Predictability in Science: Accuracy and Limitations
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PREDICTABILITY: PROPHECY, PROGNOSIS AND PREDICTION. A STUDY IN NEUROEDUCATION

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1. The Cognitive Space of Predictability

I would like to interpret predictability as a dynamical process in a cognitive space defined by three independent parameters: prophecy, prognosis and prediction. Three cognitive functions are engaged in this process: projection, anticipation and modelling which respectively apply to possible, actual and constructed worlds.

Parameters	**Functions**	**Worlds**
prophecy	projection	possible
prognosis	anticipation	actual
prediction	modelling	constructed

I will now try to describe this 3x3 table in order to display the framework of our following discussion on predictability and of the new concept of metaprediction.

Prophecy

It may seem odd to refer to prophets and prophecies in this scientific context but from the historical view of the human mind it is impossible not to consider the weight of this venerable capacity of announcing the future, denouncing the wrong paths and proposing favorable changes. Our culture is rich in prophecies old and new of every kind which are sometimes the motor of remarkable transformations in our societies. Science also has its prophetic dimension and we need to take it into account if we want to understand what predictability in science means. At particularly hard times 'scientific prophets' are most needed as John Paul II in his address of 12 Nov. 1983 to the Pontifical Academy gathered to discuss *The knowledge that builds peace* emphasized:

> Unarmed prophets have been the object of derision in every age, especially on the part of shrewed politicians, the supporters of power. But today must not our civilisation recognise that humanity has need of them?...the scientists of the whole world ought to be united in a common readiness to disarm science and to form a providential force for peace (*Papal Addresses,* 2003, p. 260).

Scientific prophecy is based on *projections*. This means that scientists may project into a possible future their personal views and wishes in order to produce a desiderable change. For instance, some fifty years ago some pioneers of artificial intelligence and computer science imagined a digital scenario for education, but this projection was received with wide skepticism and even strong opposition. Computers at that time were expensive and unaccessible to teachers and students, but good projections might work as 'powerful ideas' and may induce a radical change against all prejudices (Minsky, 1986, Papert, 1980, 1993). A decade ago Nicholas Negroponte in his book *Being Digital* (1995) described the coming of age of the digital era in education announced by the 'prophets' and today he leads an ambitious – and prophetic – program to empower millions of children with computers and communications, the OLPC, the one laptop per child initiative, a new projection towards a profound change in a globalized education (http://laptop.org/).

Something similar, and closely related to the computer revolution, is now unfolding in the new field of neuroeducation. We can make also the (prophetic) projection that in a generation from now the neurocognitive sciences will provide a radical new basis for learning and teaching and will open not only cognitive but also ethical issues of great impact (Sheridan, Zinchenko & Gardner, 2005, Battro, Fischer & Léna, in press). I will describe some landmarks in this prophetic educational endevour that has engaged many of us around the world and is leading towards a new view of the learning and teaching brains.

Projections are about *possible (future) worlds*. This means that they go beyond what is given but they are not fiction, even less science fiction. As Nelson Goodman said 'all possible worlds lie within the actual one' (Goodman, 1979). Projections are forecasts about something that will possibly happen given some necessary conditions, they are not dreams or fantasies. Projections, of course, can be seductive and tempting but can also lead astray. And most important, the ethical component is an essential part of any scientific projection and should be made explicit.

Prognosis

The term was coined by the physicians of antiquity and is still used in medicine, where prognosis and therapy are closely related in everyday medical practice. Physicians make a prognosis of the disease diagnosed in the patient. This interplay of the universality of the disease and the individuality of the suffering organism is the reason why medicine is science and art at the same time. Many disciplines share this double condition, for example in education the general sciences of teaching and learning are embodied in individual cultures and values. Neuroeducation is also under this intrinsic tension between the universal and the particular, a tension that is an important source of progress indeed.

Prognosis is based on *anticipations*. In the same way as the physician anticipates the unfolding in time of the disease and takes a number of decisions for the best treatment of the patient the scientist also anticipates the course of events and prepares the conditions or working scenarios that will help to unfold the discoveries and to control, if possible, their undesiderable consequences.

Anticipations are made in the *real (actual) world*. They should not be confused with projections which deal with possible (future) worlds. Anticipations are effective innovations, they are at the cutting edge of research, at the frontier of knowledge but never leave the real world, they never go beyond the actually given but they lead the transformation. Anticipations can fit and be successful, but they also can be premature or fail altogether.

Prediction

The capacity to predict is common to many animal species, it is a condition of survival (Llinás, 2002, Dehaene *et al.*, 2005). We need to better understand the neurocognitive processes involved in our capacity to predict. Science is the result of a consistent and permanent construction of predictions that can be traced in the evolution of the brain and in the development of the human mind. Science can be taught to children in schools because they are already able to make predictions, eager to test the validity of their own hypotheses and pleased to teach other children (Piaget, 1949, Charpak, Léna & Queré, 2005). This incredible teaching capacity is unique to the human species and can be analyzed with the conceptual tools and the technology of the modern neurocognitive sciences (Strauss, 2005, Battro, 2006).

Prediction is based on *representations or models*. We must recognize that the use of brain models and the interpretation of brain images have opened a whole new field of research. We now have the resources to explore the neuronal intimacy of several cognitive processes, and in some cases we can even predict the expected behavior from the brain images which represent the neuronal activy involved in the mental process. I call 'metaprediction' this prediction on predictions.

Models are *miniature or constructed worlds* that we can handle and simulate in our minds or in a computer. Models must be tested and when they fail the model becomes invalid. Karl Popper has also proposed that even when the model is verified it is still impossible to assert its universal and necessary validity because it could be falsified in the future (Popper, 1959). Models are not 'the' world but a – fragile and reduced – 'representation' of the world. The great discovery is that this formal constraint empowers the model to predict an event. We can, for example, identify the different neurocognitive processes that are involved in making Aristotelian or Newtonian predictions and this recent discovery implies that we can detect different models of the physical world in our brains (Fugelsang & Dunbar, 2005).

2. A Survey on Predictability

I propose now to discuss the three cognitive dimensions of predictability from the point of view of the neurocognitive and educational sciences.

a) *Prophecy, Projections and Possible Worlds*

Seymour Papert gives a lively example of a prophetic scientific vision. A mathematician by training he became a close collaborator of the psychologist and epistemologist Jean Piaget in Geneva and of the computer scientist Marvin Minsky at MIT, where they co-directed the famous Laboratory of Artificial Intelligence in the sixties. This double collaboration was substantial to introduce the computer in the schools around the world. Papert has described the elaboration of his prophetic view on the future of digital education with the following words (Papert, 1993, pp. 34-34):

> It was pure play. We were finding out what could be done with a computer, and anything interesting was worthwhile. Nobody yet

> knew enough to decree that some things were more serious than others. We were like infants discovering the world.
>
> It was in this situation that I thought about computers and children. I was playing like a child and experiencing a volcanic explosion of creativity. Why couldn't the computer give a child the same kind of experience? Why couldn't a child play like me? What would have to be done to make this possible?
>
> These questions launched me on a new quest guided by the Robin Hood-like idea of stealing technology form the lords of the laboratories and given it to the children of the world. A first step in the quest was to recognize that one of the sources of the technologist's power was the veil of esoteric mystery woven around the idea of programming...I saw the need to make computer languages that could be 'vulgarized' – made available to ordinary people and especially children.

This quotation expresses the profound personal engagement that fuels any worthy projection in the sciences and the origin of the prophetic vision that, in the case of the information and communication technologies, has changed the world of education. Papert invented the computer language called Logo that became a powerful tool in the hands of thousands of teachers and students. For those who were active in the first wave of the digital education it is clear that we are now repeating a similar cycle in the field of neuroeducation. We also feel the need to 'take away' the brain imaging technologies from the laboratories and bring them into the schools. In order to do that, first, we must have portable, reliable, simple and low cost brain imaging equipment (as was the case with the first PCs in the seventies) and second, we should train the 'neuroeducators' in the creative use of these machines. We are still quite far away from this prophetic scenario but we must prepare the field of neuroeducation to be able to cope with it, when the time will come. Only one generation ago very few were convinced by Papert's digital prophecies, similarly we shouldn't be disturbed by the skeptics of today about the future of neuroeducation.

b) *Prognosis, Anticipations and Actual Worlds*

Muchas veces me dicen que me anticipo a propiciar cosas que sólo serán posibles de aquí a 30 a 40 años. Pero eso no es exacto, porque preconizo lo que es actual y urgente, que ya existe en los países más adelantados, mientras mis contradictores no lo saben porque están 30 a 50 años atrasados y lo ignoran.

(Bernardo A. Houssay, 1967)

Anticipation is the result of a correct diagnosis of the current state of scientific research and a fair prognosis of its intrinsic development. It should not be confused with a projection, which is a forecast of future improvements. In other words, while projection invents the future, anticipation unfolds the present, they are two different – and complementary – cognitive functions. The following text is a strong statement about the value of anticipation and belongs to a master Argentine scientist, Bernardo A. Houssay, Nobel Prize in medicine (1948), the first to become a member of the Pontifical Academy of Sciences from Latin America (1936), a leading figure in promoting science in developing countries. He understood anticipation as an urgent scientific mission in his own time and country (Delofeu & Foglia, 1982):

> Several times I have been told that I anticipate and promote things that will only be possible in 30 or 40 years from now. But this is not correct because I support what is actual and urgent, what exists already in the most advanced countries, while my contradictors don't know that because they are 30 or 50 years behind and they ignore it.

In the same spirit Kim Sheridan, Elena Zinchenko and Howard Gardner (2005) anticipate some crucial ethical issues in neuroeducation when brain imaging techniques will become standard in the school practice. They take the hypothetical example of a teacher, Ms. E and a student Daniel with some minor learning disablity:

> In the first scenario we see Ms. E confronted with a variety of traditional assessments (e.g., standardized tests scores, last years' grades, current work) and a type of neurological report that will likely become standard in the near future. One of her core values as an educator is to help each student develop to the best of his or her potential, including seeking remediation for any learning disabilities. In an ideal case, a neurological evaluation yields a clear diagnosis to which an empirically valid remediation is yoked. However, it is likely that there will be many more like this hypothetical one: a report of atypical processing for which there is neither a clear diagnosis nor remediation.
>
> In assessing the fMRI report, Ms. E is expected to don a hat for which she is inadequately trained. In the face of her lack of expertise and the fMRI report's ambiguity, the report seems to reveal something 'true' about Daniel's functioning. She allows the biological finding to trump her observations as a teacher and Daniel's hitherto adequate performance in class. Drawing upon her classroom

> observations and educational training, Ms. E may have given Daniel a positive report for his current progress and perhaps worked out some in-class or at-home strategies for his minor attention and reading issues. However, faced with this picture of his brain function, she feels out of her depth and considers remediation strategies that may not be appropriate for Daniel's needs'.

The use of brain imaging technology in the practice of remediation and special intervention in this hypothetical case anticipates what might become common practice tomorrow by the increasing interaction between neuroscientists and neuroeducators in many other fields. We already have the successful example of the great change produced by the use of advanced technology in special education and rehabilitation (computer prostheses, cochlear implants, special software, robotics, etc). Something similar can be anticipated in neuroeducation when the intimacies of fundamental neurocognitive processes will become the targets of teaching and learning practices in all the disciplines, well beyond the current demands of remediation and cognitive enhancement in special cases. We expect that a new generation of 'neuroeducators' will be trained in the most diverse fields of the arts and sciences. We can expect great changes in the way we teach and learn because of this interaction.

c) Prediction, Modelling and the Constructed Worlds

> *The capacity to predict is most likely the ultimate brain function*
> (Rodolfo Llinás, 2002)

A historian of science would identify different steps of the path of predictability showing in some cases a strong weight of the prophetic dimension at the beginning of a specific scientific quest and an increasing weight of the prognosis dimension later in time. Then, at some point of the evolution of the sciences and technologies involved in our quest the new dimension of prediction will start to unfold and the path of predictability will show a radical change because of the possibility to make specific predictions in the new fields by modelling and testing. And again the new discoveries will start a new cycle of prophecies, prognoses and predictions, a quest without end.

A remarkable and most important extension of the concept of predictability arises from the neurosciences, in particular with the new possibility to make 'metapredictions' i.e. predictions about predictions during a cognitive task. A robust demostration about the possibility to infer behavior from functional brain images was provided by Stanislas Dehaene and colleagues (Dehaene *et al.*, 1998). In this experiment the subjects were asked to press a key with the right or the left thumb to decide whether digits presented visually were larger or smaller than 5. They used one-line brain activation measurements to predict the subject's decision on number comparison, reversing the standard practice which goes from the known behavior to the specific brain activity. In fact, the observers are doing a kind a 'reverse neurology', they were making 'brain predictions' on the motor behavior (*prediction 1*: left and right cortical activations predict respectively the right and left finger movements) to be applied upon the 'mental predictions' on the arithmetics (*prediction 2*: larger or smaller than 5). The whole experiment is about metapredictions: the observer predicts that a particular brain activation predicts the mental decision of the subject. Pressing the key is only the final step of a complex chain of brain events like identifying the name or Arabic symbol, interpreting it as a quantity, making a comparison with the given number (5) and making a quick decision (larger or smaller). This chain of brain events follows a well known space-time path in the cortex (Dehaene, 2006) measured in several fixed steps of milliseconds. Moreover, 'reverse neurology' opens the possiblity to predict not only some overt and well controlled behaviors – as in this experiment on number comparison – but also some covert behaviors and intimate mental processes (internal speech, emotions, visual imagery, etc) from their neuronal activity pattern. We must agree with the authors that this possibility raises important practical and ethical questions. In neuroeducation, we can imagine, for instance, that we will someday explore the learning process of the students by 'looking into their brains' in addition to the evaluation of their performance on a standard test.

A first step in this direction has already been taken, and is the following. It is well known that students have trouble overcoming naïve explanations about the movement of bodies, for instance. Andy di Sessa (1982) some decades ago showed with the aid of computers the amazing difficulty of students to interact in a Newtonian world where forces correlate to velocity and not to position as in Aristotelian mechanics. Most students have a preferred set of concepts (called phenomenological primitives by di Sessa) that are in contradiction with what they have learned in the physics class but they still use the 'impetus' idea that objects move in the direction you push them. In order to use the Newtonian model to correctly predict the movement of an object they must 'unlearn' the common intuitions of the Aristotelian physics. In a strong sense successful education implies many 'conceptual changes' of this type. The problem is that naïve students tenaciously hold on to their preferred model. In the same vein Jonathan Fugelsang and Kevin Dunbar (2005) have recently studied the brain images of students during a fMRI experiment on their preferred theories in physics. They have tested two groups of subjects, physics students and non-physics students looking at 'Newtonian' and 'naïve' movies where balls of different sizes fall at equal or different rates in a frictionless environment. If the balls fall as they expected they must press one key, if not the other key. For the naïve students the Newtonian film is erroneous, for the physics students (who made the correct conceptual change) it is the naïve film which is erroneous. In other words, the non-physics students predict that the larger ball will fall faster than the smaller one (as in the naïve film) while the physics students predict that both balls fall at the same rate (as in the Newtonian film). The difficulty in teaching physics is related to the fact that sometimes the old and naïve model persists in the student's mind even when the intended conceptual change appears to have taken place. The fMRI records an increased activation in the Supplementary Motor Area and in the Anterior Cingulate that may 'inhibit' those data that become inconsistent with the student's preferred theory in both groups. It is known that the Anterior Cingulate cortex is related to error detection and in general the medial-frontal cortex is activated by existing conceptual representations. This experiment shows that the physics students inhibit the counter-Newtonian data and that the non-physics students inhibit the counter-intuitive data. The metaprediction in this experiment is that the conceptual change should be reflected in the brain where the old model must be inhibited because it is detected as an error in order to give place to the new model. This is only a first – and indirect – method to test the value of metapredictions in neuroeducation but it opens a whole new horizon in the quest of predictability in science.

REFERENCES

Battro, A.M., Fischer, K.W. & Léna, P.J. (in press), *The educated brain*, Cambridge: Cambridge University Press.

Charpak, G., Léna, P. & Queré, Y. (2005), *L'enfant et la science. L'aventure de la main à la pâte,* Paris: Odile Jacob.

Dehaene, S., Le Clec'H, G., Cohen, L., Poline, J.-B., van de Moortele, P.-F. & le Bihan, D. (1998), 'Inferring behavior from functional brain images', *Nature Neuroscience*, 1, 7, 549-550.

Dehaene, S., Duhamel, J.R., Hauser, M. & Rizzolatti, G. (eds.)(2005), *From monkey brain to human brain*, Cambridge, MA: MIT Press.

Dehaene, S. (2006), *Psychologie cognitive expérimentale. Vers une science de la vie mentale,* Leçon inaugurale au Collège de France, 27 avril 2006.

Di Sessa, A. (1982), 'Unlearning aristotelian physics; A study of knowledge-based learning', *Cognitive Science*, 6, 37-75.

Foglia, V. & Delofeu, V. (eds.)(1981), *Bernardo A. Houssay. Su vida y su obra 1887-1971,* Buenos Aires: Academia Nacional de Ciencias Exactas, Físicas y Naturales.

Fugelsang, J. and Dunbar, K. (2005), 'Brain based mechanisms underlying complex causal thinking', *Neuropsychologia,* 43, 8, 1204-1213.

Goodman, N. (1983), *Fact, fiction and forecast,* Cambridge, MA: Harvard University Press.

Llinás, R. (2002), *I of the vortex: from neuron to self,* Cambridge, MA: MIT Press.

Papert, S. (1980), *Mindstorms: Children, computers and powerful ideas*, Cambridge, MA: MIT Press.

Papert, S. (1993), *Children's machine: Rethinking school in the age of the computer*, New York: Basic Books.

Piaget, J. (1949), *Introduction à l'épistémologie génétique*, (3 vol.), Paris: Presses Universitaires de France.

Popper, K. (1959), *The logic of scientific discovery*, Hutchinson, London.

Pontifical Academy of Sciences (2003), *Papal Addresses to the Pontifical Academy of Sciences 1917-2002 and to the Pontifical Academy of Social Sciences 1994-2002. Benedict XV, Pius XI, Pius XII, John XXIII, Paul VI and John Paul II* (2003), The Pontifical Academy of Sciences, *Scripta Varia*, 100, Vatican City.

Minsky, M. (1986), *The society of mind*, New York: Simon & Shuster.

Negroponte, N. (1995), *Being digital*, New York: Knopf.

Sheridan, K., Zinchenko, E. & Gardner, H. (2005), 'Neuroethics in education', in: J. Illis (ed.) *Neuroethics in the 21st century. Defining the issue in theory, practice and policy*, Oxford: Oxford University Press.

Strauss, S. (2005), 'Teaching as a natural cognitive ability: Implications for classroom practice and teacher education', in: D. Pillemer and S. White (eds.), *Developmental psychology and social change* (pp. 368-388), New York: Cambridge University Press.