



## Artificial Intelligence and the Fourth Industrial Revolution in Neuroscience: advances, challenges and perspectives

### Inteligencia artificial y la Cuarta Revolución Industrial en Neurociencia: avances, desafíos y perspectivas

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The Fourth Industrial Revolution, also known as Industry 4.0 or I4.0, is characterized by the convergence of digital, physical and biological technologies, including artificial intelligence (AI), big data, the Internet of Things, cloud computing and cyber-physical systems. This new paradigm is deeply transforming productive processes, models of social organization and, increasingly, research in neuroscience and clinical practice. In the field of neuroscience, Industry 4.0 provides a conceptual and technological framework that enables the complexity of the nervous system to be addressed through integrative approaches oriented towards precision medicine. <sup>(1)</sup>

The term artificial intelligence emerged in 1956 and remained largely confined to theoretical computing and academic research for decades. However, this situation has changed radically: AI has moved beyond laboratories and university classrooms to become actively and transversally integrated into virtually all areas of contemporary society. <sup>(2)</sup>

Contemporary neuroscience generates unprecedented volumes of data from advanced neuroimaging techniques, high-resolution neurophysiological recordings, genomic analyses and longitudinal clinical assessments. In this context, AI not only emerges as a computational tool, but also as a structural component of I4.0 in the field of health. It is capable of transforming heterogeneous data into useful

knowledge for understanding disease, supporting clinical decision-making and designing therapeutic interventions. <sup>(3)</sup>

Over the past decade, AI has become established as one of the most disruptive technologies in neuroscientific research. Its impact in this field has been particularly notable due to the structural and functional complexity of the nervous system, the vast volumes of data generated by neurophysiological and neuroimaging techniques, and the requirement for tools that can integrate multiscale information, ranging from molecular signals to behavioral patterns. <sup>(4,5)</sup>

AI applications in neuroscience span a wide spectrum, including signal processing (e.g. electroencephalography, EEG-related functional connectivity, electrooculography, electromyography and polysomnography), analysis of structural and functional neuroimaging, modelling of neuronal networks, prediction of clinical progression and optimization of therapeutic interventions. Deep learning methods, such as convolutional neural networks (CNNs), have particularly impressive performance in tasks involving the segmentation, classification and detection of complex patterns in brain imaging. <sup>(3,6)</sup>

In the field of neuroimaging, the most significant advance has been the automatic segmentation of brain structures. Progressive replacement of manual or semi-automatic methods by AI-based models has reduced analysis time, decrea-

sed inter observer variability and facilitated longitudinal and multicenter studies. These benefits are particularly important for neurodegenerative diseases, including the spinocerebellar ataxias (SCAs) which are a paradigmatic group due to their genetic, phenotypic, and morphological heterogeneity, as well as their high prevalence in the Americas, representing an ideal area for the development and validation of AI-based approaches, where structural changes may be subtle in the early stages and require sensitive, reproducible tools for detection. <sup>(6,7)</sup>

SCAs are a group of hereditary neurodegenerative diseases characterized by the progressive dysfunction of the cerebellum and its afferent and efferent connections, as well as other structures in the central and peripheral nervous systems showing a multisystem pattern of involvement. SCAs are an important area of research in our country, as Cuba has the highest global prevalence rate, which has led to sustained research in epidemiology, clinical, molecular biology, neuroimaging, neurophysiology, and biomarkers. <sup>(8)</sup>

Cuba has over 2,000 diagnosed patients and more than 10,000 individuals at risk. The disease progresses aggressively, with 25% of cases presenting as juvenile-onset (before the age of 22), leading to disability within 10 years and a mean survival of 16–20 years post-onset. This unique epidemiological profile, driven by a high frequency of mutable normal alleles that generate approximately 35 new cases annually, has established Cuba as a critical global research center for this neurodegenerative disease. <sup>(7,8)</sup>

In this context, AI has emerged as a key tool for objectively studying neurodegeneration in SCAs. Recent studies have demonstrated the effectiveness of convolutional networks in automatically segmenting the cerebellum and brainstem from structural magnetic resonance images. These approaches enable highly precise quantification of cerebellar atrophy, widening of cerebellar fissures and volumetric loss in deep nuclei. In many cases, they outperform classical methods. <sup>(4,5)</sup>

The application of deep learning models for volumetric assessment of the brainstem in SCA2 is of particular relevance, including the midbrain, pons and medulla. Studies in this area have demonstrated the ability of AI to detect differential patterns of atrophy in control subjects, pre symptomatic carriers and symptomatic patients. This provides objective evidence that neurodegeneration begins years before the onset of overt motor symptoms. This has direct implications for the design of clinical trials and early neuroprotective strategies. <sup>(5,6)</sup>

### **Clinical applications in translational and precision medicine**

From a clinical perspective, AI offers several potential advantages in the management of ataxias. Firstly, it facilitates

earlier and more objective diagnosis, particularly in pre symptomatic carriers, where structural and functional changes may be imperceptible to the naked eye. Secondly, it facilitates the longitudinal monitoring of disease progression through the use of quantitative biomarkers derived from imaging or neurophysiological signals. This is essential for evaluating the effectiveness of therapeutic interventions. <sup>(8,9)</sup>

Furthermore, integrating multimodal data, such as structural imaging, clinical scales (e.g. SARA or ICARS), and quantitative assessments of gait, posture, speech, and saccadic eye movements, enables the development of personalized predictive models. This approach aligns with the principles of precision medicine and is particularly relevant in ataxias, where the rate of progression and multisystem involvement can vary considerably from person to person. <sup>(9)</sup>

An area in which AI is emerging as a decisive factor is neuro modulation. Recent studies on deep brain stimulation of the dentate nucleus in patients with ataxia have shown promising results in reducing clinical severity. However, optimizing stimulation parameters remains an empirical process that is highly dependent on clinical experience. AI could contribute significantly to this field by analyzing large volumes of clinical and neurophysiological data to identify optimal stimulation patterns, thus advancing towards adaptive and personalized neuro modulation schemes. <sup>(10)</sup>

Despite its enormous potential, the application of AI faces significant challenges. One of the main problems from a methodological standpoint is the availability of sufficiently large, integrative and representative databases. Ataxias are rare diseases, which poses an additional challenge in this regard. This necessitates the development of efficient training strategies, rigorous cross-validation and international collaboration. <sup>(7,8)</sup>

Another critical challenge is model interpretability. Many deep learning algorithms operate as 'black boxes', limiting their clinical acceptance and hindering understanding of the underlying neurobiological mechanisms. Developing explainable models is therefore a priority to inspire confidence among clinicians and researchers.

From an ethical perspective, issues related to data privacy, informed consent and the responsible use of automated systems in clinical decision-making must be addressed. In contexts such as Cuba, where AI is primarily developed in academic and public health institutions, these considerations must be incorporated into system design from the outset.

### **Challenges and perspectives**

The future of AI in neuroscience and the treatment of ataxias will depend on the ability to integrate advanced computational approaches with in-depth clinical and neurobiological

knowledge. In the coming years, it is foreseeable that models combining neuroimaging, molecular biology, clinical and basic neurophysiology, and quantitative movement assessments (including gait, posture and coordination) alongside longitudinal clinical evaluations will be developed to identify progression biomarkers and generate personalized risk and progression profiles. <sup>(4,6)</sup>

However, this represents a significant challenge given that the biomarkers currently being developed for ataxias and neurodegenerative diseases in general are derived from studies evaluating specific parameters, whereas the nervous system functions as an integrated whole. Therefore, integrating different diagnostic techniques will enable the development of comprehensive models of nervous system function. Such biomarkers could detect changes prior to the development of these conditions in the prodromal stage, when neurodegeneration is incipient. This would facilitate the development of new drugs and their validation through clinical trials requiring fewer patients and shorter execution times. <sup>(11)</sup>

Similarly, strengthening local capacities in data science, biomedical engineering and computational neurosciences is essential to ensure the sustainability of these developments. Cuba's experience in studying SCA2, coupled with the increasing use of AI in neuroimaging and signal analysis, puts the country in a favorable position to contribute significantly to this emerging field. <sup>(11,12)</sup>

To address these challenges, the Cuban Academy of Sciences has formed a temporary working group comprising its regional branches – nodes of academic integration linking the eastern, central and western regions of the country – and established a neuro technology center in the north-eastern branch of Cuba. This center is home to a team of researchers specializing in image segmentation, intelligent movement analysis, and the integration of multimodal electrophysiological and neuro technological patterns.

## Conclusion

Artificial intelligence should not be viewed as a substitute for clinical reasoning or traditional neuroscientific research, but rather as a complementary tool that enhances the ability to detect patterns, integrate complex information, and generate hypotheses. In the study of ataxias, AI has already proven useful for characterizing neurodegeneration, identifying early biomarkers, and supporting the development of innovative therapeutic strategies. The current challenge lies in consolidating these advances, overcoming methodological and ethical limitations, and translating the generated knowledge into tangible benefits for patients.

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## Interests Conflicts

The authors declare that there are not conflicts of interest among them or with the research presented.

**How to cite this article**

Velázquez Pérez LC. Artificial Intelligence and the Fourth Industrial Revolution in Neuroscience: Advances, Challenges and Perspectives. An Acad Cienc Cuba [Internet] 2026 [cited in day, month and year];15(3):e3238. Available at: <http://www.revistaccuba.cu/index.php/revacc/article/view/3238>

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