Ordo ab chaos

Impact addendum

What is the main purpose of the research described in the thesis and what are the main results and conclusions?

The research summarized in this thesis aimed at understanding how we encode and process the *timing* of sensory input, and how we employ timing computations to efficiently coordinate perception and action. With a series of basic, comparative and translational studies reported in Chapters 2 to 4, I showed that neurophysiological activity in the brain provides an exquisite *sense of time*: neural waves represent endogenous oscillators, produce an *internal clock*, and are capable of tracking the precise *timing* of sensory input. Thus, I discussed that neural waves at multiple timescales (e.g., delta (δ; 1-4Hz) and beta (β; 12-20Hz)) encode the *when* of incoming sensory information, and predictively track the *when* of future sensory inputs by generating *predictions*. These so-called *dynamics of attending* are thought to play a fundamental role in our capacities to act and adapt in a dynamically changing environment.

Thus, in our research we demonstrated similarities in basic rhythm cognition between humans and nonhuman animals, macaque monkeys. Next, we provided causal evidence for a fundamental role of BG and CE in the capacities to encode, produce and synchronize with rhythms in the sensory environment. Expanding this research line, in the second part of the thesis I discussed that bodily physiological activity interacts with and influences neurocognitive functions. Heartbeat, respiration and gastrointestinal rhythms provide yet another level of *time* in the body, next to brain activity. Thus, I advanced the new framework the Body-Brain Dynamic System (BBDS) to analytically examine and characterize body-brain interactions and their influence on sensory processing, perception and action.

What is the (potential) contribution of the results of this research to science?

Altogether, the results presented in Chapters 2-4 speak in favor of a fundamental role of δ-β neural waves in rhythm processing, strengthen the notion that there exist similarities between human and nonhuman animal's rhythm cognition, and confirm the causal role of BG and CE structures in rhythm processing and production.

The second research line introduced in Chapter 5, suggests expanding the horizon of cognitive neuroscience research so to include body physiology and body-brain interactions into the

equation. As such, our novel framework argues in favor of a fundamental shift in how we study human brain and behavior: holistic, systematic, individual assessments are critical to advance our understanding of human cognition, in health and pathology.

To conclude, I discussed that time, in the body and the brain, is fundamental to structure cognition: the *sense of time*, and the capacities to track and sample sensory input, allow to temporally organize multisensory information into a coherent percept, and ultimately allow to act and adapt in a dynamically changing environment. *Ordo ab chaos*.

Conceptual and methodological advances

Across chapters, we have dedicated particular attention to intra- and inter-individual variabilities: we have developed new methodological approaches to explore variability in individual brain data, and to characterize time-varying dynamics of neural oscillatory activity. Brain functioning and behavior are variegated, multifaceted, complex, dynamic phenomena (or systems) which cannot be summarized into group averages. The typical tendency to aggregate data across individuals and hundreds of experimental trials leaves out systematic assessments of *what* happens *moment to moment*, as well as *what* determines observed behaviors. We discuss that this approach has failed and will inevitably keep on failing in understanding human cognition and disorders: future research has to dedicate more attention to the individual and his/her unique body, brain, behavioral variabilities.

These formulations may not have an immediate impact on society and ongoing scientific research, but hopefully contribute to and motivate a movement *towards* novel holistic and individualized research and therapeutic approaches. In fact, the findings on intra- and inter-individual variabilities (Chapters 2-4) have raised substantial interest in the neuroscientific community. Similarly, the framework provided by the BBDS (Chapter 5) is of cross-disciplinary interest and has been welcomed with great enthusiasm by a large crowd of scientists of different backgrounds.

Public outreach and education

This work has been presented publicly in more than 10 internal conferences and more than 10 talks in research groups across the world. Importantly, this research has reached both the

neuroscientific community, as well as the general public via in-person events, as well as through an active presence on social media (e.g., Twitter, LinkedIn, Facebook) and websites (e.g., the BAND-lab and Waves conference). Our work has further attracted the interest of NeuroTech companies, who are in contact with us to explore future applications of mobile body-brain imaging setups in future research lines. What I am mostly proud of, however, is that I recently went back to my secondary school in Salerno (southern Italy) to discuss my research on rhythm. There is where I started to play music, and where my journey to becoming a professional musician started, some years ago. It was a great pleasure bringing there my own research on rhythm and music, and meeting the sparking interest in the crowd: my family, my teachers, and many more school teachers across the Province and Campania region.

Finally, our research is being published in high-impact factor journals, a process which allowed us to receive high-standard feedback and advice to further improve the quality of our work. Through the PhD, however, I have learnt that the publication process sometimes suffers from subjective views, egoistic interests (e.g., you cannot provide evidence against a reviewer's theory) and significant delays (it may take a year to go through revisions). Consequently, receiving fair, critical and timely feedback often remains an utopia.

My research lines have also inspired my teaching: I try to convince my students that the focus on the individual and individual variabilities is important to advance science. Thus, across BSc and MSc courses, I often engage in critical discussions with students discussing the *why* and *how* examining variability is important, in healthy and clinical populations. The *how* is further implemented in my programming and signal processing courses, during which I offer ad-hoc examples on how to analyze and visualize single-participant and -trial data, and how to summarize findings with statistics.