BRAINX3: A New Scientific Instrument for the Acceleration of Hypotheses on Mind and Brain

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Abstract—"A mind which at a given instant should know all the forces acting in nature, as also the respective situation of the beings of which it consists—provided its powers were sufficiently vast to analyze all these data—could embrace in one formula the movements of the largest bodies in the universe as well as those of the smallest atom; nothing would be uncertain for such a mind, and the future, like the past, would be present to its eyes." Laplace (1814).

I. Introduction

When Galileo pointed the telescope, copied from a Flemish spectacle maker to the heavens, he was testing the then heretic heliocentric model of Copernicus. At the time that ideas were hard to develop or even express publically, data was even harder to obtain due to a lack of instrumentation. Now 4 centuries later, in the age of big data the situation has reversed: we have the capacity to rapidly accumulate petabytes of data that now seek ideas in order to become meaningful. Hence, the traditional model of science, as exemplified by Galileo, where the inquisitive human mind is testing hypotheses by matching them to experience, is challenged by an approach where an ocean of data points awaits ideas. This is largely an artifact of the increasing dependence of science on technology, which can autonomously spew out data at an ever-increasing rate. The risk of this development is that we deteriorate from a barbarism of specialization [1] to a barbarism of agnosia, where we willingly sacrifice knowledge in favor of maintaining a costly data generation machine. This is by no means an argument for a data free science, but rather an argument in favor of restoring the relationship between hypotheses and data in order to conserve the scientific model, as we know it.

In the mid 1990ies the OECD Global Science Forum showed the foresight that neuroscience would be facing a big data challenge and initiated a working group on Neuroinformatics which released two reports sketching the challenges of neuroinformatics 1999 and 20021, requesting the formation of an International Neuroinformatics Coordination Facility, which in a competitive call was placed in Stockholm. In this process two main schools of thought were at loggerheads. The first we could call the Bottom Up or Laplacian School, which believes that all data is to be collected and stored and the problem of interpretation and relevance can be postponed to some future moment relying on to be invented machine solutions. More importantly, it assumes that nature is ruled by bottom up causality, is deterministic and that through the accumulation of data, knowledge will emerge without further human intellectual interference. It is also this, so called, bottom up modeling belief that defines the philosophy implicit in current large-scale brain research projects and already articulated by Laplace in the early 19th century quoted at the beginning of this article [2]. The second school, which we could call the Counter Stream School, advocated a perspective where data should be collected, preserved and curated relative to specific theoretical and experimental contexts. Where theories and carefully selected target systems would provide a framework for the future use and interpretation of specific data sets. Now 20 years later we see that the Laplacian School has won the battle for resources but lost the one of science. This cannot be seen as a coincidence, which I further analyze in [3]. For instance, a recent study to reconstruct a 1,500 cubic micron volume of mouse neocortex showed that rather then advancing understanding, this ''omics'' effort revealed practically insurmountable problems faced by bottom up neuroscience, or as the authors put it "some may therefore read this work as a cautionary tale that the task is impossible" [4]. Laplace's determinism does not seem to translate well to the reality of empirical science as it is lived at the bench.

So if big data is the problem what is the solution? We do have to acknowledge that as the human mind is the prime instrument of science this also or especially holds for the study of the mind and its substrate the brain. Big data is not only a technical problem; it is also a psychological one. The human mind is not Laplace's demon and as a product of biological evolution has finite memory, limited reasoning capacity and comes equipped with surprising biases [5]. In addition, also our machine learning algorithms have not been able to overcome the classic symbol grounding problem or it still falls to humans to give meaning to regularities identified by automated classification and/or reasoning. Hence, given these considerations I propose that we do need to develop a new class of scientific instruments that aim at linking the human mind to data in the service of discovery. This discovery should be structured in the induction, abduction and deduction cycle of empirical science and advance theories as models of reality that are empirically adequate [6], allowing us to explain, predict and control the sources behind the observations we make. We could call these new instruments Hypothesis Accelerators and we have constructed the very first one at SPECS lab in Barcelona called BRAINX3 (Figure 1; brainx3.com).

BRAINX3 capitalizes on advances in visualization, sonification and immersive virtual reality technologies, combining them with cutting edge technologies from data

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analysis, statistics, data representation and Human Computer Interaction. It combines two fundamental components of the psychology of discovery. First, it follows a model of creativity. Since Poincare and Helmholtz the creative process is seen to comprise a number of stages [7]: preparation: the acquisition of domain knowledge; incubation: the rearrangement of knowledge by memory processes; insight/illumination: the conscious experience of a new idea; verification/evaluation: the assessment of the validity of the idea given the rules and conventions of the domain and upon acceptance elaboration to bring out all implications. The psychology of creativity directly pertains to the fundamental epistemological question of the logic of discovery or how can induction give rise to rules that can in turn be applied deductively? Charles Sanders Pearce called this stage: abduction. BRAINX3 defines a workflow that supports these four stages of the creative process. Secondly, BRAINX3 acknowledges that conscious awareness is only reflecting a sliver of mental states and experience is predated on subconscious operations [8-10]. Indeed, a relationship between states of (sub)consciousness and problem solving has been identified [11, 12] and it has been suggested that their computations are comparable [13]. Hence, using technology to either bring subconscious states to consciousness and/or to optimize conscious information processing relative to subconscious states can be considered beneficial in the exploration of large data sets because especially here humans are operating at the edge of their mental capacity.

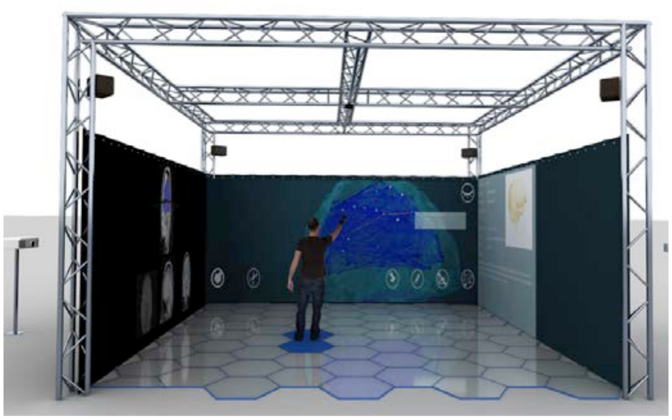

Figure 1: The BRAINX3 Neuroscience Hypothesis Accelerator [14] developed using the eXperience Induction Machine (XIM) [15] and the IQR large-scale neuronal simulator [16]. BRAINX3 divides the XIM space in four domains defined by each projection wall: Navigation overview (Left panel); Workspace (Middle); Knowledge display accessing the "semantomics" of the data derived from pertinent online databases [17](Right); User monitoring and experimental log (Back panel - not visible). The symbols at the bottom of the Workspace display represent – from left to right - "Reset", "Lesion", "Bookmark", "Stimulate", "Visualization mode", and "Analysis mode". At the right upper corner the icon for the, so-called, sentient agent is placed which provides user dependent guidance. User states are derived using a sensing glove for grasping movements and EDR, a wearable eye tracker, a sensing shirt measuring breathing and ECG [18]. The user can freely navigate through the space to control the zoom level while gestures are used to rotate the data visualization captured by a multi-modal tracking system. See text for further explanation.

The design of BRAINX3 allows the user to interact with complex neuroscience data sets through 4 distinct representations in XIM that support distinct actions of the user. XIM is an immersive and interactive 5x5 M equipped with 360 degrees projection, an interactive luminous floor, a marker-free tracking system, microphones, a spatialized sonification system and wearable sensors that has been constructed to conduct empirical human behavioral studies under ecologically valid conditions. We have used BRAINX3 for a number of studies of the human connectome most notably addressing the question of how lesions to the human brain affect its dynamics identifying a specific loss of coherence of neuronal activity and enhanced noise due to aging and or drugs [14]. We have placed emphasis on validating the approach we have taken by looking at the ability of novice users of BRAINX3 to extract causal structure from complex networks. In one study we compared the understanding of network structures between users of the state of the art connectomics tools against those using BRAINX3 and its immersive interactive big data exploration [19]. We observed that BRAINX3 users had a better understanding of complex causal structures than users of desktop tools. Subsequently we have evaluated the impact of the, so called, Sentient Agent (SA), which assesse in real time the mental state of the user by automatically evaluating their actions, ECG, EDR, breathing, eye movements and pupil dilation [20]. These measures are used to define a user model that includes their level of arousal, stress and cognitive load. The SA adjusts the complexity of the data presentation and the guiding cues in response to the state of the user. Reducing complexity at moments of high cognitive load and stress and increasing it when users signal to be under aroused. In a direct validation study of this closed loop data presentation system, we observed that users that were exploring an artificially generated network assisted by the SA made decisions more quickly. In addition the SA, on the basis of the cognitive load measures could predict their errors. This provides direct empirical support for the psychological model of data exploration that we have implemented in BRAINX3. Hence, BRAINX3 has shown to be scientifically relevant and empirically valid opening up new avenues for further applications.

II. Conclusion

The argument behind the development of BRAINX3 is that we need new scientific instruments that allow the human mind to be more efficiently connected to complex data. This is required in this case in order to re-establish the balance between data and theory in the study of the brain. BRAINX3 builds on the eXperience Induction Machine (XIM) and integrates a range of technologies from multi-modal HCI to real-time physiological sensing, large-scale neuronal simulation and omics scale data analysis. Our empirical validation studies have shown that BRAINX3 users have a better understanding of complex brain data than control groups using state of the art neuroinformatics tools. Giving further credence to the hypotheses that have driven the development of this new scientific instrument and encouraging its application to other big data domains.

The example of BRAINX3 also shows that it is of some relevance to not only develop neuroinformatics tools and use them but to also take the underlying human factors, interfaces, interaction and user models into account. In that sense the empirical validation of BRAINX3 might be relatively new for neuroinformatics tools, but should become part and parcel of the practice of developing these data accessibility instruments.

The question I have not addressed here is how data exploration is to be embedded in theory and what kinds of theories these should be, i.e. large scale brain networks can not be understood from the perspective of isolated microscopic scale theories. In our own work we have linked BRAINX3 to a multi-scale theory of mind and brain, called Distributed Adaptive Control (DAC) [21], which spans anatomy, physiology and behavior and is advanced at a range of levels from microscopic circuits [22] to integrated brain systems [23]. In addition, we have imposed an additional level of validation by linking BRAINX3 to diagnostics and prognostics in the treatment of stroke using patient specific structural and functional data [14], which we have combined with effective brain theory based (DAC) stroke interventions [24-26]. Hence, BRAINX3 foresees a future of neuroinformatics tools that will converge towards the confluence of system level brain theory, empirical observation and clinical impact as advocated all those years ago in the OECD-GSF working group. I predict that it will be a more cost effective way to make progress in understanding mind and brain and transforming this knowledge into societal relevance as opposed to churning wheel of the big data generator and waiting for the miracle of all the bits to fall in place. However, it does imply that one must have ideas that one is willing to submit to empirical scrutiny or, in other words, return to the core value of science.

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