore, it confirms that modularity of the cerebellum circuit plays an important role in the optimisation of motor control.
- Kalidindi HT, Thuruthel TG, Laschi C, Falotico E. Cerebellum-inspired approach for adaptive kinematic control of soft robots. IEEE RoboSoft 2019 (accepted).
    - Linked to Output 2, this publication demonstrates the versatility of the cerebellar model developed for saccade control. It demonstrates the capability of this model to provide complex robotic platforms (soft robots) with adaptive motor capabilities in reaching tasks.

7.2.4 Measures to Increase Impact of Output(s): disseminations

Demonstration of models and systems during SP10 and HBP workshops, providing access to hardware (SpiNNaker interface) and documentation during workshops, such as the CapoCaccia Workshop on neuromorphic engineering or the SpiNNaker user workshop, Manchester.

8. Conclusion and Outlook

The Key Results presented above address many different areas of research and exhibit varying degrees of maturity. KR10.4 (the NRP itself) holds a central position around which other KRs will remain articulated. In the final year of SGA2, work will progress at an increased pace on this platform in order to be ready for any scenario concerning the continuation of work in SGA3. The concrete implementation of workflows connecting the NRP to the other HBP Platforms will provide the core of the future HBP EBRAINS Joint Platform and is therefore a critical step. For this to happen as planned, usability and stability of the NRP will have to be improved, which will set the course for SP10 software development activities in the coming months.

KR10.2 is nearing its final release. No additional design work on hardware (mechanical design, electronics, etc.) will be performed after Version 4.0 unless absolutely necessary (e.g. to correct unforeseen structural issues). Instead, the second half of SGA2 will see ourselves and our partners (inside and outside HBP, since we already have one Partnering Project specifically for this purpose) using the robot rodent in conjunction with its virtual twin on the NRP in order to investigate various questions of major interest for neuroroboticists, such as gait control and transfer learning. This will be an important demonstration of how the NRP supports virtual prototyping and transfer learning from simulated to actual robots and, as such, will be something we look forward to showcasing to potential industrial partners in the field of robotics.

KR10.1 presents our advancements in simulating locomotion and stroke rehabilitation, focusing on models of the spinal cord and their interactions with both proprioceptive signals and efferent motor signals from the brain. It has produced top-level publications and supports an important translational aspect of the work carried out in SP10. This work is essential for any *in silico* approach of embodiment that deals with motor control. It is worth mentioning that, even if the developed spinal cord models share main components (muscle spindle, motor neurons and interneurons), they have been built to reproduce different behaviours, both oscillatory (e.g. locomotion with central pattern generators), and non-oscillatory (e.g. reaching/pulling). Both implementations of these models are being tested with the aim of reproducing realistic neurophysiological activity and represent the state of the art in their respective domain.

KR10.1, KR10.3 and KR10.5 will feed into SP10’s experimental work in SGA2, as described in the additional Deliverable “SP10 strategic experiments SGA2” produced by SP10 earlier this year. This document describes seven demonstrators (our “strategic experiments”) that SP10 uses to integrate neuroscience and neurorobotics research with the development of the NRP. To summarise, demonstrators 1-3 establish neuroscientific tools for improving brain models by replicating neuroscientific experiments and simulate cognitive architectures; demonstrators 4-7 aim to demonstrate the generation of complex behaviours (navigation, object manipulation under dynamically changing conditions). As they are built around the three aforementioned Key Results, these demonstrators exhibit a large degree of overlap.

Experiments 1-3 rely essentially on KR10.1. The first two demonstrators focus on motor control in rodents in the context of reaching and grasping tasks. Both experiments use the same rodent and spinal cord models and both experiments were originally conceived to study motor learning before and after a topical stroke in the motor cortex. The third experiment focusses on modelling locomotion in rodents (and humans) in the context of spinal cord injury treatment. Several high-profile papers were published last year, illustrating the success of our modelling approach (e.g. Formento *et al*. (2018), Nature Neuroscience, 21, 1728–1741.).

The next set of experiments focus on higher cognitive abilities in neurorobotic systems and rely on the outputs of KR10.3. Experiment 4 targets sensory guided navigation and goal-directed decision making. In this experiment, mobile robots (e.g., Pioneer 3dx and Whiskeye) perform spatial navigation tasks by emulating the neural circuit of the hippocampus and ventral striatum. Experiment 5 uses similar mobile robots to investigate how the brain cognitive architecture fuses two different streams of sensory information and how it integrates different sensory modalities to obtain an integrated semi-metric map for navigation. In Experiment 6, we study scenarios where a robotic arm performs visually-guided reaching, grasping, manipulation and sorting/placing of objects that are presented in a dynamic manner on a conveyor belt. This will allow us to assess which features of a cognitive architecture are needed to achieve visually-guided adaptive motion control with a view towards robot design for industrial applications.

Finally, experiment 7 is a direct demonstration of KR10.5 and addresses the problem of manipulating an object with initially unknown inertial properties efficiently. Demonstration of performance will be achieved through a goal-directed activity (e.g. by throwing it at a 3D target position) using learned and continuously updated internal models on a physically compliant / soft robot manipulator.

Taken together, these demonstrators will provide a natural path for HBP to link currently separated research lines. In particular, they will underpin the practical implementation of use cases that truly leverage a significant part of the HBP infrastructure as opposed to platforms in isolation. Finally, this will, in turn, produce concrete results and contribute to achieving the type of impact sought by HBP, i.e. progress in neuroscience research and development of new computing paradigms.

Annex A: Component Details

Table 3: Overview of releases and major updates related to Key Result KR10.1

ID	Component Name	Type	Contact	Info on releases and major updates
C2597	Virtual mouse musculo-skeletal model from MRI	Model	EPFL: Auke IJSPEERT	Update: will become a release upon validation by a publication. Code available at: https://gitlab.com/hbp-nrp/Mouse.git
C2601	Integration of sensory models with the musculo-skeletal virtual mouse	Model	SSSA: Lorenzo VANNUCCI / Egidio FALOTICO	Full NRP experiment will be released with paper submission planned in April. Code embargoed until paper accepted for publication
C2608	Simulation of spinal cord neuromodulation therapies for the recovery of locomotion after spinal cord injury	Model	EPFL: Grégoire COURTINE	Validation: publication in journal: https://www.nature.com/articles/s41593-018-0262-6
C2615	Robot-based training in rodents: pulling experiment	Model	SSSA: Lorenzo VANNUCCI / Silvestro MICERA	Full NRP experiment will be released with paper submission planned in April. Code embargoed until paper accepted for publication.

Table 4: Overview of releases and major updates related to Key Result KR10.2

ID	Component Name	Type	Contact	Info on releases and major updates
C2572	Assembly of Robot Rodent	Hardware	TUM: Peer LUCAS	Multiple releases in the first year of SGA2 (see text) Technical specifications: https://collab.humanbrainproject.eu/#/collab/45325/nav/311404
C2573	Development of rodent computing system		TUM: Peer LUCAS	Two releases in M1-M12 Technical specifications: https://collab.humanbrainproject.eu/#/collab/45325/nav/311404

Table 5: Overview of releases and major updates related to Key Result KR10.3

ID	Component Name	Type	Contact	Info on releases and major updates
C2526	Model of visual grouping, segmentation and saliency	Model	EPFL: Alban BORNET	Code available at: https://bitbucket.org/albornet/crowding_asymmetry_nrp.git Validation: publication (Doerig *et al.*, accepted in PLoS Comp. Biol.; DOI not available at time of writing)
C2582	Supervised learning of motion representations	Model	FZI: Camilo TIECK	Code currently embargoed (two more publications planned, one submitted and one in preparation). Validation: publication in conference: https://doi.org/10.1109/ICCI-CC.2018.8482049

C2942	Cerebellar control of complex motions	Model	DTU: Silvia TOLU	Code currently embargoed (two more publications under review). Validation: publication in conference (accepted, DOI not available)
C2943	Experiment design	Report	TUM: Fabrice MORIN	Extended description was made available in the additional SP10 deliverable, see experiments 4, 5 and 6.

Table 6: Overview of releases and major updates related to Key Result KR10.4

ID	Component Name	Type	Contact	Info on releases and major updates
C2585	NRP Closed-Loop Engine	Software	Fortiss: Axel VON ARNIM	Release 2.1 (November 2018) Release 2.2 (March 2019) Code available at: https://bitbucket.org/hbpneurorobotics/cle https://bitbucket.org/hbpneurorobotics/exdbackend https://bitbucket.org/hbpneurorobotics/gazebospackages https://bitbucket.org/hbpneurorobotics/experimentcontrol
C2583	NRP User requirement analysis	Software	Fortiss: Axel VON ARNIM	Release 2.1 (November 2018) Release 2.2 (March 2019) Code available at: https://bitbucket.org/hbpneurorobotics/neurorobotics-platform
C2588	NRP Web Cockpit	Software	TUM: Sandro WEBER	Release 2.1 (November 2018) Release 2.2 (March 2019) Code available at: https://bitbucket.org/hbpneurorobotics/exdfrontend
C2590	NRP Environment Designer	Software	SSSA: Cecilia LASCHI	Release 2.1 (November 2018) Release 2.2 (March 2019) Code available at: https://bitbucket.org/hbpneurorobotics/exdfrontend
C2592	NRP Brain Interfaces & Body Integrator	Software	EPFL: Marc-Oliver GEWALTIG	Release 2.1 (November 2018) Release 2.2 (March 2019) Code available at: https://bitbucket.org/hbpneurorobotics/exdfrontend https://bitbucket.org/hbpneurorobotics/cle
C2732	VR Neurorobotics Lab	Software	BAUW: Bernd FROEHLICH	Release 2.1 (November 2018) Release 2.2 (March 2019) Code available at: https://github.com/vrsys/guacamole https://github.com/vrsys/avango

The quality control plan for all aforementioned KR10.4 components can be found here:

https://collab.humanbrainproject.eu/#/collab/45333

Table 7: Overview of releases and major updates related to Key Result KR10.5

ID	Component Name	Type	Contact	Info on releases and major updates
C2559	Hardware and driver development of smaller musculoskeletal actuators	Hardware and software	TUM: Alona KHARCHENKO	All documentation (CAD models, electronic circuits and firmware) is available on the dedicated web page: http://www.myobrick.org
C2561	Real-Time Neurocomputing Control for MyoRobotics actuators	Software	KTH: Oskar WEINBERGER	Integration in SP9 SpiNNaker Software Environment, to be released for Workshop on Neurorobotics and SpiNNaker in September 2019 http://spinnakermanchester.github.io/workshops/ Validation: used by multiple groups for real-time robot control inside and outside HBP, e.g. CapoCaccia Workshop on Neuromorphic Engineering.
C2536	Muscle/compliant control	Model	FZI: Daniel REICHARD	The controller will be available open-source in github (planned 07/2019), following publication in Frontiers in Neurorobotics. Presentation in the ROSCon planned 11/2019 Validation: currently only in use at FZI.
C2566	Robot arm motor output, visual servoing of iCub hand	Software	SSSA: Egidio FALOTICO	Validation: already two publications (see above, ICDL-EpiRob 2018 and IEEE RoboSoft 2019) The code and model will be made publicly available with an upcoming publication which addresses the robotic implementation.
C2563	Self-adaptive and modular control of compliant actuators	Model	DTU: Silvia TOLU	Validation: Publication in Frontiers in Computational Neuroscience accepted. Presentation in the School of School of Brain Cells & Circuits "Camillo Golgi", Ettore Majorana Foundation and Centre for Scientific Culture. Lecture title: Integration of cerebellar models into robotic control loops. Erice (Italy), December 11th-15th December 2018.