New Pattern Recognition of Brain Mapping Based on Non-Extensive Statistical Systems

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***Abstract*—Nowadays, 93% of the subcortical areas are still classified as *terra incognita* [1]. Thus, they are regions totally unknown to the neuroscientists. In this context, the *Human Connectome Project* (HCP), a consortium between the universities of Washington, Minesota and Oxford, mapped about 1200 individuals in various cognitive and motor situations. This mapping resulted in a database of free access to the scientific community on the order of 64 terabytes. However, the images collected *in vivo* have low quality when compared to the histological images. One of the solutions to this problem is the combination of fMRI data with data collected in *post mortem*. Nevertheless, this combination requires the manual analysis of thousands of observed regions, which makes it almost unfeasible manually. Hence, the automation of this process depends on bigger precision of segmentation algorithms. From the 1980s, with the works of Constantino Tsallis in the field of non-extensive statistical mechanics [2], a path has been opened for the creation of new segmentation algorithms based on the Tsallis entropy. In this work, we propose the application of the sigmoid function based on Tsallis non-extensive entropy in magnetic resonance images for the segmentation of brain regions.**

I. Introduction

Brain mapping is one of the major challenges of the 21st century, since only 7% of brain regions have been observed *in vivo*. [1].

Recently, the *Human Connectome Project* (HCP) https://db.humanconnectome.org has proposed a complete mapping of the anatomical regions from the point of view of new hardware technologies, such as the use of tomographies on the order of 7 Tesla [3]. Despite the effort made by the set of universities, the scanning of machines with up to 7 Teslas (7T) *in vivo* is inferior in the sense of functional and structural observation when compared to histological techniques [4].

Fig. 1 shows a visual comparison of scanning a subcortical region with 3T and 7T *in vivo* through fMRI (functional Magnetic Resonance Imaging) and 7T *post mortem*. In this Figure, higher visual quality is observed in the histological images. In addition, the study of *terra incognita* is only possible through information collected in *post mortem*.

The obvious solution to this problem lies in the enhancement of fMRI imaging equipment. However, an alternative solution is based on the functional and structural simulation of the brain. In this type of simulation, hypotheses about interregional connections and structure of the brain can be proposed, as well as the use of mathematical-computational models to infer regions still unknown. A review of the area can be found in [5].

On the other hand, another solution could be the combination of histological results with fMRI information [5]. This combination, however, involves the analysis of thousands of areas observed microscopically manually. The automation of this process, in its turn, depends on the greater precision of segmentation algorithms, which would result in greater precision of the automatic analysis.

One of the classic segmentation techniques is the histogram thresholding (HT), proposed in [6]. This technique is based on the entropic probability distribution to find the cutoff threshold. The HT method applies only to binary thresholding using Shannon Entropy. However, this technique has become popular because of its easy implementation and low computational cost.

From the work of [6], other more advanced proposals have been studied. In the late 1980s, the works of Constantino Tsallis on the non-extensive statistical mechanics field opened the path for new segmentation alternatives based on this theory. In [7], the first work of non-extensive image segmentation based on the Tsallis entropy was proposed.

From the work of [7], several other proposals were made. In [8], a new method for the segmentation of breast cancer ultrasound images based on the Tsallis entropy was presented as part of a Computer Aided Diagnosis (CAD) system. Other proposals for the improvement of this method were presented later in [9]–[13].

Histogram-based methods require less computational resources for binarization purposes. However, in [14], it has been shown that multi-threshold processes may be more effective in the case of more detailed images. Thus, in [15], it was proposed the use of bio-inspired optimization algorithms to enable multi-segmentation, such as the Firefly algorithm, based on the firefly behavior. As the core of Firefly, the non-extensive entropy of Tsallis was applied. Further work on the method was proposed by [16], [17].

Still in relation to the image segmentation, [18] proposed the generalization of the sigmoid function using the Tsallis entropy for the creation of the q-sigmoid. Subsequently, the work of [19] extended the application of the proposal and

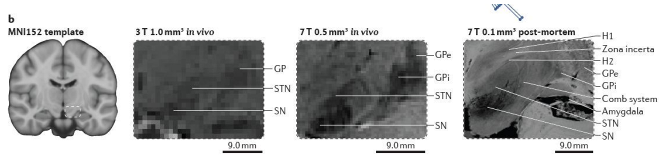

Figure 1. Visual comparison of resolution by technique. The leftmost Figure shows a sagittal (in vivo) slice of the brain and a prominent dotted region. The highlighted region is observed in detail in the second image (captured with 3T), in the third (captured with 7T), and in the fourth most right photographed with a microscope of the same tissue *post mortem*. The greater amount of observable details and regions, including the so-called *terra incognita*, is evident in the histological Figure to the right [21].

[20] presented formal mathematical theories for the method. In this paper, the use of the q-sigmoid function in the medical databases of the HCP project is proposed .

This work is organized in the following way: in Section II, an introduction is made to the q-sigmoid function with non-extensive entropic kernel. In section III, the results of q-sigmoid segmentation on the HCP database are presented. The conclusion is made in Section IV.

II. Methodology

The idea of the q-sigmoid function is based on the formalism of the q-exponential function and a simple variation of the sigmoid approach for image enhancement. In this context, we suppose $I(x, y) \in [0, L]$ (generally called only I for short) and a specific region with average luminance value β and standard deviation α. With the purpose of contrast enhancement, we consider the sigmoid transformation given by:

$$I_1(I; \beta, \alpha, \lambda) = \frac{2}{1 + \exp\left(\lambda\left(\frac{|I-\beta|}{\alpha}\right)\right)}. \tag{1}$$

Fig. 2 shows a schematic example of the use of parameters β and α in Expression (1). In this Figure, we indicate the β value in the input image as well as the range, defined through the parameter α, around the luminance given by β. We can notice that the luminances nearby β were mapped close to 1 while outside the rages $[\beta - \alpha, \beta + \alpha]$ became darker. In this way, we get an enhancement of the target region, whose pixels intensities fall in the range $[\beta - \alpha, \beta + \alpha]$, in the transformed field I_1.

On the other hand, we get an interesting effect by using another sigmoid-like function defined as:

$$I_2(I; \beta, \alpha, \lambda) = \begin{cases} \frac{1}{1+\exp\left(-\frac{\lambda}{\left(\frac{|I-\beta|}{\alpha}\right)}\right)}, & if \quad I \neq \beta \\ 1 & otherwise \end{cases}, \tag{2}$$

In this case, we also get enhancement of values nearby β in order to achieve region enhancement of an input image I with β and α defined a priori.

Following the idea of non-extensive systems for natural as well as medical images [22]–[25], and considering that extensive systems are incorporated into non-extensive systems for values of $q = 1.0$ [2], in this work we use an extended version of Equations (1)-(2), called here as q-sigmoid functions, and defined based on the q-exponential function, and described in the following items.

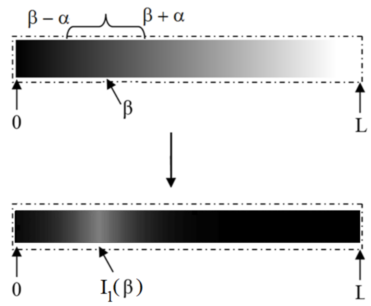

Figure 2. Example of luminance transformation obtained by Expression (1) with domain $0 \leq I(x, y) \leq L$ and parameters β and α indicated. The upper row shows the input image while the bottom shows the obtained result with enhancement of region nearby $I_1(\beta, \alpha, \lambda)$ applied [19].

- q-Sigmoid for $q < 1$:

$$\tilde{I}_1(I; \beta, \alpha, \lambda, q) = \frac{2}{1 + \left[1 + \lambda(1-q)\left(\frac{|I-\beta|}{\alpha}\right)\right]^{\frac{1}{1-q}}}, \tag{3}$$

- q-Sigmoid for $q > 1$:

$$\tilde{I}_2(I; \beta, \alpha, \lambda, q) = \begin{cases} \frac{1}{1+[1+\lambda(1-q)*F(I)]^{\frac{1}{1-q}}}, & if \quad I \neq \beta \\ 1 & otherwise \end{cases}, \tag{4}$$

where:

$$F(I) = -\frac{1}{\left(\frac{|I-\beta|}{\alpha}\right)}.$$

Under the idea that in the limit $q \rightarrow 1$, non-extensive expressions are reduced to extensive expressions, and using usual limit properties, it is straightforward to show that:

$$\lim_{q \to 1} \tilde{I}_1(I; \beta, \alpha, \lambda, q,) = I_1(I; \beta, \alpha, \lambda), \tag{5}$$

and:

$$\lim_{q \to 1} \tilde{I}_2(I; \beta, \alpha, \lambda, q) = I_2(I; \beta, \alpha, \lambda), \tag{6}$$

The idea behind the use of q-sigmoids rather than sigmoid functions generates the hypothesis that, since the q-sigmoids have the extra non-extensive parameter to control the curve's topology, one can build filters with tighter topologies to each class of applications. This idea has been used in several fields of applications, mainly in image processing and computer vision applied to the medical area [22], [23], [25]. The particular case to be studied in this work is the MRI brain images of the HCP database.

III. Results

The q-sigmoid function was systematically applied on the HCP database. Thus, for a given type of image, the regions of the brain used by the individual during the performance of the proposed activity will be highlighted, while those of non-interest will remain darkened. Initially, both the parameters and the cognitive tests were defined empirically. However, as of future work, we intend to find the parameters that best highlight the brain regions for a given activity. To perform the tests with the q-sigmoid function, the chosen values for the parameters were $\alpha = 10$, $\beta = 100$, $q = 1.1$ and $scale = 1$.

Fig. 3 shows a slice, already separated, from a volume collected from the individual with ID 101309 from the HCP project, prior to the segmentation process. From this moment, for the sake of simplification, individuals will be identified by their respective IDs.

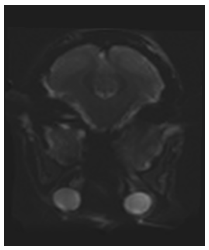

Figure 3. Task-fMRI slice collected from the individual 101309 in a language test, in which the regions responsible for the semantic and phonological processing of languages are verified.

Fig. 4 displays a set of 9 task-fMRI images of the subject 101309 after the use of the q-sigmoid function. The regions used by the individual during the execution of the test are highlighted and displayed in white, while the others are darkened. In this Figure, the highlighted regions are depicted with the parameters presented in this Section, for the phonological and semantic processing test. For comparison purposes, Fig. 5 displays another set of 9 images for the individual 101107, for the same image type and parameters. The 6 Figure displays the result of the q-sigmoid segmentation on the individual 100408 for an emotional overload test.

It is noted that the regions used by individuals during the tests were highlighted (labeled white) rather than regions that were not used (remained darkened). In this way, it is easier to understand the individual functions of each region, as well as their corresponding correlations.

IV. CONCLUSION

In this work the sigmoid function with entropic *kernel* based on the Tsallis non-extensive statistics was applied in the available medical databases of the HCP.

The sigmoid function, here called the q -sigmoid function with Tsallis entropy, was systematically applied in the project subjects. Initially, both the parameters used in the function and the activity performed by th subject were chosen empirically, but future work will be based on the best choice of these parameters for the segmentation of the regions for a given test.

Note that the q-sigmoid function, when applied to the images, highlights the regions that were activated during execution of the different cognitive and motor tests performed

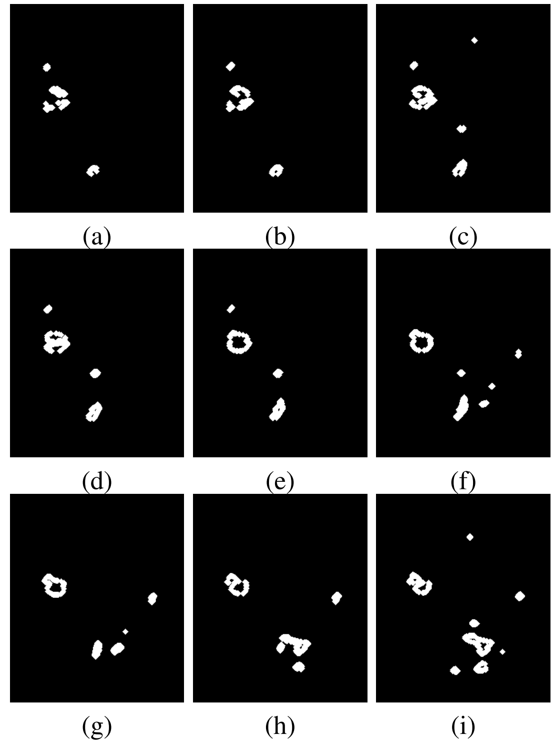

Figure 4. Region highlighting using the q-sigmoid function for the individual 101309 with task-fMRI images and the phonological and semantic processing test.

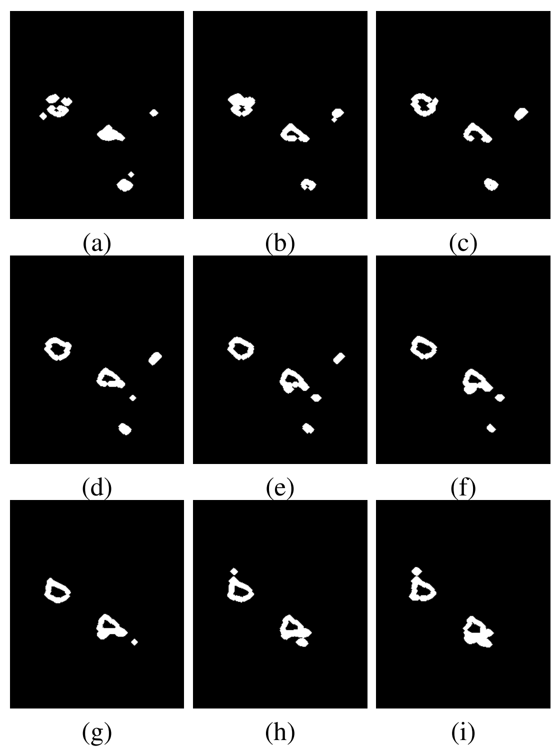

Figure 5. Region highlighting using the q-sigmoid function for the individual 101107 with task-fMRI images and the phonological and semantic processing test.

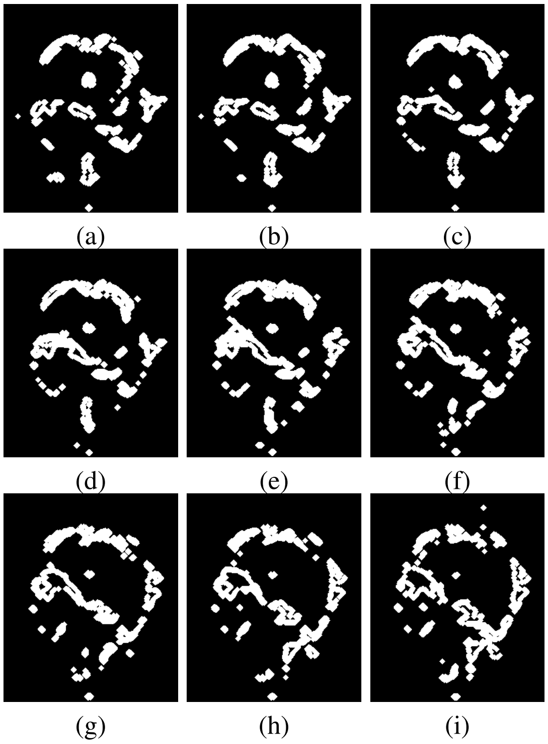

Figure 6. Region highlighting using the q-sigmoid function for the individual 100408 with task-fMRI images, in situations of emotional overload.

by individuals. On the other hand, regions that have not been used remain darkened.

Thus, the results obtained so far suggest that the proposed methodology is promising and indicates a new way of investigating methods for the segmentation of brain regions. Since the databases made available by the HCP have produced the knowledge of these new regions (also called *terra incognita*), the present work is on the way to contribute with new methods of understanding the brain correlations that, until the moment, were never observed.

Acknowledgment

We thank to FAPESP (Foundation for Research of the Sao Paulo State, Brazil - Project 2018/02612-7), CNPq (National Council for Scientific and Technological Development, Brazil), CAPES (Coordination of High Level Graduation, Brazil) and FEI (Foundation for Ignatian Education, Sao Paulo, Brazil).

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