

Highlights from the 30th Annual Meeting of the Society for the Neural Control of Movement

Marta Russo^{1,3}, Nofar Ozeri-Engelhard⁴, Kathleen Hupfeld⁵, Caroline Nettekoven^{6,7}, Simon Thibault⁸, Ehsan Sedaghat-Nejad⁹, Daniela Buchwald¹⁰, David Xing¹¹, Omid Zobeiri¹², Konstantina Kilteni¹³, Scott Albert⁹, Giacomo Ariani^{14,15}, *

¹Department of Neurology, Tor Vergata Polyclinic, Rome, Italy; ³Department of Biology, Northeastern University, Boston, MA, USA; ⁴Keck Center for Collaborative Neuroscience, Rutgers, USA; ⁵Department of Applied Physiology and Kinesiology, University of Florida, Gainesville, FL, USA; ⁶Wellcome Centre for Integrative Neuroimaging, FMRIB, Nuffield Department of Clinical Neurosciences, University of Oxford, UK; ⁷Department of Psychiatry, School of Clinical Medicine, University of Cambridge, UK; ⁸ImpACT team, Lyon Neuroscience Research Center, INSERM U1028, CNRS UMR5292, University of Lyon 1, Lyon, France; ⁹Laboratory for Computational Motor Control, Department of Biomedical Engineering, Johns Hopkins School of Medicine, Baltimore, MD, USA; ¹⁰Ottobock SE & Co. KGaA, Software & Electronics Engineering, Duderstadt, Germany; ¹¹Department of Neurobiology, Northwestern University, Evanston, USA; ¹²Department of Biomedical Engineering, McGill University, Montreal, Quebec, Canada; ¹³Department of Neuroscience, Karolinska Institute, Sweden; ¹⁴The Brain and Mind Institute, Western University, London, Ontario, Canada; ¹⁵Department of Computer Science, Western University, London, Ontario, Canada

*Address for reprint requests and other correspondence: G. Ariani, Western Interdisciplinary Research Building, London, Ontario, N6A 3K7, Canada, gariani@uwo.ca

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Introduction

The 30th meeting of the Society for the Neural Control of Movement (NCM) was originally scheduled to take place in Dubrovnik, Croatia, in April of 2020. Due to the COVID-19 pandemic, the in-person meeting was canceled and replaced by a virtual symposium showcasing the work of the society's 2020 scholarship winners (<https://ncm-society.org/symposium/>). By the spring of 2021 (April 20th-22nd), the annual meeting was ready to return, although moving for the first time to a completely virtual setting on the online platforms Pheedloop (<https://pheedloop.com>) and Gather.town (<https://gather.town>) (20).

More than ever before, this virtual format facilitated participation and social media engagement (e.g., the popular hashtag #NCM2021) from the research community all around the world (Fig. 1). Indeed, the forced choice of moving online had several positive side effects. First, rebounding from a concerning dip in academic participation from female researchers during the COVID-19 pandemic (50), with respect to previous in-person meetings, NCM 2021 showed an uptick in the percentage of female panelists (34% female attendees, 44% female speakers, 30% female submissions). Second, early career researchers had more opportunities to present their work thanks to the addition of *data blitz* sessions on top of the traditional posters, individual talks, and panel discussions. This novel category allowed for 5 minutes presentation and 1 minute for questions, followed by separate breakout rooms. Third, to enhance discussions during the meeting, panels and posters were pre-recorded and posted online in advance. Live recordings of every session allowed delegates to catch up on missed talks or re-watch talks later. These were welcome additions, as indicated by many respondents to the meeting's feedback survey.

As done in previous years (13, 27, 29), here we present highlights from the meeting. These highlights revolve around four central themes: 1) neuroplasticity, 2) complex motor skills, 3) multimodal sensory integration, and 4) the role of descending spinal tracts in motor control.

< Fig. 1 (2 columns) >

1. Neuroplasticity following altered sensory input

A particular focus of NCM 2021 was on studies using multimodal neuroimaging to understand brain plasticity resultant from exposure to body augmentation technologies or abnormal sensory input. Tamar Makin, the 2020 Early Career Award winner, was commended for their innovative work examining the drivers and limitations of plasticity in the human brain as well as their contributions to the Society—including the organization of the first all-female NCM panel in 2018. Investigating embodiment of

prostheses using fMRI, Makin and colleagues found that two-handed participants represented cosmetic prostheses more like hands and functional prostheses more like tools. However, among prosthesis users, both functional and cosmetic prostheses were not represented either as hands or as tools, but instead constituted a separate category (24, 42). Makin and collaborators explored a similar effect in another group of expert tool users, London litter pickers (42). Similar to amputees, litter pickers viewed their tool as a separate entity and not as an extension of their hand. Together, these results suggest that the human brain is plastic enough to create representations that are distinct from those shaped by evolution.

A PhD student in Makin's lab, Elena Amoruso, explicitly tested this hypothesis in their "third thumb" project (1). Participants wore an artificial thumb controlled by their toes. Coordination rapidly improved with practice and led to successful learning transfer when the controllers were switched (e.g., the toe that controlled flexion/extension now controlled abduction/adduction). When using local anesthesia to block proprioceptive and somatosensory input of the toes controlling the artificial thumb, early training was not affected, but retention of learning on the second day was smaller compared to a sham anesthesia control group—suggesting that sensory input played a critical role in learning to control the additional finger. The third thumb was also tested in a real-world context (18), where participants wore the device for ~4.5 hours a day for 5 days. Participants rapidly improved their performance and reported increasing sensations that the thumb was part of their body. Participants thus were able to develop a sense of proprioception of the thumb's position relative to their biological fingers. Together, Makin and colleagues' work demonstrates the remarkable ability of the human nervous system to undergo plastic changes—an ability Makin believes we should leverage in the development of prostheses. Similarly, Robert Nickl characterized the stability of neuronal responses to movement intention in a patient with incomplete tetraplegia who was bilaterally implanted with multi-unit electrode arrays in the primary motor (M1) and primary somatosensory (S1) cortices (33). Across 12 sessions, the number of active units was more stable in S1 than M1. However, in both areas, the number of overall active units showed a nearly exponential decline. With respect to recorded neuronal activity, in a single channel stability declined within minutes to hours. Interestingly, contralateral activity was more stable than activity in ipsilateral units. This characterization of the stability of neural activity is important for the development of brain-machine interface devices capable of decoding this representation into motor output.

The brain's ability to form new representations can also be probed by studying the neuroplastic changes driven by exposure to a completely novel environment. For example, Grant Tays investigated the impact of microgravity on fifteen astronauts who spent about 6 months onboard the International Space

Station (15, 16, 22). Participants completed MRI and behavioral testing multiple times pre- and post-flight. Their data suggested little cognitive change from pre- to post-flight but pronounced post-flight impairments to mobility, balance, and bimanual coordination (47). These performance declines extended beyond only peripheral changes such as disuse muscle atrophy—suggesting that centrally mediated processes might also contribute to these effects. Further probing central nervous system changes with spaceflight, Kathleen Hupfeld discussed their work on vestibular processing in astronauts. Hupfeld and colleagues applied vestibular stimulation (pneumatic cheekbone taps, (34)) to measure brain activity during vestibular processing at multiple times pre- and post-flight. As previously demonstrated on Earth (16, 55), pre-flight, vestibular stimulation elicited activation of the parietal opercular area (i.e., the so-called “vestibular cortex”) and deactivation of somatosensory and visual cortices. Post-flight, astronauts showed widespread reductions in somatosensory and visual cortical deactivation. Additionally, greater reductions in the deactivation of visual brain regions were associated with smaller declines in standing balance. These findings suggest that microgravity exposure results in cortical plasticity in the form of sensory reweighting—i.e., down-weighting of vestibular inputs (due to this system’s altered signaling in the absence of gravity), and concurrent up-weighting of other sensory processing regions, such as the somatosensory and visual cortices. This reweighting may facilitate more adaptable post-flight standing balance when crewmembers readjust to normal vestibular inputs on Earth.

To better characterize the mechanisms underlying cortical plasticity, Caroline Nettekoven presented their data on the relation between motor cortical gamma-aminobutyric acid (GABA), previously shown to play a role in motor learning and visuomotor adaptation (3, 21, 46). While participants adapted to a stepwise increasing rotation (or performed a control task) in the MRI scanner, Nettekoven and colleagues measured GABA concentration in the left M1 hand area. GABA concentration before adapting predicted retention of the adapted movement but not the extent of adaptation, suggesting a role for M1 GABA in maintaining but not acquiring the adapted state. This relationship between GABA and retention of the adapted movement was mediated by the change in functional connectivity between the left M1 hand area and the right cerebellar hand area. Participants with higher M1 GABA concentration before adapting showed a decrease in functional connectivity between M1 and the cerebellum during adaptation, and they better retained the adaptive movement. These findings imply a link between motor performance, motor network connectivity, and cortical inhibition, and shed light on the neurochemical bases of human motor adaptation (32). Chris Horton and colleagues provided additional evidence that region-specific cortical GABA concentrations predict aspects of human motor performance. Measuring GABA concentrations in S1 and thalamus during “go” and “stop” tasks, they found no association

between GABA and “stopping” performance. However, in the “go” task, higher ipsilateral thalamic GABA correlated with faster reaction time. These data suggest that thalamic GABA concentration supports speeded selection and execution of cued choice responses.

Together, these lines of research contribute to our understanding of how the brain adapts to perturbations or novel sensory conditions (e.g., prolonged prosthesis or tool use, microgravity, and visuomotor perturbations) and have numerous applications for improving human health, such as designing more effective prostheses and maintaining astronaut health during future missions to Mars.

2. Exploring complex motor skills beyond unimanual reaching

Another emergent theme of NCM 2021 was a renewed push to study more complex motor skills. While the definition of a “complex motor skill” may seem arbitrary, here we consider studies that examined naturalistic multi-joint movements that tend to involve interactions with tools and/or the control of many degrees of freedom (DOFs).

One example is sophisticated finger control. As Tamar Makin’s work shows, besides prompting questions about artificial limb embodiment and neural plasticity, augmentation technologies can open new avenues for studying complex behaviors by enabling previously impossible actions. Additionally, within the clinical setting, we can leverage assistive technologies to measure hand function and monitor the progress of rehabilitation. For example, Jing Xu introduced a novel device, the HAND (Hand Actuation Neural-training Device), that is equipped with force sensors capable of detecting even the smallest isometric forces from a near-plegic hand in 3D (28). They used this device to characterize finger co-activation patterns in healthy participants and stroke patients. The importance of such research is most evident in manual activities that demand finger individuation, such as producing a chord when playing the piano. By comparing naïve participants and expert musicians using a foot-controlled supernumerary robotic thumb to play the piano, Aldo Faisal asked what determines our ability to learn and use augmentation in skilled tasks. They showed that foot dexterity (and not task-relevant piano expertise) is the best predictor of future performance (44). Additionally, the observation of highly idiosyncratic learning curves prompted new questions for future research: can everyone be augmented equally? Or should we design personalized training? Regardless, it’s clear that we need real-world complex tasks to improve the training of real-world sensorimotor skills. According to Ilana Nisky, 2021 Early Career Award winner, robot-assisted surgery can bridge the gap between laboratory-based research and real-life applications. Currently, surgical training is not optimized, partly due to a lack of haptic feedback and partly due to limited knowledge on how to measure surgical skills (4, 11, 23, 30, 45, 45). Nisky’s research

used a teleoperated needle driving task and integrated data measuring the dynamics of the robotic manipulandum and modeling human kinematics to describe the quality of surgical skill throughout the learning process. A key aspect of surgical skill is that it requires extremely precise control of external tools via the coordination of multiple effectors. Similarly, watchmaking is a complex craft that includes bimanual control of 44 DOFs. To understand and model such dexterity, Aude Billard and colleagues examined cohorts of apprentices and expert watchmakers using a combination of motion capture and tactile sensing systems. They found that experts consistently used distinctive hand poses that optimized manipulability and made use of longer preparation times to reduce possible mistakes during execution time (53, 54). Moreover, their research revealed that the two hands can work together distributing control of different variables to achieve better precision than a single hand.

Combining tool use and whole-body movements is another way to increase realism and complexity in the study of motor skills. For example, Antonella Maselli presented their work on ball throwing in which they applied spatiotemporal principal component analysis and Hessian-based decomposition to whole-body kinematics to obtain compact descriptions of unconstrained throwing. They used these descriptions to quantitatively characterize performance, individual strategies, gender differences, and common patterns from a heterogeneous sample of non-trained throwers (25, 26, 48). Zhaoran Zhang also investigated ball throwing but compared movements in a virtual and a real set-up. Tolerance-Noise-Covariation decomposition revealed distinct stages of learning, indicating that subjects reached the stage of fine-tuning throwing variability in the real but not in the virtual task. These findings resonate with the reported problems in transferring therapeutic benefits from virtual to real environments (57). Expanding the research on tool use to the more exotic example of manipulating a bullwhip, Marta Russo investigated how humans can achieve dexterity in manipulating the wave dynamics of the whip's infinite DOFs. Their experimental and simulation results suggested that humans may represent control of this prodigiously complex dynamic object in terms of low-dimensional dynamic primitives. Thus, in the same set of studies, Moses Nah tested whether a distant target could be reached with a whip using a controller composed of only motor primitives. This approach was able to manage 54 DOFs by means of a single sub-movement in joint space. A detailed model of the whip dynamics was not needed for this approach. This may be a key simplification that humans leverage to learn complex motor skills, avoiding the need to internalize the detailed dynamic properties of the object being manipulated (31).

If details regarding objects' properties do not need to be internalized, then what are the neural mechanisms underlying tool use? Simon Thibault showed that there is a functional overlap between tool-

use planning and complex syntactic processing in the basal ganglia. Behaviorally, this is reflected by bidirectional cross-domain learning transfer, where tool use benefits syntax and vice-versa (6). Additionally, Raeed Chowdhury studied the neural underpinnings of highly feedback-driven tasks, such as balancing a stick on a palm. During the task, monkeys displayed multiple control schemes within each trial, suggesting that they might have had multiple goals, and thus corresponding neural strategies, in different phases of the arm motion.

Primates are not the only species that use strategies to control objects. Indeed, it is possible to perform complex tool manipulations without the benefit of specialized hands. New Caledonian crows are an excellent non-primate animal model for studying complex object manipulation, as shown by Christian Rutz's work. These animals exhibit a striking degree of dexterity with their beak when manufacturing tools from raw plant materials, using these tools to extract insect prey from hiding places in deadwood, and storing tools for future use in holes or behind tree bark (19).

Such sophisticated control of our bodies extends beyond hand and upper-limb dexterity and is also exemplified by walking. Jacqueline Palmer presented their results on the relationship between motor cortical activity and circuit-specific cortico-cortical interactions during a whole-body dual-task involving balance and cognition in older adults. Consistent with findings in younger adults, their results support motor cortical beta activity as a potential biomarker for individual levels of balance challenge in older adults (36). To capture individual differences in gait dynamics, Taniel Winner used a data-driven dynamical model: a recurrent neural network (RNN) with long short-term memory. Measuring how the internal parameters of the model discriminated individuals with or without stroke, their work showed that using advanced models over discrete summary variables increased the accuracy of group classification. The ability to discriminate between different individuals may lead to the development of individually tailored rehabilitation to improve balance and gait in elderly or impaired individuals.

Finally, speech is another example of a complex motor skill that requires the fine control of several muscles to produce a sound. To better understand this complexity, two talks focused on the effects of different perturbations during speech production. First, Zoe Swann assessed how a startling acoustic stimulus might affect word repetition in individuals with post-stroke aphasia and apraxia. Startle exposure resulted in faster and louder speech. These results were analogous to the finding that a startle during upper extremity movement produced a higher probability of muscle activity onset in severe post-stroke subjects who were unable to activate their arm muscles on their own (38). Second, Ding-lan Tang examined movement variability during speech production perturbed by auditory feedback. Motor

variability increased with auditory perturbation, and this higher variability persisted even after removing the perturbation.

The breadth of research highlighted in this section confirms a renewed interest in understanding the neural control of complex motor skills across species, body parts, interacting tools, and artificial limbs. Future work will look into transferring these abilities to robotic devices, as part of a continuing effort to close the loop between biological capability in humans and technical capability in robots.

3. Multimodal sensorimotor integration in health and injury

In motor tasks, sensory and motor circuits interact to adjust motor commands to changes in the environment and to modulate the sensory experience to optimize task performance. Here we discuss talks from this year's meeting that investigated sensory processing and sensorimotor interactions in both healthy and injured systems.

Sliman Bensmaia and colleagues tackled the question of how multimodal sensory information is represented in the cuneate nucleus, a brainstem structure that receives sensory input from primary afferents in the forelimbs. They recorded single-unit activity in the S1, cuneate, and cutaneous primary afferents in response to skin stimulation and found that responses of cuneate neurons resembled those of S1, more so than those of primary afferents. Moreover, by using their novel simulation model (39), Bensmaia's group was able to use the activity of 5-9 primary afferents from different cutaneous modalities to faithfully predict the response of single cells in the cuneate to skin stimulation. This study demonstrates that integration of multimodal sensory information occurs at the level of the cuneate, well before sensory input reaches the brain. A study led by Nofar Ozeri-Engelhard also demonstrated that multimodal integration of sensory inputs happens in the spinal cord. Using intersectional genetics, they isolated the parvalbumin-expressing interneurons located in the deep dorsal horn of the spinal cord (dPVs) to study their role in sensory processing and motor performance. With functional and histological assays, they provided evidence that dPVs form a circuit that integrates multimodal sensory information to directly communicate with motor neurons. To test whether this circuit plays a role in motor performance, they ablated dPVs and showed that mouse locomotion was perturbed. These results suggest that peripheral sensory circuits directly modulate motor output in the spinal cord to adjust motor performance to changes in the sensory environment.

As we have seen, sensory processing affects movement. However, the opposite is also true: motor circuits interact with sensory pathways to modify sensory input, and consequently, the sensory experience. Kazuhiko Seki tested the idea that a copy of the motor command (i.e., efference copy)

modulates sensory-evoked potentials (SEPs) recorded in the cuneate nucleus of monkeys, in response to sensory stimulation of primary afferents innervating the forelimb (35). SEPs were recorded during active, passive, and no movement (i.e., hold) conditions. SEP amplitude was attenuated during active movement compared to hold, suggesting that the motor command's efference copy modulated cuneate sensory responses. Although to a lesser degree, attenuation was also observed during passive movements, demonstrating that other descending sensory inputs are involved in modulating the sensory response. In support of these conclusions, Seki presented anatomical evidence that the cuneate nuclei receive top-down projections from both the somatosensory and motor (new M1) cortices, proposing these descending projections as the source of attenuation.

Eiman Azim and colleagues studied the role of descending cortico-cuneate pathways in the execution of tactile-guided movements. Using genetic tools in mice, they identified local inhibitory neurons in the cuneate that bidirectionally regulate the activity of cuneolemniscal neurons (which project from the cuneate to the thalamus). Optogenetic manipulation of these neurons altered the gain of the activity of the cuneolemniscal neurons, and accordingly, the performance of dexterous movements (8). Anatomical experiments showed that both the inhibitory neurons and the cuneolemniscal neurons receive input from the sensory cortex. This supports Azim's hypothesis that the cortex indirectly disinhibits, and directly inhibits cuneolemniscal neurons to augment sensory information necessary for optimal task performance while attenuating unnecessary information. In contrast to Seki's findings, Azim's work showed that descending pathways mostly originated from sensory areas. This discrepancy might be due to differences in species since new M1, which projects to the cuneate in non-human primates, does not exist in mice.

In the cerebellum, the efference copy of motor commands is believed to be used by internal models to predict the sensory consequences of active movements. Sensory prediction can be used to distinguish between a sensory state arising from active (i.e., self-generated) versus passive (i.e., externally generated) movement. For example, while vestibular-spinal reflexes are essential for maintaining balance in response to a passive perturbation, these are counterproductive during active movements. Indeed, Kathleen Cullen's group showed that the responses of vestibulospinal neurons in deep cerebellar nuclei (DCN) are suppressed during active compared to passive movement (5). Omid Zobeiri investigated whether Purkinje cells in the vestibular cerebellum, which inhibit DCN, can predict the sensory consequences of efference copy and in turn suppress DCN responses during active head movements. While single Purkinje cells did not encode sensory prediction, they showed heterogeneous responses to vestibular and proprioceptive sensory inputs and motor efference copy. Simulation data suggested that

combining the responses of ~40 Purkinje cells is sufficient to generate sensory predictions that suppress DCN responses during active movements, providing evidence that cerebellar internal models are encoded by Purkinje cell sub-populations.

During voluntary movements, when sensory prediction matches motor output (i.e., no sensory prediction error, SPE), DCN downregulate their responses to externally applied perturbations. But how does DCN sensitivity change in the presence of an SPE? Robyn Mildren studied how varying degrees of SPE impact the suppressed DCN response during active head movements. DCN responses were recorded from the rostral fastigial nucleus of one rhesus monkey. Different magnitudes of assistive and resistive torques were externally applied to introduce SPEs. As SPE increased, suppression of DCN responses during active movements gradually decreased, suggesting a gradual shift in encoding from self-generated to externally applied motion.

In addition to head movements, primates use eye movements to sample the visual environment. Ehsan Sedaghat-Nejad investigated the role of the oculomotor cerebellum in encoding SPEs by recording Purkinje cell activity while marmosets performed saccades to a target presented in random locations. Occasionally, the target location was quickly changed, to introduce a prediction error. They showed that Purkinje cells can be divided into subpopulations, according to their encoding of SPEs, resulting in a population activity that was predictive of the saccade termination (43).

Our brain's ability to perform two sequential saccades has been long studied by Michael Goldberg, commended for his lifelong contributions to science and to the NCM community, and selected by NCM for the distinguished career award lecture. While the first saccadic eye movement is an "easy" task for the brain, the second requires an updated representation of the initial position from which the movement starts. This position could be estimated from proprioceptive information about the eye, or from the efference copy of the first movement. To distinguish between these possibilities, the Goldberg lab investigated the lateral intraparietal area (LIP), a region that evokes saccades. In a series of experiments, they showed that although LIP receives proprioceptive information regarding eye position, this information arrives too late to alter second saccade planning (52). However, they found that LIP neurons fired before the second saccade, even though the second movement was not in their initial receptive field (10). This observation implies that the efference copy of the first saccade re-maps LIP receptive fields to generate the second saccade. What then is the role of proprioception in saccadic eye movements? Interestingly, with an increase in the number of sequential saccades, the brain shifts from an efference copy to proprioceptive-based encoding (37, 56).

Modulation of bottom-up sensory input by top-down signals is important to maintain movement accuracy. But what role do these interactions serve in functional recovery? Corinna Darian-Smith and their lab investigated this question by performing incomplete lesions of dorsal roots innervating forelimb fingers. Although these lesions produced severe deficits in prehension tasks, monkeys exhibited an impressive recovery over 1 to 3 months. To uncover the mechanism underlying recovery, the Darian-Smith lab investigated plasticity in the cuneate nucleus. Using anterograde tracers, they showed that by 5-months post-lesion, spared fibers from deafferented digits sprouted new terminals in the cuneate, which then consolidated in number by 1-year post-lesion. Similar to their work in the spinal cord (12), they demonstrated specific changes to cuneate micro circuitry following injury and recovery, in the connections between S1, primary afferents, and local interneurons. This work suggests that interactions between sensory and motor circuits in the cuneate nucleus are plastic and play a role in functional recovery from injury.

In conclusion, multiple talks demonstrated complex sensory processing throughout the brain - even early in the sensory pathway at the level of the spinal cord and dorsal column nuclei. These processes included integration of multimodal sensory information and top-down modulation of sensory signals via the efference copy of motor commands. Combining the descending efference copy with ascending sensory input allows the brain to coordinate movement sequences, predict the consequences of motor commands, and alter its response to active and passive movement. These sensorimotor interactions are critical for accurate motor performance and functional recovery following injury to sensory fibers.

4. The role of descending spinal tracts in the neural control of movement

Throughout the meeting, several talks discussed the organization of descending tracts to the spinal cord, how these participate in motor control, their development, and their role in rehabilitation from injury. Ariel Levine's group focused on a particular structure projecting onto the spinal cord from the deep cerebellar nuclei: the cerebellospinal tract (CeST). Historically, the CeST has been poorly studied, and its existence debated. Levine's team leveraged modern genetic tools to better understand the role of this tract as well as spinal cord subpopulations for integrating coordinated motor behaviors. Focusing on the contralateral CeST, they found that the interposed and fastigial nuclei project onto the cervical spinal cord and are specifically involved in motor learning on a rotarod, but not in basic locomotion. In addition, Levine and colleagues found that coordinated control of the hindlimbs is mediated by additional projections from the target cervical interneurons in lamina VII and VIII to the lumbar spinal cord (40).

These results provide some of the first insight into the descending CeST's organization and motor function. In a complementary approach to characterize cell populations, Levine used transcriptomics in mice to develop an atlas with a complete characterization of the molecular profile of spinal cord neurons (41).

Further investigating the descending pathways, Julien Bouvier highlighted the role of the reticulospinal tract for the control of coordinated motor behaviors. To explore whether the reticulospinal tract contains different functional organizations (14), Bouvier's team focused on the V2a neurons in the mouse reticular formation (49). They found that optogenetic stimulation of V2a neurons provoked complex changes in locomotor behavior including pausing, reorientation of the head, and changes in direction. The Bouvier lab was able to distinguish V2a neurons that project to the lumbar and the cervical spinal cord. Crucially, stimulation applied to lumbar-projecting neurons only arrested locomotion, whereas head rotation was observed only after stimulation of cervical-projecting neurons. This study demonstrates the benefits of combining genetic and viral tools to understand the functional heterogeneity of neural circuits.

Vibhu Sahni investigated the molecular processes during development that determine the somatotopic organization of corticospinal tracts innervation of the spinal cord. In previous work, their group had discovered anatomically and genetically distinct bulbar-cervical and thoracic-lumbar projecting populations (17). The origins of these descending axons appear to separate along the medial-lateral axis, with lateral motor cortex containing exclusively bulbar-cervical projecting axons. Recently, they also discovered a similar boundary zone between the brainstem and cervical projecting axons. The targeting of the axon terminations of these populations appears to be under specific molecular control: the *Crim1* gene extends axons past the cervical-thoracic boundary, while the *Klhl14* gene restricts the axons to the bulbar-cervical region. Additionally, their team investigated regeneration of the spinal cord after injury. They found that regenerative ability appears to be tied to the growing end of the axons during development. Lesions carried out at the growing end rather than at the upper part of the spinal cord experienced more regrowth and greater functional locomotion recovery.

On restoring lower limb motor control after spinal cord injury (SCI), Grégoire Courtine discussed their work using epidural stimulation in SCI patients. By patterning this stimulation to match the spatiotemporal activity patterns in the intact spinal cord, they demonstrated remarkable recovery of stepping motion after SCI (7, 51). Additionally, in pilot clinical studies, they found that after months of training with spinal stimulation, patients experienced some functional recovery even with the stimulation turned off. To test the role of the motor cortex in functional recovery, Courtine's team optogenetically

inactivated this region in rats during a swimming task. They demonstrated that before SCI, inactivation had no effect, but after SCI and subsequent recovery with epidural stimulation, cortical inactivation caused the animal to lose the recovered swimming ability (2). Histological evaluation revealed axonal sprouting within spared reticulospinal fibers projecting onto the lumbar spinal cord, suggesting a potential cortico-reticulo-spinal pathway mediating this functional recovery.

Several blitz talks expanded upon research focusing on the spinal circuits themselves. Rune Berg presented multielectrode spinal recordings in turtles during scratching and found spinal neurons active across all phases of the scratch cycle. They demonstrated rotational structure in the population activity and presented a new theoretical framework, called the balanced sequence generator, to model these experimental findings. In humans, Samuele Contemori demonstrated that the fast muscle responses observed within 100 milliseconds after visual stimulus onset (stimulus-locked responses, or SLRs, see (9)) are modulated by visual cues and are likely controlled by the tecto-reticulo-spinal pathway.

Overall, this year's NCM meeting provided a window into the cutting-edge research on the spinal cord and the descending tracts' role in the control of movement. The panel and talks covered a wide range of techniques and topics, encompassing molecular techniques, histology, electrophysiology, and modeling, and included work on many different species, ranging from rodents to turtles to humans.

< Fig. 2 (1.5 columns) >

Conclusions

Despite lacking some of the excitement and networking opportunities of an in-person conference, this year's virtual meeting had several positive outcomes. The most obvious upside of going online was greater inclusivity: a record number of attendees (706 participants), a doubling up in the percentage of female submissions from 2019, and a sharp increase in participation from early-career scientists and underrepresented countries. To continue this trend, the NCM board expressed willingness to consider a hybrid format combining virtual and in-person presentations for future meetings.

The studies highlighted in this article tackled motor control questions at different levels and from multiple perspectives (Fig. 2). One of the emerging themes was that investigating the brain's plastic abilities is a key asset to develop more effective prostheses and novel, individually tailored rehabilitation protocols for patients or even astronauts. Likewise, to extend our research to real-world applications it is important to design experiments that explore more complex natural movements, such as those engaging multiple joints or involving objects and robotic interfaces. Several studies highlighted how descending

424 pathways carry information about sensory prediction and interact with motor commands. Lastly, with
425 new genetic and viral tools, we are beginning to uncover the roles of specific supraspinal populations that
426 descend to the spinal cord. This approach is expected to gain momentum and reveal new understandings
427 of spinal cord function in motor control and recovery from spinal cord injury.
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590 **Figures Captions**

591 **Figure 1:** World countries color-coded by the number of people attending NCM 2021 affiliated with a
592 university located in that country. Colors are represented on a log10 scale. The number insets in
593 each country show the exact number of attendees.

594 **Figure 2:** The most common keywords reported by the attendees of NCM2021 representing what was
595 heard or learned during the meeting.

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