Dynamics as a heuristic framework for psychopathology

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Abstract

The development of the mathematics of dynamical systems now offers a rigourous framework to deal with complex phenomenon evolving with time. The possible euristic value of applying dynamical concepts to the field of psychopathology is investigated here. Three levels of applications found in the literature are reviewed: metaphoric, qualitative and quantitative. Psychopathology seems indeed a field where the concepts of dynamics can offer important tools, both theoretical and empirical. Nevetheless, specific problems should be emphasized to obtain a more profound insight in normal and pathological mental phenomenon.

Contents

1 Introduction

The science of the mind is usually fond of importing new concepts from other disciplines. In the last thirty years, the development of the scientific interest in the behavior of complex systems has led to the emergence of notions such as chaos, attractors, sensitivity to initial conditions, etc. and to related numerical methods. The goal of this article is to estimate, on the basis of a literature review[1], the possible heuristic value, for psychopathology of the tools developed within the mathematical and physical framework of dynamical systems theory.

1.1 Explanation levels in psychopathology

Since mental diseases have been studied from biological to social level, psychopathology stands at the border between natural and human sciences. From the point of view of natural sciences, mental troubles are to be reduced to biological phenomena such as Korsakov syndrome or dementia in Alzheimer's disease. For the human sciences, mental disease are thought to be due to "mind" troubles or to be related to social factors such as relationships with close relatives (*i.e.* family) or to more general factors such as social frustrations. Nevertheless, the search for a linear causality from one level to another (from biology to social or backwards) has obviously failed. For example, no biological indicators are available yet to unambiguously decide for a specific mental trouble.

Such problems have led to emphasize the need for a multidisciplinary investigation of the bio-psycho-social nature of mental troubles (Engel, 1980; Freedman, 1995). These approaches usually explain the whole disease as the *sum* of each individual factor: biological, social and psychological. Nevertheless, a complex phenomenon, such as a mental disease, can hardly fit into a linear model and a co-determination of levels seems more probable. It is thus necessary to find tools to deal with circular causality and interactions between levels.

1.2 How dynamic are mental diseases?

The hallmark of mental troubles is the compulsive repetition of actions, fantasies or patterns of discourse which can be considered as successive conscious or unconscious acts. Mental diseases have an onset, evolve and can finally disappear. Moreover, specific temporal patterns appear in mental diseases whatever the observation scale: from milliseconds (response to stimuli, biochemical modulation or neuronal electrical activity) through minutes or

[1]The literature was scanned using two data bases: "pubmed" (url:) and "PsychInfo" (url:). Key words were: chaos, nonlinear dynamics, catastrophe theory, psychopathology, psychiatry, depression, schizophrenia, personality disorders, mood disorders, addiction.

hours (clinical interview) to years (time course of recurrence) or generations. During the acute period, changes in biological and behavioral rhythms are observed and during the whole life, specific alternations between disease and remission are also observed (Keller et al., 1986). The number of recurrences increases as a function of previous episodes and the illness patterns become more rhythmic with cycle acceleration finally resulting in rapid cycling or ultradian mood patterns (Kramlinger and Post, 1996; Huber et al., 2001a).

As an explanation for the occurrence and evolution of specific pathological patterns, several models have underlined the importance of initial conditions. In the psychoanalytic tradition, or even in cognitive psychotherapy, the possible influence of interactions and learning in infancy are assumed as important vulnerability factors for the development of mental disorders. Nevertheless, a longitudinal study, of more than one hundred subjects, from infancy to early adulthood, showed that the onset of behavioral disorder was highly variable (from 2 to 16 years). In most of the cases appearing during the adolescence, data revealed neither any prodromal or pathogenic symptoms nor excessive stress in earlier period (Thomas and Chess, 1984). The structural hypothesis of universal development stages and of early determinism of mental disorders is thus severely challenged. In fact, the evolution of mental troubles are highly contextualized and related to supports or constraints continuously acting on individuals.

1.3 From dynamical diseases to psychopathology

The application of dynamical systems theory to the modeling of physiological systems led to the definition of "dynamical diseases" (Mackey and Glass, 1977; May, 1978; Mackey and Milton, 1987). The hallmark of a dynamical disease is a sudden qualitative change in the temporal pattern of physiological variables (Bélair et al., 1995). From a dynamical point of view, such changes are related to modifications in the control parameters that lead to abnormal dynamics. This kind of dynamical changes have been clearly observed in neurological diseases (Milton et al., 1989).

In a review of 32 neurological and psychiatric diseases, two main characteristics have been considered as landmarks for a "dynamical disease" (Milton and Black, 1995): the recurrence of symptoms (10/32) and the oscillations appearing in the functioning of nervous systems (22/32). Within these fields, epilepsy and affective disorders are the best candidates for the application of the "dynamical disease" concept.

Such a framework can be generalized so that psychopathology may fit into the framework of "dynamical disease". As in the case of physiological functioning, it may be hypothesized that a mental structure is an emergent property associated to an underlying dynamics. Clinical signs and symptoms, observed in psychiatry, would thus correspond to qualitative dynamical changes related to modifications in control parameters (Globus and Arpaia, 1994; Moran, 1991; Schmid, 1991). Within such a conception, mental disorders and changes in mental states (such as changes following psychotherapeutic activity) in emotional states or in developmental stages may be influenced by parameters acting at several levels from physiological to social one. The presence of a symptom would thus emphasize the stability of the system in a specific parameter domain and thus be seen as an attractor. The articulation between levels of observation would thus be defined on the basis of changes in dynamical observables.

We describe the psychopathological literature, dealing with time evolution of psychopathological phenomema, using mathematical and physical concepts from dynamical systems theory. We will distinguish three levels of application: firstly, the study of the dynamics of complex systems can offer a set of *metaphors* for the description of mental phenomena, secondly *qualitative* insights of the behavior of systems can be obtained with the study of various models (such as neural networks or catastrophe models) and then *quantitative* characteristics of dynamical behaviors can be infered using nonlinear modeling and time series analysis. At last, criticisms and interests are given in order to favor a *rigorous* development of the application of dynamical concepts to psychopathology.

2 Metaphors

On the basis of the similarities between *general properties* of nonlinear dynamical systems and temporal phenomena observed in mental life, metaphorical associations between concepts have been undertaken. We distinguish different attempts using dynamical system paradigm as a metaphor in psychopathology. It has been proposed to understand the Self as an emergent property issued from dynamics of multiple iterations of brain processes, perceptual and social experience. Moreover, psychotherapists have used terms from chaos theory as an analogy for phenomena emerging during the course of psychotherapies (psychoanalytical and systemic).

2.1 The 'Self' as a dynamical system

Object-relation psychoanalysts (Mahler, 1968; Klein, 1948) have underlined how the extended system of personal relationship influence personality development throughout life. Intersubjectivity theory (Stolorow et al., 1994) examines how the interplay between the subjective worlds of the patients and the analyst gather into a new system. These two points of view led to conceptualize the 'Self' as adaptive and multi-stable state of consciousness about oneself and the 'world'. Thus, the 'Self' is able to adopt successively a set of discrete states evolving on the basis of contextual influences from microscopic level of physiology (Freeman, 1990) through macroscopic levels of psychology, social or cultural organization. This psychic structure could thus be conceptualized as an open, complex, dynamical system (Marks-Tarlow, 1999). Healthy selves self-organize and evolve to the edge of chaos, where they are capable of flexible reorganization in response to unpredictable social an environmental contingencies (Goldstein, 1997).

In these conditions, the 'Self' finds its origin in the continuous interactions between biological roots and the history of the subject. 'Self' is thus linked to preconscious and preverbal roots. Nevertheless, language is necessary to make the 'Self' conscious (Schwalbe, 1991). Consciousness, as a recursive process operating upon internal objects and external influences, does not precede acts but emerges out of it. An iterative loop of perception-action-reflection may lead to the emergence of a new level of complexity: a consciousness of consciousness.

2.2 Dynamical metaphors for the psychotherapeutic processes

The course of psychotherapy is not a linear progression towards a new healthier mental state. Psychotherapy is a multidimensional process involving biological factors, psychological and social experiences leading the subjects towards a new state (Bütz, 1993). The course towards this change is an enchainment of stable and instable periods that could be described as a non linear dynamic phenomenon (Langs, 1986; Bütz, 1993; VanEenwyk, 1991; Spruiell, 1993; Levinson, 1994). Analysts perceive patients as different along the psychotherapy course; this change can be conceptualized as a qualitative shift in patients' state *i.e.* a bifurcation in the dynamical systems theory (Moran, 1991; Priel and Schreiber, 1994; Verhuslt, 1999).

Moreover, the process of interpretation during a psychotherapy can make the psychological system more sensitive to new perturbations (Bütz, 1993; Verhuslt, 1999). The psychotherapist's function, especially through his interventions, is to stabilize or destabilize patients' mental processes and their way of thinking or telling their narrative. The therapeutical situation can thus be viewed as a dynamical process where a common system is co-created in the interaction between therapist and patient (Elkaïm, 1990; Lonie, 1991).

The therapeutic frame (regular appointments and stable environment) is designed to allow the emergence of a sampling of the patient's inner world. This phenomenon has been interpreted through the concept of self-similarity. At any level of examination: within the whole case history, during a single session or a single dream, one can observe the patient own "signature", a recognizable pattern of his/her mental life (Lonie, 1991; Moran, 1991). Certain aspects of psychoanalytical situation such as unconscious fantasies have also been viewed as a form of strange attractor (Moran, 1991; Quinodoz, 1997; Galatzer-Levy, 1995) or the repetition of some themes in the course of the therapy as a limit cycle (Lonie, 1991).

The sensitivity to initial conditions and the unpredictability of complex phenomena is an important analogy between nonlinear dynamical systems and psychotherapeutic situations (Bütz, 1993; Lonie, 1991). Even if the individual's mental life and behaviour is powerfully affected and determined by precocious experiences, repetitions are not strictly identical and some small elements could make the evolution unpredictable. The evocation of the history of the patient or the focalization on certain events or feelings can have unpredictable effects. Therapy can thus be considered as an extended series of well-timed perturbations which serve gradually to disrupt the strange attractors characteristic of the patient's fantasy-behavioral coupling (Moran, 1991).

Systemic therapy has used the concepts from the general systems theory for a long time. The models from nonlinear dynamical systems are thus a kind of "natural" extension for this practice (Koopmans, 1998; Miller et al., 2001). The time evolution of a family system goes through ordered and disordered phases (Brabender, 2000) where the symptom signs the inability of the group to overcome crisis. Family therapist can be considered as a catalytic factor for changes in the family functioning leading the emergence of a new state (Ricci and Selvini-Palazzoli, 1984; Elkaïm, 1990).

2.3 Conclusion

The properties of nonlinear dynamical systems are obviously appealing for the description of complex mental phenomena. In fact, the metaphorical use of dynamical concepts might be a first movement to get away from strictly medical models based on a linear explanation of the onset and the evolution of mental disorders. In that sense, nonlinear dynamical analogies can offer new tools to deal with complex situations encountered in the clinical practice.

Nevertheless, several caveats need to be avoided. The distance between mathematical concepts and psychological (or psychoanalytical) theories needs to be questioned precisely (Denman, 1994; Kincanon and Powel, 1995). Does mathematics throw a light on psychology or does it darken it? What is exactly the nature of the explanation expected from such analogies (Gardner, 1994)? It is important to avoid errors due to superficial comprehension of precise scientific concepts (Sokal and Bricmont, 1999).

Finally, such analogies can be used as a starting point for a scientific enquiry into mental phenomena and should be tested on qualitative modeling or empirical quantitative studies.

3 Qualitative

Qualitative models are related to the introduction of explicit constraints on the definition of a *specific dynamical system* supposed to model the empirical system taken into account. Two types of dynamical systems have been taken as models in psychopathology: first, gradient systems related to "catastrophe theory" have been considered, then the development of neural network introduced another kind of modeling.

3.1 Gradient systems

The state of a system at time t can be described by a set of variables $\psi(t) = \{\psi_i(t)\}$ (ψ_i are thus called *state variables*) and that a set of parameters, denoted c_α ($1 \leq \alpha \leq k$), controls the qualitative properties of the system's time evolution (c_α are thus called *control parameters*). The dynamics of the system is said to be described by a *dynamical system* when[2]:

$$\frac{d\psi}{dt} = \mathbf{f}\left(\psi, c_\alpha, t\right) \tag{1}$$

with $\mathbf{f} = \{f_i\}$. The general study of systems represented by equation (1) is a very difficult problem. It can be made more tractable when two assumptions are added (Gilmore, 1981):

1. If the functions f_i are considered as independent of time, the dynamical system is now an *autonomous dynamical system* and powerful statements can be made about such systems which depend on a small number of parameters ($k \leq 4$).

2. It can be noticed that in equation (1) the functions f_i look as the components of a force. With the assumption, inspired from mechanics, that all the functions f_i can be derived as the negative gradient (with respect to the ψ_i) of some potential function $V(\psi_j, c_\alpha)$:

   $$f_i = -\frac{\partial V(\psi_j, c_\alpha)}{\partial \psi_i}$$

   the resulting system:

   $$\frac{d\psi_i}{dt} + \frac{\partial V(\psi_j, c_\alpha)}{\partial \psi_i} = 0 \tag{2}$$

   is a *gradient system* ($\dot{\boldsymbol{\psi}} = -\boldsymbol{\nabla}_{\boldsymbol{\psi}} V$). This kind of system is much more tractable than the other systems described previously.

Dynamical systems theory deals with the solutions $\psi_1(t)$, $\psi_2(t)$, ..., $\psi_n(t)$ of equation (1) which define trajectories (*i.e.* time evolution) of the system. Of particular interest are the equilibria ($d\psi_i/dt = 0$) of dynamical and gradient systems. They define the states where the system can settle in, either, a stable or unstable manner.

[2]For a more general statement about the time evolution of a system and the hypothesis that lead to the somehow reduced dynamical system description, see Gilmore (1981, p. 3–5).

Elementary catastrophe theory is the study of how the equilibria $\psi_j^e(c_\alpha)$ of $V(\psi_j, c_\alpha)$ change as the control parameters c_α change for gradient systems. In that sense, elementary catastrophe theory is a quasi-static theory since it is only concerned by the equilibrium points of a dynamics and how they change when the control parameters are varied (Thom, 1977a; Arnol'd, 1992).

These models have been mainly used to model the emergence of discontinuous behaviors out of continuous parameter variations. The application of catastrophe theory to concrete phenomenon can be divided into the *'metaphysical'* way and the *'physical'* way (Thom, 1977b).

The metaphysical way considers the generality of elementary catastrophe as justifying the use of archetype situations to describe phenomenon where the nature of the dynamical systems that produce them is unknown. This method lead to qualitative models that can be used analogically with real situations.

The dichotomy between anorexia and bulimia is an archetypic example (Zeeman, 1977). The starting point of the model was the observation that an anorexic loses access to normal attitudes toward food and that many sufferers develop bulimic phase. During theses cycles attitudes toward food switch catastrophically from one extreme to the other, and they never take on normal intermediate values. These are the hallmarks of the cusp catastrophe which was used to model this behavioral trouble. A more sophisticated model added the sleep/wake cycle to the preceding cusp model and thus develop a geometrical non-trivial double cusp model (Callahan, 1982).

Catastrophe theory has also been used in a set of other models in clinical psychology (Weiner, 1977; Galatzer-Levy, 1978; Scott, 1985). Catastrophe model based on the attention focus has been proposed to deal with manic/depressive illness (Johnson, 1986). Emotional numbing associated with post-traumatic stress disorder (Glover, 1992) and other emotional responses (Lanza, 1999) have also been modeled using cusp catastrophe such as the relationship between alcohol intoxication and suicidal behavior (Hufford, 2001). In the case of schizophrenia, catastrophe models provided ways in which neurochemical and environmental influences could interact so that very small changes in either variable may produce the rapid changes in intensity of psychosis (MacCulloch and Waddington, 1979) The dopaminergic hypothesis has also been investigated using this framework (King et al., 1981).

From a more general standpoint, the possible heuristic value of Thom's dynamical theory to the Freudian metapsychology has been evaluated (Porte, 1994). On the basis of a careful parallel between both authors, it can be estimated that positivists caveats of Freud's theory find a natural solution in modern dynamical theories.

The physical way applies when the dynamics is indeed described by a gradient system. It is the case for example in physical systems for phase transitions in thermodynamics or caustics in optics (Poston and Stewart, 1978; Gilmore, 1981).

An exemplary modeling of alcohol consumption follows such a perspective (an der Heiden et al., 1998). The model is based on the mathematical expressions relating general phenomenon supposed to drive alcohol consumption (denoted A). The authors reported several stage of a qualitative model which final expression is:

$$\frac{dA}{dt} = F - r.A + \sigma \frac{A^2}{1 + A^2} \tag{3}$$

where F (frustration) is considered as a constant force driving alcohol consumption (such as life conditions, habits, social environment...), r is related to the disagreement of alcohol intake (illness, social values...) and the last term with parameter σ is a nonlinear auto-catalytic model. The study of the equilibria of this model leads to describe the phenomenology of drinkers typology and a cusp catastrophe was found in the description of the bifurcations. The discussion of the model show how control parameters can be varied to change the drinking behavior and thus may be of interest in the clinical practice. Moreover, This study demonstrates that the interaction of very few "mechanisms" results in a large manifold of different kinds of behavior.

3.2 Neural networks

The first use of neural networks has been devoted to provide *models of brain functioning*. Two major class of models can be differentiated: parallel distributed processing (PDP) models (McClelland et al., 1986a,b) and attractor neural network (ANN) models (Hopfield, 1982; Amit, 1989). We will only review here some models using ANN to deal with psychiatric syndromes (other models can be found in Rialle and Stip (1994), Aakerlund and Hemmingsen (1998) or Huberman (1987)). Neural networks have also been used as models of *symptoms dynamics*.

Attractor neural network models are based on systems such as (Hopfield, 1982):

$$S_i(t+1) = F(\sum_j w_{ij} S_j(t) - \theta_i) \tag{4}$$

where $S_i(t)$ is the state of "neuron" i at time t, w_{ij} is the "synaptic weight" between neurons i and j and θ_i is the threshold. Such system has computational abilities since memories are stored as attractors of its dynamics; so that, as an content-addressable memory:

- memories (or patterns) are retrieved according to similarity to the input
- generalizations based on different memories are possible
- memories are distributed across all neurons, and are not localized

An alterations of these functions, related to changes in the control parameters, may thus simulate cognitive impairments in some mental disorders.

3.2.1 Models of syndromes

Manic-depressive illness An interpretation of manic behavior has been proposed on the basis of a classical Hopfield network (Hoffman, 1987). The increase of noise (related to the steepness of the slope of the transition function) causes an increase of transitions between attractors. This behavior of the network has thus been related to the transitions between thoughts in manic patients.

Another model consider depression-like and manic-like behavior as attractors of a dynamical system (Globus and Arpaia, 1994). The same formalism is thus used at a higher level where attractors represent the overall behavior. It must be emphasized, that this model is clearly similar to a catastrophe model.

Schizophrenia On the basis of ANN, schizophrenia has been interpreted as the result of the overloading of the network memorization abilities (Hoffman, 1987). In fact, overloading causes the creation of spurious attractors from which the network cannot escape. Delirium has been associated with such a process. Troubles in cortical pruning, during development, lead to a decrease of cortical synaptic contacts and would thus decrease the memorization ability of the cortical network in schizophrenic patients (Hoffman and Dobscha, 1989; Hoffman and McGlashan, 1994, 2001). The presence of spurious attractors could be the analog of the three types of symptoms: strange outputs, independent submodules, and independence of modules functioning in front of inputs. This model has been discussed in David (1994). A network based on spreading activation was also proposed to model how an initial paranoid state becomes crystallized into a fixed delusion in schizophrenia (Vinogradov et al., 1992).

The defect of generalization and/or of taking into account the context in schizophrenic patients has been related to dysregulation of dopamine transmission (Cohen and Servan-Schreiber, 1992). Such changes in the interactions between cortical and sub-cortical structures could reduce the size of attractors in patients when compared to controls (Tassin, 1996). Nevertheless, the observed increased variability in behavior among schizophrenics, could also been related to chaotic dynamics in the central dopaminergic neuronal system (King et al., 1984).

3.2.2 Time-course of affective disorders

Episodes of affective disorders have been analogically compared to firing in neuronal networks (Huber et al., 2000b,a, 1999). A mathematical model based on a nonlinear dynamical system influenced by noise has been proposed:

$$\tau_x \frac{dx}{dt} = -x - \sum_i a_i^{\nu} w_i (x - x_i) + S + gw \tag{5}$$

where τ_x is a relaxation time constant, a_i^{ν} represents the activation states ($\nu = 1$ or $\nu = 2$), i ranges over four different states, w_i are coupling constants and x_i describes different activation levels. S represents the control parameter (corresponding to an ongoing disease process), and gw represents a Gaussian white noise to take into account environmental or endogenous stochastic influences.

The dynamic behavior shows that, in the course of the illness, noise might amplify sub-clinical vulnerabilities into disease onset and could induce transitions to rapid-changing mood pattern. In this model, based on cooperative effects between deterministic and random dynamics, noise increases the spectrum of dynamic behaviors.

Furthers modifications of this model, based on a feedback mechanism for episode sensitization, permits to strongly support the importance of episode sensitization as fundamental mechanism for the disease's progression in affective disorders (Huber et al., 2001a,b).

3.3 Conclusion

The introduction of specific kind of dynamical systems as models in psychopathology provide a global framework for the description of changes in psychopathology. Based on the generality of the formalism it is thus possible to describe various levels of observations within the same model. Nevertheless, even if these models introduce more constraints than in analogical use of dynamical concepts, it is not always clear whereas they constitute real model or mere elaborated metaphors.

These models thus need development towards empirical empirical tests. The introduction of quantitative methods may fill the gap between qualitative modeling and empirically observed dynamics.

4 Quantitative

Empirical studies quantifying the characteristics of observed dynamics are needed to estimate the scientific and clinical value of dynamical paradigm in psychopathology.

4.1 Data fitting

The presence of a "catastrophe" can be infered either on the basis of observation or from the study of a model. Empiricists would prefer that "catastrophe" could be proved and measured on the basis of experimental data.

The theoretical analysis of the behavior of systems in the neighborhood of singularities allow one to define critical phenomena that should be observed for a catastrophe model to apply. These phenomena have been called *catastrophe flags* (Gilmore, 1981). The first ones (modality, inaccessibility, sudden jump) have usually been taken as qualitative indices for the 'metaphysical' application of catastrophe theory. The other one (divergence, hysteresis, divergence of linear response, critical slowing down and mode softening, anomalous variance) are usually more difficult to observe or to describe. Such 'flags' have been infered in development stages (van der Maas and Molenaar, 1992).

Three quantitative approaches to the problem of testing the fit of behavioral data to catastrophe models have been developed. The first has taken stochastic difference equations as a basis and uses the methods of moment to estimate model parameters (Cobb and Watson, 1980). The second uses polytope search curve-fitting procedure to obtain maximum likelihood estimates of the model from the observed data (Oliva et al., 1987; Lange et al., 2001). The third approach is in the form of least-square regression (Guastello, 1982, 1987). This last method has been discussed in Alexander et al. (1992) and Guastello (1992).

The analysis of a cusp catastrophe used to model adolescent alcohol use have shown that dispositions should be viewed as the normal parameter and situation pressure as the splitting parameter of the cusp (Clair, 1998). Statistical analysis of empirical data using polynomial regression have shown that the cusp model better fit the data than the alternative linear models (Clair, 1998). Such procedure have also been used in the test of anxiety theory in the context of sport performance (Hardy, 1996).

4.2 Time series analysis

It is out of the scope of this review to develop a complete methodological overview. For complete references, see Kantz and Schreiber (1997); Grassberger et al. (1991); Abarbanel et al. (1993); Ott et al. (1994); Badii and Politi (1997).

Time series analysis deals with the quantification of the 'complexity' in the sequence of observed data. From the dynamical point of view, the first step is the reconstruction of the trajectory of the system within its phase space, then geometrical indices (such as dimensions) or dynamical indices (such as entropies) are computed. It has been shown that these indices should be statistically validated using surrogate data methods (for a review see: Schreiber and Schmitz, 2000). When data are discrete (or when the continuous dynamical system is 'properly' discretized), the characterization of the dynamics uses symbolic methods (Badii and Politi, 1997).

4.2.1 Brain dynamics

The central nervous system can be considered as a complex system which can be modeled within the dynamical system theory. For example, nonlinear dynamics provides new methods for the investigation of EEG signals.

Depression Studies of brain dynamics in depression have mainly shown a decrease of the first Lyapunov exponent for sleep stage IV in depressed patients when compared either to controls (Roschke et al., 1995b) or schizophrenic patients (Roschke et al., 1994). Unipolar depression is characterized by specific brain dynamical patterns of low complexity which evolve during pharmacological treatments (Nandrino et al., 1994; Pezard et al., 1996). Nevertheless, the recovery of a healthy brain dynamics is dependent upon clinical history: in the case of patients with recurrent episodes, even after a clinical improvement similar to that of first episode patients, brain dynamics did not recover the complexity level of control subjects. Changes in brain dynamics have been correlated with clinical evaluation of depressive mood in three depressed patients (Thomasson et al., 2000). These results were confirmed in the case of a 48-hour rapid cycling patient (Thomasson et al., 2002).

Schizophrenia Brain dynamics was studied in schizophrenic patients both during sleep and awake states. REM sleep in schizophrenic patients is characterized by a lower Lyapunov exponent (Roschke et al., 1995a). This altered brain dynamics could correspond to an impairment of the safety function of dreams (Keshavan et al., 1990). In addition, it has been shown that EEG's dimensionality was reduced during sleep stages and REM in schizophrenic patients (Roschke and Aldenhoff, 1993).

During awake states, nonlinearity and correlation dimension computed with spatial embedding of EEG data are lower in schizophrenia (Lee et al., 2001b; Jeong et al., 1998). Moreover, Lyapunov exponents also decrease in schizophrenia (Kim et al., 2000). When time embedding is used, spatial heterogeneities are demonstrated by correlation dimension (Lee et al., 2001a).

Finally, using mutual cross prediction (Le Van Quyen et al., 1998), it has been shown that the driving system was shifted to the frontal channel after 4-week trial with clozapine in schizophrenia (Kang et al., 2001).

Other physiological indices Time series of heart period and respiratory rhythms obtained from normal controls and patients with panic disorder were analyzed (Yeragani et al., 2000, 2002). Results showed that approximate entropy and largest Lyapunov exponents were higher in patients in normal breathing condition (Yeragani et al., 2002).

4.2.2 Symptoms dynamics and therapies

Mood disorders The alternation between depressed and manic episodes in bipolar troubles constitutes an important illustration of symptoms dynamics (e.g. Wehr and Goodwin, 1979; Wehr et al., 1982). In order to assess whether the time evolution of mood modifications in bipolar trouble are related to stochastic or deterministic dynamics, daily scores to analogical mood scales have been recorded from one to two years and a half (Gottschalk et al., 1995). Linear (autocorrelation function and power spectra) and non-linear (phase space embedding, correlation dimension, recurrence plots and surrogate data testing) were performed on the data obtained from seven rapid-cyclers and twenty-eight control subjects. Six out of the seven patients depicted convergent estimates of the correlation dimension whereas none of the controls did. Together with the complex power spectra this result indicates that mood in patients with bipolar disorder is not really cyclic contrary to the current opinion. Nonetheless, self-rated mood in patients is more organized than in control subjects and can be characterized as a low-dimensional chaotic process.

In a similar study (Woyshville et al., 1999), patients and control generated time series data, using a visual analog scale to quantify their mood. The results showed that patients display more variability but less complexity (measured by fractal dimension) in their time series than controls.

Schizophrenia Time-course of schizophrenic episodes can be investigated as a non-linear phenomenon. Daily assessment of psychotic derealization in fourteen schizophrenics have been studied during a period lasting between 200 and 770 days. Phase space reconstruction, nonlinear forecasting methods and surrogate data testing were applied to these time series. Time evolution of psychotic symptoms were classified as non-linear dynamics (8 patients out of 14), linear dynamics (4/14), and stochastic evolution (2/14). These results show that schizophrenia can be considered as a nonlinear dynamical disease, controlled by a low dimensional attractor (Tschacher et al., 1997). More descriptive methods might also be valuable to the interpretation of symptoms trajectories in schizophrenia (Tschacher and Kupper, 2002; Kupper and Tschacher, 2002)

Addiction Single-case studies have shown that daily alcohol consumption assessed during a five-year period can be modeled using multi-scale nonlinear methods (Warren et al., 2003; Warren and Hawkins, 2002).

Psycho-social crisis intervention In a sample of 40 in-patients of a psychosocial crisis intervention unit, time series data were obtained by self-rated evaluation on mood, tension and cognitive orientation (Tschacher and Jacobshagen, 2002). In crisis intervention, outward cognitive orientation generally preceded improved mood so that cognitive orientation is responsible of the experienced affective effects of crisis intervention.

Psychotherapy courses To test empirically the proposal that psychotherapy can be viewed as a self-organized dynamical system, 28 psychotherapy courses have been evaluated (Tschacher et al., 1998). The course of the therapies was characterized by a decrease of degree of freedom and an increase of order. Moreover, these results were independent of the kind of therapy and increase of order was related to positive outcomes of therapy.

4.2.3 Dynamics of cognitive processes

Time series generated, in a simple binary choice task, by schizophrenics were more interdependent than that of controls, suggesting that their behavior is less complex (Paulus et al., 1996, 1999). Moreover, schizophrenic patients exhibited significantly less consistency in their response selection and ordering, characterized by a greater contribution of both highly perseverative and highly unpredictable subsequences of responses within a test session (Paulus et al., 1996). Schizophrenic patients also are significantly less influenced by external stimuli than are normal comparison subjects (Paulus et al., 1999). This dysregulation is stable over time and independent of psychosocial factors and symptomatic fluctuations (Paulus et al., 2001).

In motor and perceptual tasks, schizophrenic patients exhibit a higher instability in their movement's process (horizontal finger oscillations) and a higher reversal rate in the perception of an ambiguous figure (the Rubin vase) compared to matched controls. Moreover, motor and perceptual measures were unrelated. These results suggest that alterations observed in the motor and perceptual dynamics in schizophrenia are be supported by a common underlying mechanism (Keil et al., 1998).

Dynamical quantification of language in schizophrenia (Leroy et al., 2003) have shown that the probability transition between macro-clauses and micro-clauses is lower in schizophrenic patients than in controls. This result can be view as a deficit in the dynamical access to the context level in schizophrenia.

4.2.4 Clinical Interviews

During clinical interview, one can focus either on the patient himself, or on the patient-therapist interaction.

Brain dynamics In a pilot study (Rockstroh et al., 1997), time series were obtained from electroencephalographic records during clinical interviews with 10 schizophrenic (6 paranoid, 4 disorganized) and 2 depressive patients. The time sequence of thought disorders (unusual thought contents, sudden change in topic, thought stopping,...) were also assessed.

The paranoid subgroup has been characterized by a lower complexity but more critical transitions in the EEG when compared to disorganized and depressive patients. But, such results are hardly correlated with a particular symptom, or to an underlying cognitive process. Furthermore, sudden phase transitions in brain activity were significantly enhanced prior to expressions of thought disorders that were detected by the interviewer and an observer in the conversation, compared with time periods during the interview without such symptoms.

Cardiac dynamics Since cardiological markers are related to the emotional behavior, they might be of interest to assess the complexity of patient-therapist interaction (Redington and Reidbord, 1992; Reidbord and Redington, 1992, 1993). Patient's cardiac dynamics is less complex when talking about important topics than for more distant topics. In the case of the therapist, it has been shown that cardiac dynamics depict a higher complexity when the therapist feels something *with* the patient rather than *about* the patient. Similar results were found in a study of 20 patients where variation in the complexity of heart's dynamics was observed when topics changes (Pincus, 1991).

Patient-therapist interaction The communicative process between patient and therapist needs to be studied (Langs and Badalamenti, 1994). To contribute to the construction of research methodology, patient-therapist interactions were encoded by means a matrix, in which each column represent a time series obtained by responses at questions about the sequence of interactions (Rapp et al., 1991). By this method, time series were obtained and a complexity score was computed.

Psychotherapy is also viewed as a chaotic process, and tools of non-linear dynamics are used to quantify this qualitative hypothesis. A single case was analyzed, by means of a time series obtained from the patient-therapist interactions (Schiepek et al., 1997). It has been shown that the time series is non-periodic, and the technique of surrogate data demonstrates that this non-periodicity is caused by a chaotic dynamics, and not by a stochastic process (or by noise). Fractal dimension and largest Lyapunov exponents revealed the presence of an attractor, which characterized the chaotic process of the therapy. Nevertheless, from a clinical point of view, the goal of a therapy is to lead the patient toward change rather than to stability, thus the methods used to characterize stationary dynamical systems are hardly adapted. The same data were thus re-analyzed (Kowalik et al., 1997) and demonstrate that, critical transitions appear during the therapeutic process, so that a non-stationary approach of the phenomena is necessary.

4.2.5 Family system

Family systems may be described by a 5-R's model where the four components (rules, roles, relationships and realities) are determining the fifth R (response pattern). In order to test the basic assumption of this model a family discussion was video-taped and analyzed (Pincus, 2001) using the orbital decomposition procedure (Guastello et al., 1998). The author make the hypothesis that the family response patterns during the discussion will show evidence of both coherence and complexity.

The family conversation was transformed into a symbolic sequence. Entropy measurements demonstrate the existence of a local coherence for string lengths equal to 3 and provide evidence for low dimensional chaos within the global family discussion.

4.3 Conclusion

These studies demonstrate the importance of temporal evolution in psychopathology. Aside from methodological drawbacks, dynamical processes have been characterized at several levels from physiological to linguistic one. Moreover, several studies have shown correlation between dynamical processes at different levels: brain dynamics and mood assessment, cardiac dynamics and emotions induced during interviews.

5 Conclusion

We have explored three ways of using mathematical and numerical dynamical concepts in psychopathology. We can conclude that the metaphorical description of mental troubles and changes are beginning to be modeled and tested empirically. More efforts are still needed to introduce an adapted methodology to the field of psychopathology. In fact, empirical tests decribed here are usually either data fitting to models or time series analysis (either of continous or discrete data). These two approaches are mainly "data-driven" *i.e.* they do not rely on a "theoretical" model to be tested in the data exploration (even when they are based on a model such as a catastrophe model). This interaction between models and data exploration is certainly a promising perspective of the application of dynamical systems to psychopathology.

The application of dynamical methodology to the "human sciences" are, however, still in its infancy. Several problems are to be worked out:

1. The development of accurate quantitative tools on short time series are clearly needed since the numerical methods imported from physics are highly data demanding.

2. The emphasis has been mainly given to deterministic modelling because of the fascinating properties of deterministic chaos. Nevertheless, stochastic or deterministic description are only a problem of scale and choice (in physics, molecular dynamics are deterministic but stochastic and statistical description of a gas is usually prefered for macroscopic scale). Thus, the choice of a model should not be obscured by some 'fascination'.

3. Quantification has long being the ideal of science. However, carefully designed qualitative models might be more informative than the computation of (ill-founded) quantitative indices.

Psychopathology is an adapted field for dynamics since it deals with entities with clear time evolution. Nevertheless, it could be misleading to imagine that dynamics can be directly imported in the field of psychopathology without considering its specificity. Different scales usually means that different tools adapted are to each kind of measures.

The behavioral, biological and clinical data that are mostly used in the study of mental troubles are observed from one sample at a single time point. Those data are informative but lack sensitivity to the frequency of behavior and hence to its temporal organisation. Thus the measurements of dynamical complexity are complementary to the first kind of empirical data. These studies are an useful tool for the comprehension of mental and behavioral changes. They allow one the study of the interaction between several factors and thus avoid the reduction of mental trouble to the effect of one single factor.

Because several levels interact, it is important to focalize attention on break or changes of state. The ruptures or the dynamical changes are observable at the different observation levels. Clinical data are concordant with such a point of view since changes are simultaneously observed in neurophysiology, in the strategy of thinking, the kind of beliefs, the types of behavior or the transactional activities. The only common point susceptible to be study is these ruptures in dynamics.

Moreover, open systems are by definition coupled with their environment. Studying human being implies that researchers take into account the contexts in which a behavior is developed. We must not have only knowledge about the system itself but also about the way it uses to interact with its environment. Contexts are necessary the broadest possible and imply physiological parameters, ecological, familial, social and cultural elements. A last point must be underlined: the role of observers. An observer placed in an environment has necessarily an effect on the observed system.

The generalisation of the "dynamical disease" concept to mental troubles may open several clinical perspectives:

1. From the point of view of diagnostics, the possibility of defining dynamical characteristics specific of a disease (such as a specific rhythm in a biological functionning) would offer a tool for the biological side of psychopathology.

2. From the point of view of therapeutics, the isolation of factors that may influence the behavioral and/or mental changes would offer, to the clinicians, several paths of action. In that case, changes would be possible either on the basis of a changes in the control parameters or on the basis of a perturbation depending upon the level of the intervention (biological, psychological or social). It is thus possible to imagine new therapeutical ways based on valid models of the dynamics underlying the mental trouble.

3. From a theoretical point of view, the model of a "dynamical disease" underlying mental troubles seems more legitime than a linear "medical" point of view. Clinical signs or symptoms can be considered as discontinuous changes based on continuous changes in control parameters. Thus dynamical systems theory seems particularly well adapted to the study of mental troubles.

   It is thus important to develop the methodology of dynamical systems towards (rigorous) applications in the "human sciences" and then to integrate these tools into more classical psychopathological studies. It seems particularly important to emphasize the study of temporal dimension of psychopathological phenomena.

   Such a dynamical point of view decrease the ontological gap that has been hypothesized between normal and pathological mental activities: it favors an underlying continouous point of view even if the behavioral observables are clearly discontinuous.

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