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Computational diagnosis of Shwachman-Diamond syndrome through cognitive and dialogical investigations

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Abstract

Shwachman-Diamond disease is a rare autosomal recessive disorder with a ubiquitous impact on the physiology, life, and autonomy of individuals, including functional and cognitive abnormalities, leading to academic and social difficulties. In general, how the nervous system of individuals with Shwachman-Diamond syndrome is affected has received relatively little attention compared to the large number of studies that have investigated the physiological and biomolecular characteristics of this clinical condition.

The objectives of this doctoral work were multiple: first, to (i) characterize the impact of the SBDS mutation and Shwachman-Diamond syndrome on intellectual and cognitive functions; and (ii) to develop a differential diagnosis method to discriminate Shwachman-Diamond syndrome from other neurodevelopmental pathologies.

The methodological approach adopted throughout the project was based on multidimensional analyses, first of all in the psychometric evaluation of cognitive functions on the intellectual, attentional-executive and social levels; but also through an ecological evaluation of pragmatic competences with the help of an original device developed specifically for the study; and also through an integrated interactive evaluation by algebraic analysis using the Topological and Kinetic model of Trognon (2TK), specifically developed in this doctoral work and applied to all the verbal materials observed during the thesis. The major originality of this work being the development of computational and algebraic tools, notably by machine-learning and deep-learning, and allowing to make use of all the collectable data in the field of human and social sciences and psychology in a combined way, in order to carry out clinical predictions or being able to be used as a dynamic tool of assistance to the clinical monitoring or the decision; and whose main strength is that all the tools developed have been tested beforehand on material from published archives, allowing us to verify that the tools developed allow (i) access to all the information highlighted in the original work and (ii) offer reading frameworks specific to the 2TK model and congruent with the models from which it originates; even before analyzing the first original data from this work.

Our results suggest that Shwachman-Diamond syndrome primarily impacts the individual's integrative abilities, including difficulties in integrating local cues

into a global context and selective difficulties in second-order theory of mind. More specifically, studies suggest that individuals with Shwachman-Diamond syndrome show a dissociated profile, with elementary cognitive functions (working memory, speed of information processing, first-order theory of mind) preserved; in contrast with integrated cognitive functions (perceptual reasoning, second-order theory of mind, pragmatic skills) impaired. They are thus congruent with data from the neuroscientific literature, which suggests that both computational centers of the central nervous system, the prefrontal cortex and the anterior cingulate cortex, are affected in Shwachman-Diamond disease.

Thus, these results challenge the current view of Shwachman-Diamond patients, which considered intellectual deficit as the cognitive feature of the disease. Indeed, we have shown that only integrative skills allow the diagnosis of Shwachman-Diamond disease by automated methods.

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Chapter 1

Introduction

Shwachman-Diamond syndrome (SDS) (Shwachman et al., 1964) is a rare autosomal recessive disease with an annual incidence of 1 in 200,000 births (5 new cases per year in France), induced by a mutation at the q11 locus of chromosome 7, in the region of the SBDS gene (Boocock et al., 2003). The SBDS gene is a near-ubiquitous gene and is expressed in almost all adult tissues, including the myocardium and central nervous system (S. Zhang et al., 2006). In mice, loss of function of this gene induces embryonic death (ibid.). In humans, mutations in the SBDS gene most commonly produce exocrine pancreas failure, bone marrow failure, and skeletal dysplasia (Cipolli et al., 1999), but other features have already been reported in the literature such as heart failure (Kopel et al., 2011; Savilahti & Rapola, 1984), which can become lethal in some cases.

A more recent study described the impact of SBDS mutations on nervous system development. These data suggested that SDS patients show global shrinkage of cortical volumes in both hemispheres, particularly in the anterior cingulate cortex and hippocampal regions. They also observed diffuse brain abnormalities in the gray matter as well as disruptions in myelin connectivity (Perobelli et al., 2015).

Although these brain data could help explain some of the clinical symptomatology seen in SDS patients, there is little data available in the literature regarding the linguistic, psychological, and psycholinguistic impact of these alterations. Currently, it has been shown that subjects with SDS exhibit diffuse cognitive alterations, including impaired intellectual efficiency and a dysexecutive syndrome (Aggett et al., 1979; Cipolli et al., 1999; Kent et al., 1990; Kerr et al., 2010; Perobelli et al., 2015), despite significant intragroup variability

(Perobelli et al., 2012). However, no data exist regarding the impact of these cognitive abnormalities on social interactions and in particular in the case of the most natural human social interaction: dialogic interaction.

Some works have already examined the conversational behaviors associated with certain mental pathologies such as schizophrenia (Musiol & Rebuschi, 2007; Trognon, 1992), or autism (Gerardin-Collet, 1999); as well as with certain degenerative or traumatic pathologies such as Alzheimer's disease (Jacob, 2017) or polyhandicap (Bocéréan & Musiol, 2017; Verhaegen et al., 2008), and traumatic brain injury (Dardier et al., 2003; Peter-Favre, 1999). Shwachman-Diamond Syndrome, on the other hand, has never been the subject of a systematic study, although an exploratory study has been carried out which concluded that these patients have retained pragmatic abilities (Batt et al., 2017; Canton et al., 2016).

However, while in that exploratory study, the dialogic part and the neuropsychological assessment were designed separately, they were integrated in a joint reading in the present work, so that the assessment of dialogic conducts is not one task among others, but positioned as a super-ordinate task and whose behavioral measures are explainable and objectifiable in their cross-observation with psychometric data (intellectual functions ; attention and executive functions; social cognition), using an ecological dialogical device created for the experiment, the Trognon Ecological Side Task for the Assessment of Speech-Act Processing (TEST-ASAP). This task is subdivided into three subtasks in order to measure the inferential aspects on the one hand; the behavioral induction under instruction without benefit and the behavioral induction requiring a prior inference but carrying benefits, thus allowing to highlight dissociations, this task being integrated into the neuropsychological evaluation process, allowing to guarantee its ecological aspect.

These dialogic data were recorded, transcribed verbatim, and then analyzed using Trognon's Topological and Kinetic (2TK) model, a mathematical analytical framework for unifying the three dominant approaches to interactive analysis: Computational Linguistics and Theoretical Linguistics and Ludics (Girard, 1987, 2001; Lecomte & Quatrini, 2011), Computational Linguistics and SDRT (Asher & Lascarides, 2003; Caelen, 2003; Caelen & Xuereb, 2014, 2017), and Interlocutionary Analysis (Trognon, 1992). The joint use of human-computer interaction and human-human interaction analysis techniques to study natural dialogue is justified here by the construction of the task, whose outcome and course are predictable in the neurotypical subject (i.e. ideal dialogue having the characteristics of a cooperative dialogue where the interactants help each

other towards a common goal), and of which all other configurations would be considered as artifactual (i.e. non-optimal and detected by these methods).

The originality of this work lies in the multidimensional exploration of the psychological and cognitive parameters that describe the clinical symptomatology of patients suffering from Shwachman-Diamond syndrome, and in the production of elements that will allow us to develop multidimensional automated diagnostic algorithms and to provide their proofs of concept, the use of which could go beyond the scope of the present work.

Finally, we will integrate the cognitive and dialogical findings into the general theory of the Global Network Workspace (Dehaene et al., 1998), a computational model of human consciousness that allows for the dissociation of perceptual and integrative processing, and whose two identified critical integrative centers (i.e., prefrontal cortex and anterior cingulate cortex) are altered in their neuroanatomy and projections in Shwachman-Diamond syndrome (Perobelli et al., 2015). This theoretical framework has already been successfully employed and has led to very specific hypotheses about the nature of the alterations observed in schizophrenic subjects and their etiology (Berkovitch et al., 2017, 2018).

Thus, the present work is organized as follows: the first part will be devoted to the description of the epistemological framework in which the present work is situated. First, the theory of the Global Network Workspace will be described, both in its fundamental canonical descriptions and with the help of an example drawn from the literature: that of schizophrenia. We will then describe to what extent this computational model of consciousness allows us to glimpse a new level of analysis in the psychological sciences: computational psychology, allowing us to account simultaneously for events taking place at different levels of organization. In the remainder of this section, we will describe existing integrative analytic techniques and situate them in a general epistemological lineage in the philosophy of science, which has its origins in the literature of fundamental physics and whose development is situated in the epistemological lineage of the development of cognitive psychology and computational sciences.

Thereafter, we will describe all existing data available on Shwachman-Diamond syndrome, from its original physical medicine descriptions to its most recent biomolecular and neuroanatomical descriptions; as well as all available epidemiological data.

In the following section, we will describe the materials and methods that were used in this study. In particular, we will describe in great detail and in full

the Topological and Kinetic model of Trognon (2TK), a mathematical analytical framework that unifies exploratory approaches from the dominant theories of linguistics. We will also provide in this section very detailed examples, both in their analysis and in their formalization, in order to allow the use of the model in further work.

The following section will describe the results obtained in the present work. First, it will present proofs of concept to validate the use of computational strategies on psychological and/or psychometric data through the analysis of data from the archives of the Lorraine University; thus, it will be possible to verify that the results provided by these methods are at least as effective as traditional techniques for solving psychometric problems and making inferences about dialogic interaction. Second, it will present the data observed in the present study on two experimental groups: subjects with Shwachman-Diamond syndrome, as well as control subjects matched by age and gender parameters. In this section, the data will be analyzed both using classical statistical techniques; and both using computational techniques developed in the present work. The elements of differential diagnosis that have been retained will also be described.

Finally, the last section will deal with the integration of the results of the present study into the epistemological framework of the work. The data that have been measured will be discussed in their cross-reading with the predictions formulated by the postulates of the Global Network Workspace theory, and more generally, will be discussed with the objective of providing fundamental elements that will help to orient future work that will seek to specify the etiology of Shwachman-Diamond syndrome.

Chapter 2

Epistemological framework

2.1 Consciousness as the central theory of psychological sciences

2.1.1 Conception of consciousness: from structuralism to the present day

Since the first developments of the discipline of psychological sciences, the main approach that has influenced its understanding has been the physiological approach derived from medicine and biology. The different psychological currents that have followed one another since the opening of the first experimental psychology laboratory in the world, in Germany, in the 19th century by Wilhelm Wundt, have, although differing fundamentally in their understanding of a scientific psychological theory and in the methods employed, nevertheless retained a common object of study, which is human consciousness.

Although his concept has been repudiated by the behaviorist current and has been largely transformed by the psychoanalytical currents, we will consider in the rest of this work that these two currents are rather derived from the epistemological lineages of Titchener and Freud; contrary to the current cognitivist and computational theories which are rather derived from the epistemological developments of Wundt and the structuralist current, functionalism, the Gestalt school, and the cognitivist current; in which this work will aim to place it. Indeed, and if we place ourselves in this epistemological lineage, it is indeed the consciousness which is at the center of the investigations: it was first considered

as a whole of summed psychic elements: the sensations (i.e. the perception) and the feelings (i.e. their effects on the psyche). Two qualities were thus considered: the type of sensation and their intensity, and consciousness was thus considered as a sum of elementary sensations on which simple concrete conjunctions produced an abstract complex formation (Petitot, 1999).

Subsequently, functionalists, such as William James and John Dewey, were interested in the dynamic properties of consciousness, and notably highlighted that it was rather the nature of the relations that mental states maintained with sensory inputs (e.g. visual, auditory...) and other mental states that could determine the conscious state in which an individual could find himself; and they were interested in the function and the goal of any behavior (Pacherie, 1995). Epistemologically close to psychological conceptions from the exact sciences, notably from certain authors such as Erwin Schrödinger (Schrodinger, 1958), functionalists thus began to consider activity as a critical condition for the adaptation of the species, whose initiation of behaviors would be dictated by a "conscious organ" and curiosity, directed by learning and optimization of behaviors in a perspective of conservation and optimization of energy expenditure.

The next major contribution to the study of consciousness was made by the Gestalt or Psychology of Form movement, represented in particular by three German psychologists, Max Wertheimer, Kurt Koffka, and Wolfgang Köhler. In their work, they brought two considerations that proved crucial in the study of consciousness later on: they considered mental experiences as an organized whole, as a form, rather than as a simple sum of simple elements; and defended the idea that the organization of subjective sensations and the activation of neurons have similar structures (B. Smith, 1988; Wagemans, 2015). This prediction, although made even before the discovery of the action potential, was experimentally confirmed very recently in a computational neuroscience study that looked at suicide risk, and which was able to successfully predict suicide ideation based on the neural activation pattern in functional imaging following the presentation of words loaded with emotional valences, based on the hypothesis that these words will be represented in cardinal points understandable in psychological terms and discriminable between experimental groups (Just et al., 2017).

Finally, the last stage in the development of the conception of consciousness, and which brings us to the dawn of contemporary psychology, is situated in cognitive psychology, whose first desire was to be part of the set of sciences that

study human intelligence and the functioning of the mental abilities of species, from the bio-chemical-physical substratum to its formal structure and its psychological, linguistic, and anthropological expressions (Nicolas & Ferrand, 2008). This epistemological school, built on the analogy and metaphor of the computer, considers a level of analysis specific to the mind: cognition. It was initiated by Macy's lectures and thus considers the nervous organ and the mind it generates as a process of processing, storing and retrieving information; supporting the idea that the activity was directed towards the realization of a finalized action, thanks to a feedback control (Fremont-Smith, 1951). This conception of the mind has been particularly crucial in the development of contemporary psychological theory, as it is the first psychological theorization that no longer places consciousness at the forefront of volition, placing it instead in an administrative role that would act as a veto to interrupt behaviors, rather than as a motor that directly drives them. Thus the idea began to emerge that consciousness could represent an insight into the computational processing going on in the central nervous system, which would make its decisions autonomously by informing us of them, and by allowing the possibility of interrupting a behavior in progress. This idea was strongly reinforced by the later work of the neuroscientist Benjamin Libet, in his well-known experiment that led to the discovery of the motor preparation potential in the supplementary motor area (Libet et al., 1983). The principle of this experiment was simple: a subject implanted in the supplementary motor area was seated in a chair and faced with a clock whose hand could complete one revolution in 2.56s. The hand was rotated, and the subject had a button on his seat to stop the rotation of the hand. The only constraint imposed on the subject was to verbally notify the moment when he decided to act, just before pressing the button. Thus, Benjamin Libet was able to observe changes in brain activity as early as 200ms before the verbal notification of the action. Later work by Itzhak Fried went further, and showed changes in activity at the unit neuron level up to 2000ms before the verbal notification of the action (Fried et al., 2011). Thus, we understand that when an individual thinks of consciously and voluntarily deciding to carry out an action according to his free will, the computational processing associated with the production of this action has already been engaged almost two seconds before all the neurophysiological processes that will allow the individual to become aware that he has made the decision to act. Thus, the conception of consciousness as an informational function reinforces Erwin Schrödinger's physicalist conceptions, and allows for a glimpse of the conception of perception in informational terms,

which allowed for the link between the emergence of conscious information and information theory (Shannon, 1948); and between the emergence of conscious information and the production of Bayesian models of the world that allow for effective interaction with it (Courville et al., 2006; K. Friston, 2012; Piantadosi et al., 2008; Vilares & Kording, 2011), which we will discuss later in this work. Finally, cognitive psychology has led to the emergence of two critical models that were initially contrasted, before being understood as two dual processes that act in symbiosis : a connectionist model, inspired by physiology and behaviourism, which conceives of intelligent operations as a self-regulating system, composed of specialized modules specific to precise operations, autonomous, possessing a precise cortical topology, and directed by a central system in charge of coordinating and centralizing the information processed by specific modules, notably supported by authors like Jerry Fodor or Noam Chomsky (Chomsky, 1980; Fodor, 1986). The second model that has emerged is that of connectionism, which is based on thermodynamic energy principles that take place at the neuronal level. The connectionist model thus considers symbolic representations as not carrying physical meaning, but as carrying high-level representations that emerge from neuronal interactions at the physical level, thus considering the representation as a crystallized pattern of neuronal activity, whose stabilization is critically conditioned by the frequency and recurrence of these activities, in accordance with Hebb's Rules, or theory of neuronal assemblies (Hebb, 1949), which later proved to be critical in the description of the phenomenon of synaptic plasticity, theorized initially by William James (James, 1890) and Santiago Ramón y Cajal respectively at the beginning of the 20th century (Mendelzweig, 2010) ; and fully confirmed experimentally almost a century later (Bennett et al., 1964; Diamond et al., 1964; Hubel & Wiesel, 1962; Stiles, 2000).

Today, models of consciousness are situated at the intersection of these symbolic and connectionist models, and can only be fully understood by situating them in the epistemological lineage of scientific psychology initiated by Wilhelm Wundt, which has been built in its history through paradigms aiming to get closer and closer to the standards of exact sciences in the treatment of psychological data.

Thus, the accumulated knowledge in psychology and in all disciplines that have brought an integrative perspective of psychology on many fields allows, from our point of view, the modeling of complex psychological processes on many levels with the help of computational sciences, which allow complex inferences to be made from multidimensional data, the reason that prompted the American

Physical Association to place computational analysis as the Gold Standard of basic and applied research in contemporary physics (Carleo et al., 2019; *Machine Learning Takes Hold in the Physical Sciences, n.d.).*

2.1.2 The Global Network Workspace: towards a computational theory of psychology

2.1.2.1 The Global Network Workspace: A neural model for modeling effortful cognitive tasks

The Global Network Workspace model was born from the hypothesis of the existence of specific neural bases allowing the realization of a conscious mental effort (Dehaene et al., 1998). Indeed, it had already been shown by anatomical, neurophysiological, and imaging means that certain types of tasks could be performed without effort, by mobilizing very circumscribed neural systems specialized in all the aspects in which sensorimotor processing can occur (Cheng, 1986; Felleman & Van Essen, 1991). In contrast, humans are also able to implement these capacities in a combined way, in order to produce an integrated use of the cerebral processors to solve new tasks (Hermer & Spelke, 1994), and allowing an ascent to consciousness of the computational outputs of the specialized processors in order to perform operations on this information, such as memorization, evaluation, or even verbal report, thus repudiating the canonical idea of cardinal regions of the central nervous system, given the number of projections that exist between these different processors, although they may seem isolated from each other (Baars, 1993; Posner, 1994; Posner & Dehaene, 1994; Shallice, 1988).

(Dehaene et al., 1998) have thus proposed an architectural formalization of a neural network characterized by a long-distance connectivity distributed throughout the central nervous system, producing a "Global Workspace" that could efficiently interconnect and coordinate the computational processing taking place at the scale of the central nervous system, thus allowing their emergence into consciousness.

2.1.2.2 The two computational spaces of the central nervous system

(Dehaene et al., 1998) propose in their work a model of the central nervous system made up of two computational spaces composed of neuronal types and very distinct topologies.

First, they propose a "processing network" composed of neurons functionally specialized in the processing of a given quality of information (Baars, 1993) and of modular subsystems including primary sensory processors (such as V1); or unimodal processors (such as V4); up to heteromodal processors such as F5 (i. e. "mirror neurons" that can combine visual-tactile information to extract categorical or semantic information (Shallice, 1988). In this computational space, each processor has its own distinct cortical topology, characterized by local or medium-range connections encapsulating all information relevant to its function (Mesulam, 1998).

The second computational space proposed by (Dehaene et al., 1998) is the Global Network Workspace, composed of a set of cortical neurons distributed ubiquitously in the central nervous system (i.e. not belonging to specific cardinal points), and capable of receiving and sending information to neurons that are homologous to them in other cortical regions. These neurons could be located mainly in pyramidal layers 2 and 3, which are very present in the dorsolateral prefrontal cortex, which would link afferent and efferent associations to layer 5, corresponding to the thalamic nucleus, thus contributing to the stability of the workspace activity by giving it dynamic access to processing networks (Llinás & Paré, 1991; Munk et al., 1996)

2.1.2.3 The five subsystems of the Global Network Workspace

According to (Dehaene et al., 1998), the Global Workspace could, through its afferent and efferent projections to the processing network, mobilize and dynamically reconfigure five distinct neural networks that are the perceptual networks, the motor networks, the long-term memory networks, the evaluative circuits, and the attentional circuits.

The perceptual circuits, first of all, play a critical role in allowing the workspace to access the present state of the external world, thus allowing access to the content of any object or speech within the workspace. They are represented in particular by the temporal and infero-parietal regions including language comprehension (i.e. Wernicke's area); as well as the ventral and lateral regions of the temporal lobes, focused on object identification (Mesulam, 1998).

The long-term memory circuits allow the Workspace to access past events. They are mainly represented by the hippocampal and para-hippocampal regions which play a crucial role in accessing past experiences, notably thanks to the stimulation of specific neurons distributed in the neocortex and encoding the

memory traces of previous perceptions (Mesulam, 1998).

Moreover, the workspace can attribute a positive or negative value to any representation present within it thanks to its evaluation circuits (Dehaene & Changeux, 1991, 1989; K. J. Friston et al., 1994; Schultz et al., 1997). These circuits, including the cingulate cortex, hypothalamus, amygdala, ventral striatum, and orbitofrontal cortex, have catecholaminergic and cholinergic projections to the prefrontal cortex, allowing the evaluative circuits to be directly activated by the content of the workspace, This allows a dynamic self-evaluation (Dehaene & Changeux, 1991) that regulates the activity of the workspace by maintaining or deleting its content according to its calculated intrinsic value (Dehaene & Changeux, 1991, 1989, 1997; Schultz et al. , 1997)

Workspace is also able, through its attentional circuits, to mobilize its own circuits independently of the perceived external world. Indeed, as noted by (Dehaene et al., 1998), a change in the content of the Workspace will not necessarily lead to changes in the individual's behavior, but will necessarily result in the selective amplification or attenuation of signals coming from a subset of the neurons located in the processing networks. These circuits are mainly represented by the sub-regions of the parietal lobe, known to play crucial roles in visual-spatial attentional processes (Mesulam, 1998; Posner, 1994; Posner & Dehaene, 1994).

Finally, motor programming circuits allow the content of the workspace to be used dynamically to guide future behaviors, thanks to a large hierarchy of integrating neurons allowing the abstract planning of the individual's actions, and thus allowing the implementation of the motor intention (Dehaene & Changeux, 1997; Jeannerod, 1997). These motor circuits are very extensive and could include the premotor cortex, the posterior parietal cortex, the caudate nucleus, a supplementary motor area, the cerebellum, as well as the left infero-frontal regions, including Broca's area. Current data suggest that it is these connections between language regions, motor regions, and high-level integrative regions that allow the production of the active representation of the state of the workspace, and that would allow access to the property of reportability, which allows us to describe or comment on any object or event using words or gestures (Weiskrantz, 1999).

2.1.2.4 The integrating centers of the Global Network Workspace

The connectomic analysis of the processing networks and of the Workspace led (Dehaene et al., 1998) to theorize two major integrating centers through the interactions they have through their projections on the high-level perceptual, motor, attentional, memory, and evaluative circuits: the cingulate cortex (anterior and posterior) and the dorsolateral prefrontal cortex.

The Global Network Workspace model has thus made it possible to establish certain predictions about the functioning of this network: notably, and first, its activity should be absent during routine tasks; appear suddenly when new or nonroutine tasks are introduced; vary during initial learning of a new type of task; remain stable and high during performance of a known, high-effort, nonroutine task; decrease as exposure to the task increases; and be able to temporarily mobilize, in a top-down fashion, other units involved in specific components of the task. These predictions have been experimentally verified by the authors in theoretical neuroscience simulation experiments using artificial neural networks based on the classical McCulloch-Pitts architecture trained on Stroopian tasks (Dehaene et al., 1998). Moreover, these predictions and the data obtained from the computer simulation experiments are consistent with the experimental literature in biology and neuroscience. Indeed, it had already been shown before the initiation of this work that the dorsolateral prefrontal cortex and the anterior cingulate cortex possessed similar properties to the theorized integrative regions of the Global Network Workspace. Indeed, brain imaging experiments have shown that, during the performance of active tasks requiring significant cognitive effort (including the Stroop test), the activation of these two brain regions was strongly correlated with the level of difficulty of the task (J. D. Cohen et al., 1997; Pardo et al., 1990; Paus et al., 1998). It has also been shown that, during the routinization of these tasks, there is a decrease in the activity of the prefrontal cortex and the anterior cingulate cortex; this decrease is instantly cancelled out when a non-routine condition is introduced (Raichle et al., 1994) or even when an error related to the task is detected, thus producing a strong modulation of activity in the anterior cingulate cortex (Carter et al., 1998; Posner & Dehaene, 1994). Similar and complementary observations have been made in other types of tasks, notably in the Wisconsin Card Sorting Test, where the activity of the dorsolateral prefrontal cortex produces a strong activity when subjects have to infer the new sorting rule (Konishi et al., 1998). Three other interesting observations have also been made: the dorsolateral prefrontal

cortex and the anterior cingulate cortex have the capacity to maintain their activity even in the absence of external stimulation, for example during delay periods in delayed-response tasks (J. D. Cohen et al., 1997), as well as during tasks requiring an active pseudo-conscious internal resolution process such as mental arithmetic (Roland & Friberg, 1985), or even during focused-attention tasks (Corbetta et al, 1991; Posner & Dehaene, 1994), where the concomitant activity of the dorsolateral prefrontal cortex and the anterior cingulate cortex has been strongly correlated with a process of selective attentional amplification by modulating the activity of the posterior regions (Corbetta et al., 1991; Posner & Dehaene, 1994).

2.1.2.5 Preliminary integration of assumptions from the Global Network Workspace theory

In conclusion, (Dehaene et al., 1998) describes the activity of the Global Network Workspace as a distinct subset of neurons pooling all the information available in the networks to which it is connected, modulating their expressivity at the network level by signal amplification or suppression. This activity is dependent on the degree of familiarity of the subject with the task (i.e. its routine character) and would be observed during exposure to new tasks; remaining in contrast silent during quasi-automated tasks, not requiring any particular cognitive effort, thus delegating the processing of the task to specialized processors that will produce a response that will be coherent between the stimulation received and the memory traces corresponding to the correct realization of the task.

Thus, the model argues for a top-down mobilization of the processing networks by the Global Network Workspace through top-down excitatory connections that modulate the activity of the processors through inhibitory gating interneurons that have the property of putting a multiplier weight on the post-synaptic effect of neuronal firing. This type of selective amplification has already been observed experimentally (Moran & Desimone, 1985; Motter, 1994). Finally, the activity of the Workspace is characterized at the scale of the entire nervous system, with activation patterns characterized by sudden, coherent, and exclusive activations of a subset of the neurons of the Workspace, the other neurons belonging to the network being inhibited. Thus, the Workspace is interconnected in such a way that only a single representation can be active at a given time, whose activation is represented by the global phenomenon of ignition (Dehaene et al., 1998).

2.1.2.6 Contribution of the Global Network Workspace model to the study of pathology

2.1.2.6.1 A practical example: the autism-spectrum disorder

Autism spectrum disorders represent a complex chronic developmental pathology with heterogeneous combinations of symptoms across sensory, cognitive, and communication domains (Huguet et al., 2013). Regarding social interactions, the difficulties of individuals with ASD were central to the first descriptions of autism by Leo Kanner and Hans Asperger who, as early as 1940, highlighted the extreme loneliness of these individuals (Kanner, 1943). Currently, researchers agree that individuals with ASD have difficulties across a wide range of social-cognitive modalities, particularly in theory of mind and metacognition, the cognitive process of representing the mental processes of others in an explicit and conscious manner (Grainger et al., 2014; Lee et al., 2019; Shea et al., 2014). In particular, it is these skills that make possible the processing of indirect speech acts that are pragmatically rather than semantically situated (Kissine, 2015).

At the neuroscientific level, current evidence considers theory of mind and metacognition as pertaining to post-perceptual processing whose decisions in terms of discrimination would be automated, based on Bayesian associations between heteromodal stimuli and influenced by attentional, memetic, and decision making systems (Shea et al., 2014); and whose critical functional cardinal point would be in the anterior cingulate cortex (Abu-Akel & Shamay-Tsoory, 2011; Haas et al., 2013; Kanske et al., 2017; Rilling et al., 2007; Wittmann et al., 2018), a region that we have previously identified as a critical and ultra-connected computational hub of the Global Network Workspace.

Thus, in a dynamic understanding of autistic pathology at the level of theory of mind, two types of explanatory predictions could be made by posing the data of the problem in the analytical framework provided by the Global Network Workspace model. First, one could imagine a first hypothesis, close to the lesion hypotheses, which would consider that the disorder of theory of mind comes from a primary (neuroanatomical) deficit of the anterior cingulate cortex, hindering its function, although the low-level perceptual processing is physiologically functional and the information efficiently transits without loss to the anterior cingulate cortex. This theory would be supported by a very large body of imaging and electrophysiology work showing both neuroanatomical and neurophysiological features of the anterior cingulate cortex in subjects

with autism (Chan et al., 2011; Joshi et al., 2019; Simms et al., 2009). On the other hand, one could imagine a second hypothesis, closer to the disconnective hypotheses, in which the anterior cingulate cortex would be functional, but the information it would access would be corrupted by abnormalities in information transmission, which would produce sequential errors that would pile up as information is abstracted in the more integrative regions, thus corrupting the decision making process of categorization or adaptive response. Again, there is a great deal of evidence in the literature that could support these hypotheses: indeed, autism has, for a decade, been considered a Functional Disconnection Syndrome that is observable from childhood (Geschwind & Levitt, 2007; Peters et al., 2013; Robert Melillo & Gerry Leisman, 2009). Numerous subsequent diffusion tensor imaging studies have also been able to measure lower fractional anisotropy in autism compared to control subjects, particularly in long-distance connections involving, among other things, projections from or to the prefrontal and anterior cingulate cortices, as well as to the thalamus (Aoki et al., 2013; Cheon et al., 2011; Hoppenbrouwers et al., 2014; Jou et al., 2011; Shukla et al., 2010). This hypothesis is also supported by work done in molecular biology, which showed by Genome-Wide Association Studies that individuals with autism very often carry genetic mutations at the level of the sequences encoding Shank family proteins, whose crucial physiological functions are at the level of stabilizing the molecular scaffolding of the synapse, thus allowing neurotransmission that strongly limits information loss (Monteiro & Feng, 2017). It was also shown that the autistic symptomatology presented by the patient was discriminable and predictable based on the mutated Shank protein and mutation type (Leblond et al., 2014). These results were confirmed in the mouse model, in a work where ProSAP1/Shank2 deleted animals showed major deficits in motor skills, grooming, and social interactions (Schmeisser et al., 2012).

Finally, one could even imagine a combined hypothesis, following the "use it or lose it" principle well known in neuroscience (Bruer, 1999), which postulates a development and maintenance of nervous system state as a function of brain activity, that the neuroanatomical deficit observed on imaging in postmortem studies would be secondary to the disconnection syndrome, thus only accounting for the final result of years or decades of network dysfunction on a global scale. However, we did not find any work in the literature specifically investigating this causal link.

2.1.2.6.2 A detailed example from the literature (Berkovitch et al., 2017): schizophrenia

Schizophrenia is a complex chronic psychiatric disorder with heterogeneous combinations of symptoms that can be divided into three categories: positive symptoms, corresponding to behaviours and thoughts that are not observed in the healthy subject (i.e., positive symptoms: hallucinations, disorganized speech and behaviour, delusions); negative symptoms, corresponding to social withdrawal, abulia and anhedonia; ; as well as cognitive symptoms, which may correspond to different patterns, according to the criteria of the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-V) (American Psychiatric Association, 2013). From an epidemiological perspective, the most detailed study regarding the prevalence of schizophrenia appears to be the Global Burden of Disease Study 2016. This would result in 0.28% of the world's population being affected (Charlson et al., 2018), although there appears to be significant variation based on geographic location (McGrath et al., 2008; Perälä et al., 2007).

Schizophrenia, as currently conceived, seems to represent a pathology of choice for the study of disorders of consciousness due to the dissociative nature of the clinical condition. Indeed, very clear dissociations between explicit and implicit processes are observed in schizophrenia: although almost all high-level functions (e.g. memory, attention, processing speed, executive functions) are dysfunctional, it has already been suggested by some data in the literature that schizophrenia would specifically affect explicit cognitive processing, while implicit abilities would remain preserved (Berna et al., 2017; Danion et al., 2001; Huron et al., 1995). For example, it has been shown that schizophrenic individuals show selective difficulties in explicit memory retrieval (e.g., such as autobiographical memory), while no difficulties in implicit dimensions of memory (measured by familiarity tests) could be demonstrated (Huron et al., 1995). The same dissociation is observed in the cognitive processing of emotions, where some work has shown preserved abilities in implicit emotion processing at the neurophysiological level that contrasted with failures in explicit emotion classification tasks (Linden et al., 2010; van't Wout et al., 2007). Similarly, grammar learning, usually considered implicit, appears to be preserved in schizophrenic patients (Danion et al., 2001).

As noted by (Berkovitch et al., 2017), this dissociation between explicit and implicit processing could be explored in the comparison between conscious

versus subliminal processing. In particular, they report experimental results, where when a digit is presented during a fixation window and, after a variable delay followed by a mask consisting of letters, schizophrenic patients require a longer delay than their control counterparts to perceive the digit; and tend to report unexpected events less frequently during inattentional blindness tasks (Hanslmayr et al., 2013), including attentional-blink effects of much greater magnitude than their control counterparts, associated with a decrease in the P300 component, characteristic of the ignition phenomenon and conscious access (Mathis et al., 2012). These findings are all the more surprising given that subliminal processing of stimuli appears to proceed normally in schizophrenic individuals, suggesting a dissociation between preserved subliminal processing and impaired conscious processing. This hypothesis was tested experimentally in a study in which schizophrenic and control subjects were asked to compare a target number with the number five. The presentation of the number was preceded by a very rapid presentation of another number used as a primer and which could be rendered invisible by masking (i.e. by presenting highly noisy masks before and after the target stimulus). They observed that, in the control group, performance in the target task was directly dependent on the congruence (i.e., the same information was given by the primer and by the target) between the primer and the target in the conscious (i.e., unmasked) and subliminal (i.e., masked) conditions; as well as the speed of response, which was positively correlated with the congruence between the primer and the target. In contrast, in the patient group, the priming effect could only be observed in the subliminal conditions but not in the conscious conditions. These observations (i.e., impaired conscious processing in contrast to preserved subliminal processing) have been verified in a large number of studies, where a high threshold of access to consciousness associated with an abnormal activity pattern has been observed in a large number of tasks, including inhibition (Huddy et al., 2009), number comparison and conscious priming (Del Cul et al., 2006), and conflict detection (Carter et al., 1998; Dehaene et al., 2003).

This dissociation can also be observed, as noted again by (Berkovitch et al., 2017), that dissociation between conscious and unconscious processing could be observed in paradigms involving metacognition abilities, which allow one to represent or dynamically track one's own mental states. For example, in studies that investigated the dissociation between conscious and unconscious processing using unconscious error monitoring paradigms by measuring subjective and electrophysiological error detection data in schizophrenics matched to

control subjects in number comparison tasks on masked stimuli, It has been shown that schizophrenic individuals have difficulties and impaired abilities to monitor their own errors under conscious conditions, as evidenced by electrophysiological recordings measuring very low error-related negativity (Carter et al. , 2001; Charles et al., 2017; Foti et al., 2012), a critical electrophysiological component measured in the anterior cingulate cortex during conscious error detection (Manoach & Agam, 2013). Interestingly, and in this same study (Charles et al., 2017), and even though patients' performance was inferior to controls in the masked conditions, the study also highlighted that error-related negativity only appeared during conscious conditions, thus showing a dissociation between preserved subliminal error monitoring and impaired conscious error detection ability.

Finally, in the phenomenological approach to perception, schizophrenia is described as a disorder of the sense of self in which objects related to the self are experienced as belonging to the external world, such as external objects, including a weakened sense of existing as a conscious and coherent source of action (Sass & Parnas, 2003). Again, (Berkovitch et al., 2017) have associated these phenomenological observations in terms of conscious processes of agentivity and self-monitoring, citing in particular the very famous example from the literature, where it was shown that schizophrenic individuals presented difficulties in discriminating their own hand from an alien hand, during discrimination tasks on presentation of a video tape on a screen showing either the individual's hand or an alien hand roughly reproducing the subject's movements (Daprati et al., 1997). They also cite a recent study that investigated delusions of control (i.e. the deficient representation of the link between conscious intention and action) and the sense of agentivity in schizophrenic patients by manipulating behavioral responses through subliminal priming. The authors thus observed that schizophrenic individuals exhibited a normal influence of subliminal priming on motor performance, but a reversed influence of primings on sense of agentivity, showing a dissociation between actual motor performance and the subjective sensation of controlling one's actions (Voss et al., 2017). These observations thus suggest an automatic processing of preserved motor operations that contrasts with the conscious aspects of motor behaviors that appear critically affected (Berkovitch et al., 2017).

Thus, the authors considered that the Global Network Workspace theory might prove to be a prime theoretical framework to study the dissociation between conscious and unconscious processing in schizophrenia. Thus, and as

explained in the previous sections, the Global Network Workspace theory predicts that certain information is relevant in the perceptual and cognitive context through a network of high-level, long-distance interconnected regions, where the prefrontal cortex and anterior cingulate cortex play critical roles as key nodes. Thus, once information reaches the prefrontal cortex (i.e. bottum-up process), a top-down amplification of the signal, ignition, characteristic of conscious access (Del Cul et al., 2006; Sergent et al., 2005) is performed to broadcaster the information to all other regions of the central nervous system, allowing the information to be consciously accessible, and subject to introspection and deferability (Berkovitch et al., 2017). The realization of the ignition phenomenon being directly dependent on the initial amount of sensory evidence (Del Cul et al., 2006) and the availability of neural networks supporting the attentional amplification function (Sergent et al., 2005). During this global episode, all other information encapsulated by other neurons in the Global Workspace is inhibited and is unavailable for any further processing of another stimulus that will remain at the preconscious level, thus producing the limitations observed in attentional-blink and divided attention tasks, where the central dedication of cognitive resources to a given stimulus is perceived at the experiential level by the subject as a conscious perception (Berkovitch et al., 2017; Dehaene et al. 1998, 2006; Dehaene & Changeux, 2011; Dehaene & Naccache, 2001). Thus, according to (Berkovitch et al., 2017) and in agreement with the previous section, the Global Network Workspace model predicts two mechanisms that may affect conscious processing: first, information might turn out to be too weak at the sensory level to be amplified, thus leading to a bottom-up deficit leading to a higher threshold for access to consciousness. On the other hand, sensory processing could be optimal, but insufficiently amplified by top-down amplification processes, thus failing to produce or maintain global and tonic activity (Van den Bussche et al., 2010).

These two types of hypotheses, opposite in conception, carry with them a certain amount of evidence that has been accumulated in the neurophysiology literature. Concerning the primary sensory deficit (i.e. bottom-up hypothesis), some authors have suggested, as predicted by the Global Network Workspace model, a higher threshold of access to consciousness in schizophrenic individuals due to a primary sensory deficit (Green et al., 2011). This hypothesis is notably supported by electrophysiological observations investigating the P1 visual component in response to low spatial frequency stimuli, which showed abnormal activities in schizophrenic individuals and were attributed to specific

dysfunctions of magnocellular visual pathways impeding bottum-up information transfer processes, in contrast to preserved parvocellular visual pathways (Javitt, 2009). However, this type of hypothesis is currently strongly contested by current research: indeed, and first of all, there is currently no concrete evidence that the magnocellular pathway is impaired in schizophrenic individuals (Herzog & Brand, 2015), especially since the hypothesis of impaired bottum-up processing seems inconsistent with data suggesting full preservation of unconscious processing, especially in subliminal priming tasks (Dehaene et al., 2003; Del Cul et al., 2006). In addition, more recent studies that have investigated bottum-up alteration in inattentive conditions where top-down amplification components were minimized (Berkovitch et al., 2018). Thus, they constructed a masking task with different levels of difficulty for two conditions: a focused attention condition where only one task had to be performed, and a distraction task where the primary task was made more complex by the addition of a concurrent task. Thus, in the inattentive conditions, the evoked components were similar and indistinguishable between schizophrenic individuals and their control counterparts, particularly in the amplitudes of the N1 and N2 events, which exhibited the same pattern in both groups, including an increase in amplitude correlated with the increase in delay between masks, suggesting preserved bottum-up processing in schizophrenic individuals (Del Cul et al., 2006; Kouider et al., 2013). In contrast, major alterations in information processing were observed by the authors in focused-attention conditions: they highlighted that the N1 component was insufficiently amplified, leading to a non-linear and delayed ignition with a critically reduced P3 component, characteristic of conscious access, in agreement with very many previous results (Charles et al., 2017; Jeon & Polich, 2003; Mathis et al., 2012; Oribe et al., 2015), with some data showing a progressive reduction of this component in visual tasks during disease progression (Oribe et al., 2015).

Thus, the authors propose a model of schizophrenia based on electrophysiological recordings and suggesting conserved subliminal and preconscious processing in schizophrenia, in contrast to impaired conscious processing due to failed top-down amplification or inappropriate or biased top-down amplification of the Global Network Workspace (Berkovitch et al., 2017). Finally, the authors propose to explain this top-down amplification deficit through the predictions given by Bayesian models of perception. Indeed, and as noted by the authors, in the Bayesian predictive coding framework, perception is viewed as a statistical inference that combines sensory evidence (i.e., bottom-up processes) with pre-

dictions made top-down based on innate or acquired priors (K. Friston, 2005b), whose weights are modified upon detection of a mismatch between priors and sensory evidence, thus generating a backpropagation prediction error signal to update internal models of the world and minimize subsequent surprises. This model would explain both types of positive symptoms observed in schizophrenia and considers that hallucinations could be observed as an imbalance in the balance between priors and sensory inputs; whereas delusions could result from a failure to update beliefs that would result from alterations in the processes of dissemination or generation of prediction error signals (Fletcher & Frith, 2009; Powers et al., 2017). These predictions are supported by extensive empirical data showing that the perception of schizophrenic individuals was largely biased toward the sensory inputs presented to them, with lower sensitivity than controls to visual illusions, which normally arise from a strong combined effect of priors and sensory interpretation (Notredame et al., 2014; Teufel et al., 2015). Furthermore, it has been shown in feature-tracking experiments that schizophrenic individuals had difficulty in tracking smooth trajectories of predictable visible targets; but showed superior performance to controls in tracking targets with non-predictable trajectories, suggesting reduced accuracy perceptual predictions in schizophrenics, but again reinforcing the evidence for adaptive sensory processing in this population (Adams et al., 2012). Other modeling done in the Bayesian predictive coding framework has proposed an alternative, but non-exclusive, hypothesis based on an imbalance in the excitation/inhibition balance at the cellular level, leading to a pathological form of causal inference named the circular propagation of beliefs (Jardri & Denève, 2013), which would produce a reverberation of bottum-up sensory information and top-down predictions that would produce a misinterpretation of priors as sensory evidence and vice versa: namely, a misinterpretation of sensory evidence as priors. Thus, experimental evidence has suggested that schizophrenic individuals overestimate the sensory evidence they perceive through bottom-up inference loops, amplifying it by multiple combination between sensory evidence and priors leading patients to observe "what they expect to observe" (Jardri et al., 2017). The computational models that were constructed by Jardri and colleagues with free parameters that measured the effect of overactivity of bottom-up loops predicted the positive symptoms observed in schizophrenic participants; whereas free parameters that measured the effect of overactivity of top-down loops correlated strongly with negative symptoms. Furthermore, and very interestingly for the remainder of the present work, the joint modeling of the two circular loops

predicted with high accuracy the clinical measure of thought disorganization, a critical and iconic observation of schizophrenic psychopathology.

Finally, (Berkovitch et al., 2017) considers, within the Global Network Workspace theoretical framework, that although the accumulation of unconscious sensory evidence is preserved, the Bayesian inferential deficit arises at the point where conclusions from sensory evidence are inferred by discrete, nonlinear sampling of the distributions computed by the unconscious processors (Kraepelin et al., 1971), thus producing a reduced Global Network Workspace ignition associated with a reduced P3 component as well, reflecting a failure to update beliefs in accordance with incoming sensory evidence, as postulated in Bayesian theories. The authors go even further, considering that the presence of erroneous inferences and the higher threshold of access to consciousness for information could mutually reinforce each other in schizophrenia. Indeed, and given that expectations are known to facilitate conscious access (Aru et al., 2016; Berkovitch et al., 2017; Gaillard et al., 2006; Melloni et al, 2011), any deficit in the ability to make inferences from sensory evidence would mechanically result in elevated thresholds for access to consciousness ; and that the dissociation between conscious inferential representations and unconscious processing of stimuli would lead to inadequate inferences that would stabilize or worsen over time, also contributing to the disorganization syndrome observed in schizophrenic individuals, whose patients may no longer be able to consciously explain aspects of their intuitions, emotions, and behaviors, which would emerge implicitly and be guided by unconscious processing, and which would occasionally access consciousness in an anarchic manner, thus leading to the impossibility of combining components of their experience of self into a coherent narrative (Mishara et al. , 2014).

Thus, through the theoretical neuroscience model of the Global Network Workspace, the team of (Berkovitch et al., 2017) were able to propose a theory-driven global model of schizophrenic symptomatology, which they were able to couple with observations made at the neurobiological, biomolecular, cognitive, psychological, and phenomenological levels; and whose final observations help explain observations that have been made in the humanities, including psycholinguistics and pragmatics (Fouqueré et al, 2021b; Musiol & Rebuschi, 2007; Musiol & Trognon, 2000; Musiol & Verhaegen, 2014; Verhaegen, 2007), giving them a materialist, bio-physical-chemical consistency, as well as providing a working basis in terms of computational theory for any further investigation of a pathological condition; thus justifying our further use of these analytical methods, of which we will carry out a state of the art and whose capabilities in terms

of computational modeling of psychological processes we will later analyze.

2.2 The pragmatic approach in computational psychology

From the earliest attempts at interactive psychology, long before the very conception of the definition of the discipline of psychology, language has been studied in its integrative and dynamic properties. As early as antiquity, the Greek philosopher Aristotle was the first to theorize about rhetoric, defining it as "the learning of the ability to discern in each case what is potentially persuasive" (Aristotle, 1991) by focusing on three analytical axes spread over three books: rhetoric, speaker psychology, and stylistic effects; considering two types of evidence supporting rhetoric and of a different nature: first, independent and external evidence or *antheknaî* (i.e. all those which are not provided by the speaker but pre-exist his action); in opposition to the dependent and internal proofs or *euteknaî* (i.e. all those which it is possible to gather thanks to rhetoric and proper to the knowledge and expertise of the speaker). If we place this ancient definition in the context of current knowledge, we could already make an analogy between Aristotle's predictions and current knowledge, considering the *antheknaî* as the sensory evidence of Bayesian models; and considering the *euteknaî* as the priors encoding the perceptual models of the world and which are directly dependent on the speaker's experiences and background.

Subsequently, although interactive (or more generally, discursive) analysis has persisted in a very large number of disciplines such as logic (Hamblin, 1976; Krabbe, 1985; Rahman et al., 1997; Walton et al., 2008; Walton & Krabbe, 1995), social psychology (Ghiglione & Trognon, 1993; Markova, 1994; Vernant, 2008), linguistics (Caelen, 2003; Caelen & Xuereb, 2017; Labov & Fanshel, 1977, 1977; Roulet, 1987, 1995; Weigand, 2010),; and even in different schools, such as interactional sociolinguistics (Gumperz, 1982), and conversational analysis (Sacks et al, 1974; Schegloff, 1996), it has ultimately focused on the study of architectural or global properties of dialogue in its physiology, with little comparison of theoretical models with the predictions they are capable of producing in a pathological context.

However, one particular stream, pragmatics (Gazdar, 1980; Grice, 1975; S. Levinson, 2006; S. C. Levinson, 1983, 2006; S. C. Levinson et al., 2000a; Sperber & Wilson, 1986, 1991), has been particularly interested in the applicability

of psycholinguistic models for the study and understanding of pathological processes, including their subsequent contribution to physiological processes. The pragmatic current thus experienced its golden age when cognitive psychology established its dominant position over the other epistemological currents of the psychological sciences, thus leading to the development of a cognitive theory of pragmatics constituting the essence of the famous pragmatic approach to the analysis of psychopathological conditions (Trognon, 1992). Highly influenced by functionalist doctrines, the pragmatic approach in cognitive psychopathology considers that the causal explanation of psychological processes cannot do without an explanation in terms of physical principles, whose representations that emerge refer to computations operated from abstract, but formalisable laws. This approach - which seems to be compatible with the theories of contemporary computational neuroscience - already predicted at the time that the interactive schizophrenic symptomatology stemmed from a decontextualization of information in schizophrenic individuals, stemming from an erroneous integration of the elements of the context which must, in physiological conditions, be rigorously organized. As "context" is currently conceived as an integration of sensory evidence into a larger phenomenological framework, which may include the individual himself, or even another individual or group of individuals, as well as one or more events that may be derived from the immediate perceptual context, the common-ground of speakers, or even general societal knowledge; its correct integration is critically dependent on the prefrontal cortex (Duff et al., 2011; Judo et al., 2010; Oosterwijk et al., 2015; Spaak & Lange, 2020; Wilson-Mendenhall et al., 2013), which we have defined as one of the main computational hubs of the Global Network Workspace. Thus, the predictions made by the pragmatic approach to cognitive psychopathology, which, although derived from ad hoc and non-standardized observations on heterogeneous dialogical material, made fundamental predictions of schizophrenic pathology that have been confirmed nearly two decades later by the most advanced computational neuroscience models described in the previous section; thus justifying our interest in this disciplinary school.

Thus, in the present work, we defend the position that contemporary analytical techniques of the time, computational sciences, which are built with the objective of making possible the joint analysis of highly dimensionalized data, including in the joint analysis of fundamentally heterogeneous dimensions ; could extend the predictive and analytical potential of discursive and interactive analyses, and could notably allow to reach a goal initially pursued by the schools

of interactive psychopathology, namely the highlighting and dissociation of elementary cognitive processes put into exergue during interactive events as well as their differential expression at the level of the dialogical system in the case of pathology; as well as to link them to other objectivizable dimensions obtained, for example, through electrophysiological or psychometric measurements.

2.2.1 Computational interactive psychology: the epistemological situation of the study of the interactive system as a physical system

2.2.1.1 The Information theory

Shannon's Information Theory (Shannon, 1948) is a probabilistic physical theory for estimating the information content of a set of data or messages. According to Shannon, information has a particularly important random property. Indeed, a random event is, by its very nature, uncertain. It is precisely this uncertainty that is used as a metric for information, the latter being defined solely by its probability ($I = -log(P)$). Thus, the more uncertain the information is, the more interesting it is. In contrast, a certain event contains no information. It is therefore more a theory of probability than a pure logical theory.

Information is measured by Shannon in binary units (i.e. bits), which can be defined as an event that resolves the uncertainty of a receiver placed in front of an alternative whose only two outcomes are equiprobable. Thus, the more possibilities that this receiver can envisage, the more informative events the message contains (thus increasing the quantity of bits transmitted). Of course, the receiver does not measure the information contained in a message in bits, but this is the case of the communication channel constructor, who uses this information in bits to make the transmission of the message more economical and reliable.

Shannon's theory is associated with two notions: that of redundancy and that of noise. Redundancy is defined, according to Shannon, as any element that is useless for the transmission of information. Subsequent work in linguistics has shown that the information is neither in the word, nor in the syllable, nor in the letter (Shannon & Weaver, 1948). Thus, in a sentence, there are syllables that are useless for the transmission of the information contained in the word, and could well represent this concept of redundancy. Concerning noise, Shannon uses the example of the routing of telecommunicative information through a

material channel (i.e. electric wire, radio waves...) which produce pseudo-random disturbances of all outgoing and jamming the message.

From a neuroscientific point of view, Shannon's information theory is used in theoretical neuroscience to estimate the amount of information related to the stimulus and contained in the neural response (Quiroga & Panzeri, 2009) :

$$H(S) = -\sum P(s) log_2 P(s) \geqslant 0$$

Or the marginal entropy of stimulus space, which informs us about the amount of information that can be extracted, the greater the entropy, the more information.

$$H(S|R) = -\sum_r P(r) \sum_s P(s|r) log_2 P(s|r) \geqslant 0$$

Or the conditional entropy, which informs us on gains related to the reduction of uncertainty.

Which give us the following relation :

$$I(S;R) = H(S) - H(S|R) \begin{cases} 0 : \text{If S and R independent} \\ H(S) : \text{Perfect discrimination} \end{cases}$$

Thus, information theory has already been applied to multiple levels of organization such as synapses (Zador, 1998), unit cells (Rieke et al., 1997), and neuronal populations (Brunel & Nadal, 1998). We will argue here that information theory can explain the updating of internal Bayesian models of the world by the living beings we will now describe.

2.2.1.2 The Bayesian predictive coding

The hierarchical Bayesian predictive coding framework (K. Friston, 2005; K. J. Friston et al., 2002; Rao & Ballard, 1999) is a theoretical model in which the brain continuously predicts future events, using Bayesian statistics to update past beliefs based on sensory inputs, thereby minimizing prediction errors leading to reduced behavioural errors. These beliefs are represented at the neural level by an "internal model of the world" (i.e., a hierarchy of assumptions

about the world (K. J. Friston et al., 2002)) that would represent the physical level as the experiential reality of living beings. In this framework, perception is considered as a statistical inference that combines bottom-up sensory inputs with top-down inferential predictions, based on acquired or innate priors (i.e. distributed probabilities representing a belief, before they are updated by actual sensory information). In case of incompatibility between priors and sensory inputs, a prediction error signal is sent in the bottom-up direction to update the "internal model of the world", and minimize surprise effects later (Charles et al., 2017). Thus, the prediction error is represented by the difference between what happens and what was predicted.

Predictions are thus formed by a top-down processing called "backward chain", where high-level hypotheses are transformed into low-level hypotheses (i.e. predictions from sensory inputs). This top-down form increases the "forward chain", i.e. the bottom-up processing, where sensory inputs are incrementally transformed into more abstract hypotheses (Kwisthout & van Rooij, 2013).

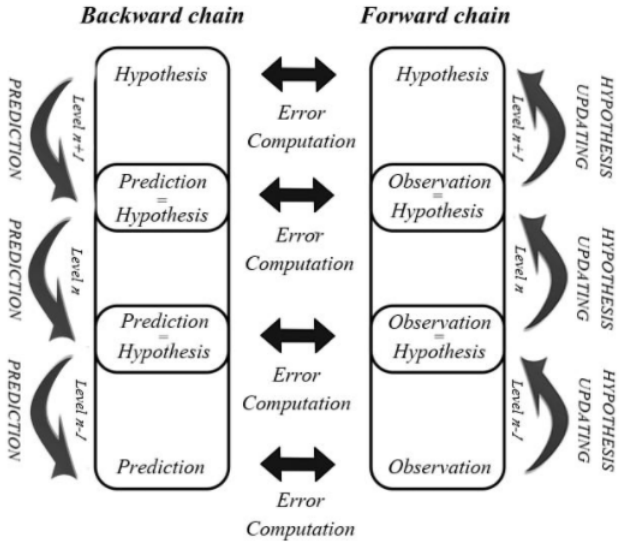

Figure 2.1: Schematic picture of the interaction between the backward chain (left) and the forward chain (right). Adapted from (Kwisthout & van Rooij, 2013) by Manon Richard.

The example used by (Kwisthout & van Rooij, 2013) to describe the predictive coding framework is the binocular rivalry in vision sciences (Hohwy et

al., 2008). In this experiment, the image of a house is presented to a subject's left eye, and the image of a face to his right eye. The subjective experience of the images will alternate successively between the face and the house, rather than as a combination of stimuli taken separately. Indeed, since the house-face combination is not familiar and is not represented in the internal model, the combination will have a low prior probability, which is why the subject will only observe a house or a face. The observation thus produces a prediction error: a mismatch between what has been predicted (e.g. the face), and what is observed (both a face and a house). This mismatch will produce an update of the hypothesis and thus of the model, by taking the posterior probability in conjunction with the prediction error, and the hypothesis will be shifted to a house, rather than to the combination of a face and a house.

This framework is becoming an increasingly popular model of perceptual, behavioural and neural phenomena in cognitive neuroscience, notably thanks to its spectacular explanatory results in various fields of investigation such as neural repetition-suppression (Summerfield et al., 2008), motor planning (Brown et al., 2011) or even the understanding of action (Den Ouden et al., 2012; Kilner et al., 2007a, 2007b).

2.2.1.3 Towards a quantum theory of social interaction ?

In the field of quantum physics, the world has two major qualities:

- it is realistic (i.e. reality is objective and does not depend on an observer or a measurement)
- it is deterministic (i.e. reality is not random but is the consequence of variables producing systematic and predictable results, provided that the information necessary for its understanding is available).

Concerning the realistic nature of the world, there are many forms of interpretation of concepts that have an appeal to realism. The most central and consensual of them all is the concept of mind-independent reality, which states that there is an objective reality different from that inferred in the human brain (Alai, 2017; d'Espagnat, 2011; Psillos & Ruttkamp-Bloem, 2017; Zwirn, 2017). Open realism (d'Espagnat, 2011), in particular, thus postulates the existence of two realities: the phenomenon (i.e. the world as perceived in the mind (Le Bihan, 2016)); and the mind-independent reality (i.e. the world as it really is). Thus, this distinction leads to two main forms of realist interpretation

(d'Espagnat, 1989): One form considers that independent reality cannot be subjected to investigation, and thus considers that physics can only describe and analyze phenomena, whose components are unknown; another form, known for scientific realism, postulates that physics can describe independent reality directly.

In any case, we will rather take here the point of view of pragmatic realism, which considers that in the context of the study of physics, or science in general, it would be favorable to consider realism in its specific intrinsic context (Forbes, 2017; Healey, 2018; Ruetsche, 2015; Saatsi, 2017).

From a psychological point of view, the same rules seem to apply and there seem to be two realities: the world as it really is, and the world as it is perceived and known by living beings. From this point of view, the world as it really is would be shared by all living beings (who ignore its laws) whereas the perceived world would be unique to each of these living beings and would depend on the observable measurements made by their sensory systems. Indeed, the perceived and experienced world could be represented from a neuroscientific point of view by the Bayesian "internal model" of the world that we have previously described. This difference could also be raised in logical or philosophical terms with the assertion "All crows are black", known as Hempel's Paradox (Hempel, 1945), which would be true in the internal model of all people who have encountered only black crows in their lifetime and false for independent objective reality since there are albino crows (which are not considered as logical exceptions (Cohen, 2020)).

Concerning the deterministic character of the world, although there are also many definitions of determinism, we will take the point of view of (Rummens & Cuypers, 2010; Van Strien, 2014) who consider determinism as the involvement of any group of systems isolated from other systems in the production of a single result for a single set of possible conditions. In contrast, indeterminism is the absence of determinism. These properties of determinism can be characterized as ontological (i.e. a component of independent reality); or epistemic (i.e. a component of our knowledge of independent reality). Thus, it has been shown theoretically that the analysis of classical mechanics implies epistemic indeterminism, since it is impossible to be certain of the physical laws that are attributed to certain theoretical models, which consider that well-identified systems can be treated as isolated, with laws that would describe how these systems evolve from their initial conditions. However, it has also been shown that no system can be totally isolated from the others, and that in the known

universe, laws cannot be separated from their initial conditions (Smolin, 2015).

Thus, ontological determinism generally underlies epistemic indeterminism (Werndl, 2011), since :

- Applying a simple law can generate complex unpredictable behaviour (Werndl, 2009), so determinism does not always imply predictability of system behaviour (Hoefer, 2016; Oldofredi, 2018);
- There are analytical limitations of science in the precision with which initial conditions can be specified (Gazeau, 2018; Gisin, 2019).

From a psychological point of view, one might wonder whether the concept of determinism is compatible with the free will of living beings. Even if the debate on the compatibility between quantum mechanics and the notion of free will is still open (Esfeld, 2015; Gisin, 2019; Gerard 't Hooft, 2007; Gerard 't Hooft, 2015; Kastner, 2016), ontological determinism is not fundamentally opposed to epistemic free will (i.e. the freedom to choose an initial condition, regardless of the subject's past, to infer possible evolutions) (Gerard 't Hooft, 2007; Landsman, 2017). Indeed, the free behavioural choices of living beings are likely to be linked to past events they have experienced (Gerard 't Hooft, 2007; Gerard 't Hooft, 2015), even if these events are difficult to describe and evaluate under practical conditions (Kastner, 2016). Some theoretical psychologists such as (Putnam, 1981) have already formulated the hypothesis that if identical brains were placed in a jar when faced with a given stimulus, they would likely all produce the same response. These postulates are only beginning to be investigated and partially validated by recent research in cognitive neuroscience (Ashby et al., 2017; Levin et al., 2019; Plonsky & Teodorescu, 2020). This work follows on from the electrophysiology work carried out by (Libet et al., 1983), who realized that when a person performs a voluntary motor act, the motor cortex initiates the cerebral activity corresponding to the motor act approximately 300ms before the conscious decision to act. This so-called "motor preparation potential" component raised an important question about the role of conscious will in initiating action, where the free tree would represent a kind of conscious vessel that would be there to stop any inappropriate behavior according to the information available in the Global Network Workspace (past experiences; goals; Baars & Bernard, 1988 ; 1997 ; 2002).

However, quantum physics teaches us that everything is different below a certain scale: that of atoms and particles. For example, if a particle has two

possible states 0 and 1 (e.g. like an electric switch). According to the Copenhagen interpretation, while a switch can only be in one state at a time (i.e. on or off; 1 or 0), the particle is in a "superposition of states", i.e. both 1 and 0 (thus contradicting the possibility of a unique and objective reality for the particle) (Bohr, 1928). This superposition disappears only when an observer decides to measure his state, causing the collapse of the wave function (i.e. the physical system has its state reduced to that which has been measured) (Giacosa, 2014; Schlosshauer, 2005; Von Neumann, 1983).

Thus, the particle does not follow a deterministic but a probabilistic logic. We cannot predict the state it will be in, but we can calculate the probability of obtaining one state or another (i.e. a 50-50 chance of being in state 1 or 0).

From a neuroscientific point of view, an analogy of social interaction (dialogical or not) with the interaction of particles could be made. Indeed, we know that during a dialogue between a speaker A and a speaker B, there is a planning of the possible course of the dialogue represented in the nervous system of each of the speakers (Fouqueret et al., 2018). Thus, when producing a statement from speaker A to speaker B, inferences of the effect of the statement from A to B should obviously be maintained in the nervous system of A, as possible continuations of the dialogue. These inferences will only be lifted at the moment of the production of a response utterance from B to A, which would correspond to the measure of the effect of the utterance from A on B, and thus to the collapse of the superposed states in A. From this point of view, one could define an iterative "dialogic time" that would represent the successive measures of the effects of the utterances (i. e. as vectors of transformation of the state of the interaction under the impulse of the speechs acts) by their destination interlocutors and thus the passage from the inferential to the observable (i.e. the "collapse" of the inferences).

2.2.1.4 The thermodynamics of interaction : energy trade-off, the goal and the cost

The first principle of thermodynamics teaches us that the total energy of an isolated system remains constant. Thus, the events occurring in the system only result from transformations of certain forms of energy into other forms of similar or different kinds of energy. There is therefore no production of energy *ex nihilo*, it is only transmitted from one system to another through transformations.

$$S_{created} = \Delta S_{sys} + \Delta S_{ext} \geqslant 0 \,\text{for}\, a\,\text{non}-\text{isolated system}$$

Moreover, in thermodynamics, we know that equilibrium corresponds to the most probable macroscopic configuration of the system (i.e. that which is achievable by the greatest number of microstates). The macroscopic state of thermodynamic equilibrium of an isolated system is therefore the one for which the entropy of S is maximum taking into account the constraints imposed on the system. Thus, particles isolated from the external environment will exchange energy by interacting with each other, until they reach a state where the global statistics of the system will remain invariant over time and where no more information will be exchanged.

Therefore, the entropy of an isolated system (i.e. not exchanging material or energy with the outside), cannot decrease. It increases with each irreversible transformation of the system, or remains constant if this transformation is reversible:

$$S_{created} = \Delta S_{sys} \geqslant 0 \,\text{for an isolated system}$$

However, entropy reduction of a non-isolated system is still possible. Indeed, if the increase in entropy of the external environment more than compensates for the decrease in entropy of the system :

$$\Delta S_{sys} < 0 \implies \Delta S_{ext} \geqslant |\Delta S_{sys}|$$

From a neuroscientific perspective, there is no doubt that any neural event (or its consequences in terms of information processing or action) consumes energy (e.g. ATP). And there is no doubt that this energy is used to stabilize the system at energy efficient levels. (Schrodinger, 1958) had actually made this assumption in the epistemological study of consciousness. As described earlier, he postulated that consciousness was a learning engine, having a role in establishing routines for interacting effectively with its environment. Then, once the routines are established, it gradually fades away to make room for automatisms, explaining why older people perceive time as passing more quickly, as the time of consciousness is gradually reduced. Thus, it is clearly visualized

how learning a method of executing a process balances the energy balance of learning time through future optimization of executions.

A similar mechanism could be postulated from an interactive point of view, where separate and isolated systems (i.e. humans) could communicate in order to exchange information, process it optimally and produce results while minimizing energy costs. Each statement (or act) would thus induce a transformation of a particular state of the system, which, after having processed the information until reaching a stable state, would remain frozen until its further transformation by the following act.

From a psychological point of view, the act of language could thus be considered as a request for the initiation of a cooperative behavior whose realization would be conditioned by an exchange of energy favorable to the interactants. Let us take the example of the well-known indirect speech act "It is cold" and imagine a situation with two conditions. In both conditions, there are two neurotypical and peer interlocutors, who would be in the same room and each sitting in a different chair, separated by a desk and facing each other, one with his back to the window and the other with his back to the entrance. The window is open in the middle of winter, and it is cold in the room. In condition 1, interlocutor A is sitting on the seat with his back to the entrance, while interlocutor B is sitting with his back to the window; and in condition 2, interlocutor A is sitting on the seat with his back to the window, while interlocutor B is sitting with his back to the entrance.

The first interlocutor (A) says "It is cold". Two responses are possible: first, it is possible that interlocutor B gets up and goes to close the window; but it is also possible that he replies "Close the window, then!". Both responses are valid, and would represent a request-response pair (RAP) in rhetorical models of dialogue (Caelen & Xuereb, 2017). However, it is very likely that these responses are not equiprobable in the two conditions, and that speaker B would only stand up to close the window in condition 1. Conversely, it is also very likely that speaker B would only respond to speaker A to close the window himself in condition 2, where speaker A would be leaning directly against the window.

This example illustrates the principles that should underlie cooperative behavior. In both conditions, speaker A produces information that underlies a dialogic goal in the sense of (Caelen, 2003). He wants the temperature to warm up. This information is processed by speaker B's nervous system, which will produce an appropriate response.

In condition 1, speaker B has his back to the window. It is therefore less costly for speaker A to make a verbal request, rather than to stand up and close the window himself. Conversely, Speaker B, who understands the implicit request, may feel that it is as costly for him to make a verbal response and process the responses as it is for him to close the window, and he may also feel that it would be less costly for him to close the window than for Speaker A. Thus, the cooperative behavior will have been less costly for the dyad, rather than for the isolated individual that is Speaker A.

In contrast, in condition 2, speaker B is facing the window from the desk. It seems unlikely that he would get up to close the window while speaker A is leaning against it; and it also seems unlikely that the request is a request for action! Rather, it would seem that speaker A did not notice that the window was open, and therefore tells him to close it himself. Indeed, here, by taking up this notion of cost, we realize that the cost of the cooperative interaction of condition 2 is more important than the realization of the action by speaker A in isolation. This is the economic reason why the cooperative action of closing the window would not be performed. Thus, the cooperative action of closing the window would not be performed for an "economic" reason in terms of energy.

From a theoretical point of view, this hypothesis could be justified very early on in the framework of the relevance theory developed by Sperber and Wilson (Sperber & Wilson, 1986, 1991) in the continuity of Grice's work, which postulates that human communication aims at recognizing the communicative intention of its interlocutor through a cooperative effort, and through a system of context-indexed inferences where the speaker will select the inferential interpretation that will generate a maximum of effects with a minimum of effort. Finally, and in a general way, the behavior of biological organisms is characterized by optimization, even from the recognition of their environment by building and optimizing internal models of environmental dynamics, thus generating sensory inputs. They also optimize their behavior by adapting it to the environment, thus increasing their probability of survival and reproduction. The self-organization of biological organisms could thus be represented by a cost minimization function (Dayan et al., 1995; Linsker, 1988; Sutton & Barto, 1998). A canonical class of neural networks encoding rating-models has been theorized where neural activity and plasticity would minimize a cost function, with a modulation of plasticity depending on the durations of the occurrences, thus allowing active inferences to be made in order to minimize the risk of future behavioral outcomes. They are thus mathematically equivalent

to variational free energy minimization models (i.e. Markovian decision process models), allowing neural substrates to achieve an optimal level of control of the environment through the optimization of internal Bayesian models. This theory is supported by recent work in artificial and theoretical neuroscience (Isomura et al., 2022). As each action is guided by a computation of the cost/benefit balance of the behavior, this computation, which could be performed by the striatum (Wieland et al., 2015), could thus condition the success of a speech act, the inference of its pragmatic meaning, as well as its satisfaction, which will itself be conditioned by an inference of the cost/benefit balance for each speaker. This computation could be interpreted as a decision element in the selection of the communicative intention among the inferences that have been stacked, and as a necessary element for the acceptance of the cooperative act, and then for the subsequent respect of the principle of cooperation as described by the maxims of (Grice, 1975).

2.2.2 Contemporary models of interaction analysis: state of the art

2.2.2.1 Linear Logics and Ludics

2.2.2.1.1 Ludics theory

The Ludic theory, developed by J-Y Girard, is a way to reconstruct logic based on the notion of interaction. It relies on the notion of proof analyzed in the framework of linear logic which has two interesting properties: its formulas can be polarized (i.e. negatively or positively), allowing to determine which elements can enter in interaction; it allows to produce proof-nets, which can by this way be proved by their connections rather than by formulas. In this way, it is possible to interpret concepts from a dialogical point of view and to analyze interactive processes using the traces they produce. Each intervention will thus consist in the opening of a new locus where the polarized pragmatic element (negatively or positively) carried by the statement will be located, and on which a pragmatically relevant element of opposite polarity can be connected (creating an interaction within the network). In a model derived from game theory, the concept of proof is superimposed on the concept of design. A design is a set of actions, constituted in chronics (i.e. sets of actions relevant to each other from the pragmatic point of view), themselves organized in a semantically coherent

set (i.e. the design). The starting point of the analysis is thus the action, which corresponds to the smallest functional unit of the Game theory, and which can be defined according to three parameters: its polarity (positive or negative), its focus (i.e. the location where the action occurs) and its branching (i.e. the finite number of locations that can be reached in one action). A fourth parameter could be described, that of a special positivity having a character of closure of an issue under discussion: the daimon. It thus represents a positive variable where no locus can be fixed.

The action is defined as follows by (Girard, 2001) :

Definition 1 (Actions) *An action κ is :*

- *either a positive proper action $(+, \xi, I)$ or a negative proper action $(-, \xi, I)$ where the focus of the action is a locus, and the ramification I is a finite set of integers ;*
- *or the positive action daimon denoted by $\dagger$.*

Where :

- +/-represents the polarity ;
- ξ represents the location of the action ;
- I represents the ramification of the action.

Thus, the succession of mutually consistent positive and negative actions form chronicles, representing concatenations of mutually relevant information that are dynamically organized as the exchange proceeds. In general, the chronicle can be decomposed in the following way: its starting point is an initiating sequence (i.e. an initiating action) located at a defined position, itself connected to a locus allowing the location of an action that can be connected to it; it is then elaborated iteratively by a sequence of actions having different focuses and alternating polarities; then it ends with a positive sequence of the "daïmon" type.

The chronicle is thus defined in the following way by (Girard, 2001) :

Definition 2 (Chronicles) *A chronicle $\mathfrak{c}$ is a non-empty and finite alternate sequence of actions such that :*

- *The base of the chronicle is a sequent* $\Gamma \vdash \Delta$ *of loci where the set* Γ *contains the initial focus of a negative action, if there is one and* Δ *contains the initial loci of future positive actions ;*
- *a positive proper action is either justified (i.e. its focus) is built by one of the previous actions in the sequence, or it is called initial ;*
- *a negative action may be initial, in such a case it is the first action of the chronicle. Otherwise it is justified by the immediate previous positive action ;*
- *actions have distinct focuses ;*
- *if present, a daimon ends the chronicle.*

Since the chronicle consists of alternating positive and negative sequences, it is constructed iteratively with the progression of the exchange following three rules that can be interpreted in logical terms as hypersequentialized calculus, i.e. rules that have an arbitrary number of premises. These rules define how an action will be connected to the network: the daimon, the positive rule, and the negative rule, and are based on the evidence focus theorem (Andréoli, 1992). This theorem considers that some connectors are deterministic and reversible (i.e. negative sequences, which can be read in all directions and can be applied deterministically); and others are non-deterministic and non-reversible (i.e. positive sequences, which can only be read in certain directions and cannot be applied deterministically). In other words, from an informational point of view, no information is lost when using a negative rule (i.e., such as and in linear logic (Girard, 1987)) whereas irreversible choices are made when using the positive rule (i.e., such as exclusive conjunctions and disjunctions in linear logic). Thus, when topologically encoding a column within a fork follows the following rules (Lecomte & Quatrini, 2011):

Definition 3 *A design (as dessin) based on a fork* $\Gamma \vdash \Delta$ *is a tree of forks built by means of the three following rules :*

- *Daïmon :*

$$\frac{}{\vdash \Delta}\ \dagger$$

- *Positive rule :*

$$\frac{...\xi.i \vdash \Delta_i...}{\vdash \Delta}\,(+, \xi, I)$$

- *Negative rule :*

$$\frac{... \vdash \xi.I, \Delta_I...}{\xi \vdash \Delta}\,(-, \xi, \mathfrak{M})$$

With $I = i_1, i_2, ..., i_n$*, and with* $\xi.I$ *as the sequence* $\xi.i_1, \xi.i_2, ..., \xi.i_n$

As stated by (Lecomte & Quatrini, 2011), $\mathfrak{M}$ is a set (maybe empty or infinite) of ramifications, then a set of finite sets of integers. Thus, for all $I \in \mathfrak{M}$, all the Δ_I are contained in Δ.

These rules can be interpreted in dialogue as follows (Lecomte & Quatrini, 2011):

- Positive rule (choose a component where to answer) : Choose $i \in \{1, ..., P\}$ $(a \oplus -member)$ and decompose the context Γ into disjoint pieces ;
- Negative rule (the range of possible answers) : nothing to choose, simply enumerates all the possibilities

Thus, two chronicles can be separated by the chronicle coherence property, which assumes that the separation of two chronicles is coherent if and only if the chronicles differ in their negative actions, in the sense that the negative actions attributed to their respective chronicles have distinct loci, and thus separable interactions. Girard thus defines chronicle coherence as follows (Girard, 2001):

Definition 4 (Coherence of chronicles) *Two chronicles* c_1 *and* c_2 *are coherent, when the two following conditions are satisfied :*

- *either one extends the other or they first differ on negative actions, i.e., if* $c_1 = w\kappa_1$ *and* $c_2 = w\kappa_2$ *are coherent then either* $\kappa_1 = \kappa_2$ *or* κ_1 *and* κ_2 *are negative actions.*
- *when they first differ on negative actions and these negative actions have distinct loci then the loci of following actions in* c_1 *and* c_2 *are pairwise distinct.*

Then, the set of congruent and separable chronicles in terms of coherences can be gathered into a design, whose properties follow from the previous definitions and which are defined as follows by (Girard, 2001):

Definition 5 (Designs) *A design $\mathfrak{D}$, based on $\Gamma \vdash \Delta$, is a set of chronicles based on $\Gamma \vdash \Delta$, such that the following conditions are satisfied :*

- *The set is prefix closed.*
- *The set is a clique of chronicles (the chronicles are pairwise coherent).*
- *A chronicle without extension in $\mathfrak{D}$ ends with a positive action.*
- *$\mathfrak{D}$ is non-empty when the base is positive (in that case all the chronicles begin with a unique positive action).*

The design can thus be represented by a tree that gives an account of all the actions organized in chronicles. The following example concerns a design made up of two chronicles, each made up of four actions and ending with a daimon:

$$\mathfrak{c}_1 = (+, 1, \{1\})(-, 1.1, \{1, 2\})(+, 2, \{1, 2\})(-, 2.1, \{1\})\dagger$$
$$\mathfrak{c}_2 = (+, 1, \{1\})(-, 1.1, \{1, 2\})(+, 2, \{1, 2\})(-, 2.2, \{1\})\dagger$$

On this example, the two sets of the prefixes of $\mathfrak{c}_1$ and $\mathfrak{c}_2$ represents a design, which is represented by a tree of actions (Faggian, 2002 ; Figure 2).

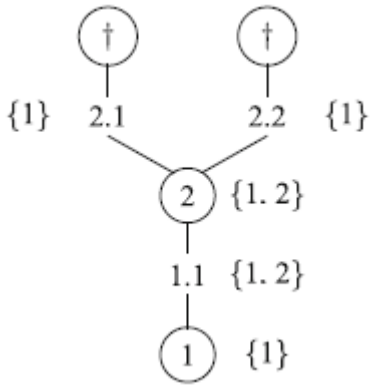

Figure 2.2: Tree of actions from the two chronicles in Example 1. The circles highlight positive actions; the nodes without circles highlight negative actions; and the lists of integers for each node represents the focus of the action, and the set annexed to each node is a branch. Adapted from (Lecomte & Quatrini, 2011)

Finally, the set of designs constituting the dialogue will form the network, which is defined by (Girard, 2001) as the finite set of designs on disjoint bases.

2.2.2.2 An example of topological encoding in Ludics

As noted by (Lecomte & Quatrini, 2011), the three rules used in the representation of designs in terms of evidence can be interpreted in dialogical terms. Indeed, the negative and positive rules can be transposed respectively as performing an intervention at an address (positive rule) and expecting a reaction to be localized there (negative rule). Thus, by conforming to the positive rule, the interactant of the first speaker selects a location among all those available in the foreground of the dialogue, and thus decides the information (i.e. the content) that he wishes to connect to it.

This transposition is illustrated by the following example, taken from the work of (Lecomte & Quatrini, 2011):
- U1A: This year, for my holidays, I will go to the Alps (0.1) with friends (0.2) and by walking (0.3).
- U2B: Well, in the Alps, there are a lot of winter entertainments, skiing (0.1.1), cross-country skiing (0.1.2), bobsleigh (0.1.3)...

Concerning A's utterance (utterance 1), he presents three sub-themes that can be discussed (i.e. they are questions under discussion: QUD in the sense of (Ginzburg, 2012)). This is done using the following positive rule, which offers three possible answer "choices", opening three addresses (0.1, 0.2, 0.3, all three of which follow from 0). The formalization has been adapted from (Lecomte & Quatrini, 2011) and simplified.

$$\frac{0.1 \vdash \Delta_1 \qquad 0.2 \vdash \Delta_2 \qquad 0.3 \vdash \Delta_3}{\vdash 0, \Delta}$$

Here, $Delta \cup 0$ represents the set of discussion topics (i.e. QUD) that are available, and the 0 represents the anchor location of utterance U1. At this stage of the dialogue, utterance U1 gives interlocutor B the possibility to continue the discussion on three possible topics: the destination of the trip (i.e. the Alps), the composition of the group of travelers (i.e. friends), and the way to get there (i.e. by foot). Three locations (0.1, 0.2, 0.3) or addresses are thus connected to the location 0 on which they are anchored. The intervention is thus encoded as the positive action (+, 0, 1, 2, 3). Thus, speaker A infers at the end of the intervention that three continuations are possible for the dialogue based on the addresses that his intervention has opened. This state can be represented as follows:

$$\dfrac{\dfrac{\vdash 0.1.1, \Delta_1}{0.1 \vdash \Delta_1} \quad \dfrac{\vdash 0.2.1, \Delta_2}{0.2 \vdash \Delta_2} \quad \dfrac{\vdash 0.3.1, \Delta_3}{0.3 \vdash \Delta_3}}{\vdash 0, \Delta}$$

Then, speaker B responds to speaker A through U2. The second speaker will then perform an action which will represent the negative equivalent as a selection among the choices proposed by A. In our example, speaker B chooses to elaborate the exchange on the sub-theme of the Alps, by introducing a new sub-theme (winter activities) through the action $(-, 0.1, I)$. We can now represent the dialogue as follows:

$$\dfrac{\dfrac{\vdash 0.1.1, \Delta_1 \qquad \dfrac{\vdash 0.1.2, \Delta_1 \qquad \vdash 0.1.3, \Delta_1}{0.1 \vdash \Delta_1} \qquad 0.2 \vdash \Delta_2 \qquad 0.3 \vdash \Delta_3}{\vdash 0, \Delta}$$

In this representation, the three sub-themes formulated by B (skiing, cross-country skiing, and bobsledding) are connected to the theme that motivated their production, in the same way as before. It is also important to note that, more rigorously, the themes "winter entertainments", in the same way as the other structural themes (the year, the vacations" should themselves have been encoded as a theme from which the following sub-themes would flow.

2.2.3 Ludics and interaction

From the ludicist point of view, interactions correspond to normalization processes in some particular sub-networks of designs, called cut-nets (Girard, 2001). In these networks, which represent dialogical stacks of confronting designs (one design per interactant), the addresses are all distinct and are only present once in a negative position on one base, and once in a positive position on another base, creating a temporally linked pair and allowing for an association between the respective designs, which defines the cuts. In this sense, ludic realizes a generalization of the cut elimination theorem from a proof-based theoretical perspective (Dragalin & Mendelson, 1988; Feys, 1965; Gentzen, 1935; Girard, 2001; Lecomte & Quatrini, 2011; Takeuti, 2013). This theorem is essential to prove the assertion that a sequent calculus is equivalent to the usual form of the predicate calculus, in a sense that the formula is deducible in the predicate calculus if and only if the sequent $\Rightarrow \phi$ is deducible in the sequent calculus. It can be defined as follows : if the given sequents $\Gamma \rightarrow \Delta\phi$ and $\phi\Gamma \rightarrow \Delta$ are both deducible in the sequent calculs, then $\Gamma \rightarrow \Delta$.

Thus, the following cut rule :

$$\frac{\Gamma \to \Delta\phi; \phi\Gamma \to \Delta}{\Gamma \to \Delta}$$

is the associated deviation rule in which the normalization theorem asserts that this rule is admissible in the calculus.

The cut-elimination theorem thus allows the positive and negative sequences of different designs to interact, bringing out the Ludical definition of interaction (Girard, 2001) :

Definition 6 (Interaction on closed cut-nets) *Let $\mathfrak{R}$ be a closed cut-net, the design resulting from the interaction, denoted by $[[\mathfrak{R}]]$, is defined in the following way: with $\mathfrak{D}$ as the main design of $\mathfrak{R}$, and the first action κ.*

- *if κ is a daimon, then $[[\mathfrak{R}]] = \{\dagger\}$*
- *otherwise κ is a proper positive action $(+, \sigma, I)$ such that σ is part of a cut with another design. Let $\mathcal{N}$ be the set of all ramifications of (negative) actions on the same focus σ in this design) :*
  - *If $I \notin \mathcal{N}$, then interaction fails.*
  - *Otherwise, interaction follows with the connected part of subdesigns obtained from I with the rest of $\mathfrak{R}$*

This interaction property thus allows us to deduce two interesting dialogical parameters: the convergence of the interactants, which can be interpreted in cooperative terms, and the temporal aspect of the dialogue. Concerning the convergence, the ludic theory embarks with it the notion of orthogonality, which allows to compare two designs from their counter-designs from the separation theorem (Girard, 2001), thus :

Definition 7 (Orthogonality) *Two designs $\mathfrak{D}$ and $\mathfrak{E}$ respectively based on $\vdash \xi$ and $\xi \vdash$, are said orthogonal when $[[\mathfrak{D}, \mathfrak{E}]] = \{\dagger\}$. $\mathfrak{D}^{\perp}$ denotes the set of all designs $\mathfrak{E}$ such that $\mathfrak{D}$ and $\mathfrak{E}$ are orthogonal.*

Concerning the temporal aspect of the dialogue, Ludician concepts allow us to track the trace of the interaction, which simply consists of the iterative sequence of action sequences that are visited during the normalization process and which can therefore be represented by a finite sequence of actions that follow one another (Lecomte & Quatrini, 2011). It is defined as follows by (Girard, 2001).

Definition 8 (The trace of an interaction) *Let $(\mathfrak{D}, \mathfrak{R})$ be a closed cut-net such that the normalisation process stops on convergence or divergence after a finite number n of steps. The trace of interaction, seen from $\mathfrak{D}$'s view is denote by $\tau\mathfrak{D}$. We define by induction on $1 \leqslant k \leqslant n$ the initial subsequences of $\tau\mathfrak{D}$:*

- *Case $k = 1$:*
  - *If the interaction stops in one step : either $\mathfrak{D}$ is equal to $\dagger$, in this case, $\tau\mathfrak{D} = \dagger$, or the main design (which is not $\mathfrak{D}$, is equal to $\dagger$ and in this case $\tau\mathfrak{D}$ is the empty sequence, or the interaction fails and $\tau\mathfrak{D}$ is put equal to Ω, the symbol used for divergence.*
  - *Otherwise let κ^+ be the first action of the main design. The first action of $\tau\mathfrak{D}$ is κ^+ if $\mathfrak{D}$ is the main design and is $\overline{\kappa^+}$ otherwise.*
- *Case $k = p + 1$: the prefix $k_1...k_p$ of $\tau\mathfrak{D}$ is already defined*
  - *Either the interaction stops and :*
    - *if it converges, then $\tau\mathfrak{D} = \kappa_1...\kappa_p$ if the main design is a subdesign of R, or $\tau\mathfrak{D} = \kappa_1...\kappa_p\dagger$ if the main design is a subdesign of $\mathfrak{D}$*
    - *if it fails, $\tau\mathfrak{D} = \kappa_1...\kappa_p\Omega$*
  - *or the interaction does not stop. Let κ^+ be the first proper action of the closed cut-net obtained after the step p, $\tau\mathfrak{D}$ begins with $\kappa_1...\kappa_p\kappa^+$ if the main design is a subdesign of $\mathfrak{D}$, otherwise $\tau\mathfrak{D}$ begins with $\kappa_1...\kappa_p\overline{\kappa^+}$*

Because of this property of momentarily capturing the temporal aspects of dialogical interaction, Ludic is a theory capable of connecting to theories allowing the characterization of functional and kinetic linguistic units, which we will develop in the following sections and which will thus allow us to characterize actions as well as their transitions dynamically with respect to the temporal aspects.

2.2.4 Foundations of the kinetic module: speech act theory, rhetorical relations and SDRT

2.2.4.1 Definitions of the functional units to be considered: the speech act as a ludic action, definition of functional units

2.2.4.1.1 From pragmatics to the speech acts theory

The first works defining the notion of pragmatics were carried out by (Morris, 1934) for whom "pragmatics is that part of semiotics which deals with the relationship between signs and the users of signs". Through the foundation of his theory of signs, Morris operated a tripartition of semiotics which considers that language is accomplished on three planes :
- the syntactic level, characterized by the relations that the signs maintain between them ;
- the semantic level, characterized by the relations that signs maintain with things and states of affairs ;
- and the pragmatic level, characterized by the relations that signs maintain with the agents who produce them, and thus ultimately their use in communicative contexts.

The speech acts theory considers that the minimal unit of human communication is neither the sentence nor the word, but the performance of certain types of acts producing particular effects in their context. The work of (Austin, 1970) has thus shown that the literal form of sentences does not always make it possible to predict semantic and pragmatic meanings, and that the latter should rather be considered in relation to the use made of them by the subject of the utterance (i.e. the speaker's intention). Austin thus concludes that some literal statements do not carry any information about the implied facts. Thus, a given proposition can have a completely new effect on a given dialogical system, depending on who is saying it, the context in which he is saying it, and the time at which he is saying it, thus sweeping aside the idea of a recursive evaluation of sentences and words. With this work, Austin broke with the descriptivist conception of language that had prevailed until then, and that may still persist in non-dialogical paradigms of data science, and thus brings out the idea that language can also be used to perform actions. Subsequently, (Searle, 1982) supplemented Austinian theory by re-examining his classifications, judging that

they were not based on any clear principle or set of principles, thus creating overlapping categories. He thus proposed five classes to categorize speech acts: assertive, directive, commissive, expressive, and declarative. We will present their properties in the next section.

2.2.4.1.2 Properties of speech acts

Following (Austin, 1970), (J. R. Searle & Vanderveken, 1985) postulate that a speaker who uses an utterance with a communicative intention always intends to perform an illocutionary act in the context of its utterance, suggesting that it is in the performance of such acts that human agents express and communicate their thoughts (Vanderveken, 1993). In the same work, they axiomatize the theory of speech acts by categorizing illocutionary acts into five classes of elements that have illocutionary forces F and propositional contents p of their own that can be represented on the form $F(p)$:

Illocutionary act	**Speaker's expectations**	**Effects of the proposition on the world**
Assertive	Gives an account of a state of the world	Adjusts words to the world
Directive	To make the listener do something	Make the listener adjust the world to the words
Commissive	Commit to doing something	To commit to adjusting the world to the words
Expressive	To give an account of one's mental state	(Empty adjustment direction)
Declarative	Change the state of the world	Adjusting the world to words and words to the world

Table 2.1: Classification of illocutionary acts according to Searle & Vanderveken, 1985

Thus, (Searle & Vanderveken, 1985) postulated that a speech act is accomplished by means of the enunciation of an utterance, by the representational or cognitive function of its content and the illocutionary force that it applies to the interactive system. This work also describes the nature of illocutionary forces, which it represents as a function with 7 variables:
- The illocutionary goal: which represents the purpose of the illocutionary act (i.e. the intention pursued) by the person performing the act. It is fundamental in its definitional properties of the speech act and in its directionality (i.e. it determines the direction of adjustment of the world and thus its relation with the world) ;
- The mode of accomplishment: which represents how the speaker must reach his goal (i.e. the set of conditions necessary for the goal to be reached) ;
- The propositional content conditions: which represent the syntactic-semantic constraints that the force imposes on the proposition carrying the propositional

content of the act ;
- The preparatory conditions: which represent the intrinsic variables carried by the context and respective to the enunciator of the act, its addressee, their relations, interests and intentions ;
- The conditions of sincerity : which represent the psychological states, beliefs, and intentions conventionally expressed during the accomplishment of the act. The conditions of sincerity of an illocutionary force thus determine the mental state that the speaker expects to have if he wanted to sincerely perform the speech act ;
- The degree of power: which represents the degree of explicitness of the intentional state ;
- The degree of force: which accounts for the intensity with which the illocutionary goal is achieved.

Finally, this work has opened the way to two important properties of speech acts: success and satisfaction of acts. Thus, the success of a speech act without defect would depend on certain conditions which are the following:
"- The speaker, in this context, achieves the illocutionary goal of F on the propositional content P with the required mode of achievement and degree of force of the illocutionary goal of F ;
- it expresses the propositional content P and the latter satisfies the propositional content conditions imposed by F ;
- the preparatory conditions of illocution and the propositional presuppositions are obtained in the world of enunciation and the speaker presupposes that they are ;
- he expresses and possesses the psychological state determined by F with the characteristic degree of sincerity" (Searle & Vanderveken, 1985: 24).

A speaker succeeds in performing a speech act in a possible context of enunciation if he succeeds in making the addressee grasp exactly what he is communicating, so that he can create the conditions to succeed in actually performing the act in this particular context, as noted by (Ghiglione & Trognon, 1993).

The satisfaction properties of speech acts were only described a few years later, when (Vanderveken, 1988) integrated the notion of the perlocutionary function of language, which represents the psychological effect that the locutionary act produces on the receiver, in contrast to the illocutionary act. He thus introduced the second property of speech acts: satisfaction. According to

(Vanderveken, 1988), the satisfaction of a speech act is conditioned by the obtaining in the world of an enunciation context for the speech act to be satisfied in this context, and thus, an act is satisfied only if its propositional content is true in the direction of adjustment of its illocutionary goal.

2.2.4.1.3 Speech acts and inferential pragmatics

The work of (Searle & Vanderveken, 1985; Vanderveken, 1988) has thus made it possible to create a general formal semantic theory of speech acts, describing their properties and their conditions of realization. These were completed in particular by (Grice, 1975; Sperber & Wilson, 1991) on the basis of the notion of inferential pragmatics. According to this work, for the communication of a language act to be successful, the recipient must be able to infer the communicative intention of his partner (Grice, 1975; M. Musiol & Trognon, 2000; Sperber & Wilson, 1991). It is this inference that allows us to access the explicit propositional content (e.g. by determining the reference of indexicals, semantically enriching or restricting quantifiers) and to measure the propositions implicitly conveyed by the utterance in the strict conversational context of the utterance (Chierchia, 2004; Gazdar, 1980; Horn, 1989; Horn, 1972; Levinson, 1983; Levinson et al., 2000b). Thus, inferential pragmatics can be interpreted as a true theory of language mind based on computational inferences about context, allowing the perception and conceptualization of intentional behaviors by conspecifics and the attribution of mental states to others (Friederici et al., 2017; Frith & Frith, 1999, 2006; Frith & Frith, 2005; Shallice, 2001). The inferential model of pragmatics thus proposes to describe communicative processes as the mental operations that, given the utterance of a certain assumption by a speaker, cause the interlocutor to arrive at a given assumption, possibly different from the one predicted by the original speaker. From this point of view, communication theories must therefore describe, with the help of non-linguistic principles, the inference processes necessary to access the meaning communicated by the utterance, given that we have shown that the semantic representation of a sentence is incapable of providing a reliable interpretation of the actual communicative intention by itself. For this reason, the work of dialogical linguistics from the pragmatic school was subsequently interested in the dynamic properties of dialogue, particularly in the kinetic sequence of speech acts and in the characterization of iterations by the transitional effect of speech

acts relative to the strict dialogical context in which it was uttered.

2.2.4.2 From act to response: rhetorical relations and characterization of transitions

2.2.4.2.1 Discourse analysis

The starting point for the characterization of the transitions of dialogical events is to be found in formal linguistics. In the theoretical school of discourse analysis, conversation can be observed as a sequence of linguistic acts (i.e. illocutionary acts) corresponding to intended actions whose realization is promoted or fully realized by the use of language. It is therefore a deductive approach whose objective is to model conversational interaction based on experimental data or data obtained in an ecological context.

The first discourse analysis models developed were essentially based on the concept of conversational coherence, where the notion of language act and the principles of relevance and cooperation were central. In a transitional analytical logic, we can cite the therapeutic model of (Labov & Fanshel, 1977), which was based on production rules linking programmed actions to the statements that carry them out, and which included a certain number of interpretive rules that made it possible to encode the transitions between statements and actions; as well as the hierarchical and functional model of Geneva (Moeschler, 1985; Roulet, 1995), which considers conversation as a series of illocutionary acts following a dichotomous organization, some of which are subordinated to the others (the directing acts), and which conceives of discourse as a hierarchical discursive framework organized according to three conversational structures: exchange, intervention, and speech act:
- The exchange is the smallest dialogical unit composing the interaction. It is composed of at least two conversational contributions (i.e. two turns of speech) from different speakers. The two contributions can be located in two different exchanges, in which case we say that they are embedded. In this sense, the exchange can be interpreted in a ludic sense as designs ;
- The intervention is the largest monological unit of the exchange. It consists of one or more speech acts. The principle of composition underlying the intervention, i.e. in its quality of being able to be composed of several interventions, exchanges, or even to take place over several turns of speech, makes it possible to bring it closer to the Ludic concept of chronicles ;

- The speech act is the smallest monologic unit constituting the intervention. We can thus bring it conceptually closer to the ludic action.

In addition to its hierarchical properties, the model of (Moeschler, 1985) has made it possible to introduce a fundamental concept in the analysis of dialogical transitions, namely the functional component of conversational structures, i.e. the interpretative characterization of structures and constituents by the attribution of dialogical functions that can be objectively observed by the effects of speech acts on the dialogical system. It thus allows the characterization of certain illocutionary functions that allow the determination of the initiative and reactive functions of the acts, as well as their interactive functions, by associating each subordinate constituent with its directing constituent. The model has since been adapted to a more dynamic perspective (the model being considered too static by its authors) by freeing itself from the principles of atemporality and incompleteness. These principles remain however interesting in the analysis of the dialogue as we will see in section X which concerns the topological deviation paradigm of the 2TK model.

2.2.4.2.2 Conversational analysis

Conversational analysis can be seen as the ethnomethodological equivalent of discourse analysis, due to its sociological tradition. It aims at describing the course of everyday conversations in natural situations (Cosnier et al., 1988). Although it fundamentally rejects the notion of language, this school has nonetheless highlighted fundamental properties of dialogue, notably by focusing on its sequentiality and temporality, especially through work on the adjustment of the turn of speech and the alternation of interlocutors (Sacks et al., 1974). This work considers conversation as a system of interaction directed towards a goal and on which as few external constraints as possible should weigh, allowing the derivation of intrinsic rules of speaker alternation and where sequentiality intervenes both in the cooperative elaboration of the interaction and in the inter-comprehension of its components (Trognon, 1994). It is therefore based on the partners' reciprocal pragmatic knowledge, which makes it possible to infer and plan the probable course of the interaction at that precise moment of the exchange. In this sense, it can be compared to the Ludic concept of planning the exchange.

2.2.4.2.3 Interlocutory logic

Interlocutionary logic (Trognon, 2003) is a method of analysis based on conversational and discursive analysis to study the way in which the dynamics of interlocution produce information on the socio-cognitive levels from a pragmatic point of view. It is based firstly on speech acts and their properties, applying them to the content of interventions in their reciprocal relationship (Ghiglione & Trognon, 1993). This analytical framework conceives the interventions as sets of language acts, whose reciprocal relations are governed by logical rules. Conversation is thus based on the individual properties of the acts and the logical relations that the interlocutory acts weave between them (Ghiglione & Trognon, 1993), thus allowing them to be seen in terms of networks. The analysis of the relations between acts is derived from the properties formalized by (Searle & Vanderveken, 1985; Vanderveken, 1988). Although relations were not formally categorized in interlocutionary logic models, forcing conclusions to be drawn on the basis of ad hoc models, interlocutionary logic allowed the formalization of conversational sequences, conceiving conversation as an organized structure, which comprises turns of speech dependent on units of constitution, so that the explanation can be sought at the level of speech acts and logical relations which articulate their properties in their intrinsic sequentiality, while considering the language and social facts inextricably linked (Ghiglione & Trognon, 1993; Trognon & Brassac, 1992; Trognon & Kostulski, 1999).

Thus, interlocutionary logic can be considered as a theory of the logical form of interlocutionary events as they are phenomenally organized through sequential productions distributed among several interlocutors, and making use of logical methods compatible with the highlighting of phenomenal properties such as natural deduction or the method of sequences, in order to put the phenomenon of interaction at the center of the dialogical system (Trognon & Batt, 2007). This is why interlocutionary logic has been chosen as the tool of choice for studying the role of interaction in cooperative problem solving (Trognon, Batt, & Laux, 2006; Trognon, Batt, Schwarz, et al., 2006, 2006; Trognon et al., 2007; Trognon & Batt, 2007), as well as for the study of free dialogue (Batt et al, 2004), which makes it all the more attractive given its compatibility with models from human-computer interaction, which put the notion of cooperative goal resolution at the center of the dialogical system (Caelen, 2003), and which have recently been generalized to ordinary dialogue (Caelen & Xuereb, 2017).

Because of its histological and dynamic properties, interlocutory logic has allowed many advances in psychopathology, particularly in the apprehension of cognitive deficiencies in pathological subjects on the basis of cognitive-conversational analysis (Michel Musiol, 2002). Indeed, since language use relies on an integration of multisystemic information (social, memetic, perceptual cues, etc.), we can expect that the pathological cognitive properties that govern language use can be observed either in natural situations or in experimentally controlled situations where language is used in a dynamic interactive context (Musiol & Trognon, 2000; Trognon, 1992), thus making it possible to derive an interlocutory symptomatology that will be interpretable on neurocognitive and psychopathological levels not only from the point of view of the sender, but also from the point of view of the receiver (Bernicot et al, 2002), given that the properties of the conversation reflect the cognitive organization of the subject, particularly in the relationship between thought patterns and the structure of the conversation (Michel Musiol, 2002). It is precisely this possible dissociation that inspired the topological deviation paradigm that we will describe in section x.

2.2.4.2.4 Contributions of the study of human-computer interactions

Interlocutionary logic has thus made an interesting contribution to the study of dialogical dynamics by the possibility it offers to highlight the constitution of the pragmatic network of the interaction by characterizing the transitions of speech acts by their effect on the dialogical system. However, as mentioned above, interlocutionary analysis did not provide a strict characterization of the effects of speech acts and therefore did not propose a ubiquitous model. This is the reason why we are now going to focus on the human-computer interaction literature which has retained our interest for three reasons: first, it allows the characterization of speech act duals by their effect on the dialogical system in a systematic way, given that their nature aims at the optimization of interactive systems between artificial and biological agents in a perspective of observation of a task directed towards a goal (that of solving the task, even dialogical) while remaining compatible with the theory of speech acts ; secondly, because this literature has converged towards interlocutory analysis in its effort to generalize to the dialogue as a whole; and finally, because this literature stemming from

theoretical computer science has been thought in a desire to open up the possibility of computer implementation of the models produced, and is therefore open to the possibility of encoding.

The work of (Caelen, 2003) has thus made it possible to re-specify the notion of language acts from the point of view of human-computer interaction, and therefore in frameworks designed to be reproducible. Based on (Vanderveken, 2001), he introduces the notion of goal in the theory of speech acts by postulating that the dialogue takes place in a framework defined by the following elements :

- the conversational goal: which gives the purpose of the conversation ;
- the sequences ;
- the different topics explored in the discourse ;
- the background of the conversation (the context, including the environment of the task and the social roles).

He thus defines the conversational goal as a predicate, which can either be a situation to be reached in the world or a mental state to be satisfied. He gives the example of the following formula: $b = (x, y) : circle(x) \wedge square(y) \wedge red(x) \wedge (on(x, y))$ which carries with it the goal of getting a red circle on a square, and thus a state of the world to be achieved. Thus, he brings the notion of dialogic goal closer to the general paradigm of dialogic planning by realizing the distinction between task planning (i.e., solving a problem with the help of operators who have the ability to perform elementary actions) and dialogue planning (i.e., organizing turns of speech with a strategic view to resolving the exchange). He thus proposes a redefinition of speech acts in a problem-solving perspective, based on the work of (Searle & Vanderveken, 1985) :

Act (Caelen, 2003)	Searle equivalent (Searle, 1969)	Meaning (Caelen, 2003)
F^A	Declarative	Do or carry out an action (in verbal or non verbal)
F^F	Directive	(make do) ask the hearer to carry out an action
F^S	Assertive or expressive	(make-known) communicate an information
F^{FS}	Directive	(do make-known) ask for an information
F^P	Promissive with delegation	(do can) give a choice, make an invite
F^D	Directive	(do must) oblige without giving an alternative

Table 2.2: Characterization of speech acts in Caelen models and relationship with their source models.

Thus, (Caelen, 2003) proposes to model the man-machine dialogue through a logic of action, which naively assumes that the interactants build their dia-

logue in a rational way (i.e. around coordinated actions) by respecting a priori the normalized social conventions in an optic of goal resolution. This approach thus conceives the dialogue as both constructive (i.e. it tends towards the construction of a common goal through the respective objectives of the interactants based on common knowledge) and co-interactive (i.e. the agents coordinate their actions to solve the goal). One could assume that this theory is restrictive, as noted by the author himself, but it is of particular interest to us in the constitution of a unified model given the possibility that it offers to measure the efficiency of the dialogue by measuring the level of coordination between two agents in a perspective of solving a task interactively while allowing to model the common knowledge of the interactants, which opens the way to a possible extension of this work by means of a model of artificial neural networks based on knowledge (KBANNs).

Subsequently, (Caelen & Xuereb, 2014, 2017) generalized this model of human-computer interaction to the general-purpose dialogue (i.e. between two human agents), drawing in particular on interlocutory analysis. They proposed a characterization of speech act doublets based on the rhetorical relations that these acts share:
- Plan Elaborations (P-Elab): Plan Elaboration, is a contribution to the construction of a joint plan leading to build the framework of action ;
- The subordinate questions (Q-Sub) : Question Subordination, are requests for clarification about mutual knowledge (extended to requests for clarification, correction, reformulation, precision, etc... noted Q-Sub:clarification, QSub:precision, etc...) ;
- The questions and related answers (QAP): Question Answer Pair, the answer P is supposed to provide information relative to the question Q ;
- R-Elab: Action Elaboration, is a contribution to the construction of a goal. - Action delegations (RAP): Request Answer Pair, is a request for action followed by real actions to try to resolve the current goal (can be incomplete and/or partial) ;
- Elaborations of knowledge (Elab): Elaboration, are contributions of mutual knowledge built during the dialogue. Can by constructive questions (Elabq), assertions for example) or by the clarifications, corrections, reformulations, precision, etc... ;
- The incidences (I): are acts that break abruptly the current topic by introducing a new topic.

- Replicas (R): Closing coordinations.
- Continuations (C): are acts that continue the discourse in the same topic without making the goals progress (e.g. mmh ; i see ; yeah ; etc...) or to close a series of statements concerning one particular topic.

This definition allows us to characterize the speech act doublets by the rhetorical relations they maintain, and thus by their dynamic effects on the dialogical system.

Now that it is possible to characterize the functional units of interaction (i.e. speech acts), as well as the relations they maintain (i.e. rhetorical relations), and to topologically position these elements, we will present the SDRT, a theory of discourse coherence allowing to characterize the dynamic and kinetic properties of dialogue.

2.2.4.3 Characterization of dialogue dynamics using the Segmented Discourse Representation Theory (SDRT)

The Theory of Segmented Discourse Representations (SDRT) is a comprehensive theory that proposes to analyze the formal structure of discourse through the combined points of view of the tradition of formal semantics in philosophy of language and discourse analysis in computational linguistics, i.e. by explicitly modeling the semantic-pragmatic interface while allowing to account for the discourse links that exist between the different propositions and segments of the discourse (Busquets et al., 2001). The SDRT is thus the result of the unification of two research streams: formal semantics, which gave rise to dynamic semantics (DRT); and discourse analysis, which highlights the discourse macro-structure by breaking down the dialogical network into segments (i.e. functional units carrying meaning at the discourse level) and their hierarchical organization.

2.2.4.3.1 From formal semantics to DRT

Formal semantics had as its primary goal to model the semantics of natural languages by means of model theory, proposing to determine the meaning of a sentence by establishing the truth conditions of this sentence in all possible worlds (i.e. it is a vericonditional theory). It was initially proposed by Richard Montague (Montague, 1974) and was mainly based on the principle of compositionality, a mathematical concept representing syntactic structures

and the space of semantic values as algebras, their interpretation being based on semantic homomorphisms allowing to associate syntactic rules and semantic rules, behind the postulate that each sentence in natural language has a typed logical correspondent which is then evaluated in the set of possible worlds (Gamut, 1991), a process which can be realized in the Λ-calculus formalism (Krivine Jean-Louis, 1990). However, the Montagovian approach encountered certain problems of interpretation, especially in the area of anaphoric relations between pronouns and definite descriptions, which motivated later work to focus on theories that allow for the semantic interpretation of discourse, in particular the theory of discourse representations (DRT), which we will present below.

DRT was proposed by Hans Kamp (Kamp, 1981; Kamp & Reyle, 1993) and aimed at interpreting discourse through its semantics (i.e. through the kinetics of the linguistically meaningful units that follow one another), and thus offered a representational theory of discourse that postulated an intermediate level of representation between the syntax of a text and its interpretation in a model (Busquets et al., 2001). It is based on the representation of Discourse Representation Structures (DRS), making this theory a non-compositional one. Generally speaking, a DRS is a partial description of how the world should be organized if the discourse is true, and is therefore based on the concept of discourse truth, which can only be satisfied if the partial model (i.e. the DRS) can be embedded in a complete model of reality. Thus, meaning is the relationship established between the contexts in which a discourse is performed and the situations described by the utterance of that discourse (Busquets et al., 2001). Moreover, the SRDs are interpreted according to the dynamics of the dialogue, allowing the introduction of a referent or discourse marker as a potential antecedent for subsequent sequences, in order to incorporate the dynamic view of meaning from the point of view of cognitivist approaches such as (Fodor, 1990), thus placing the context as the main variable of the meaning of the sentence (Groenendijk & Stokhof, 1991).

2.2.4.3.2 Towards the SDRT

The works that investigated dialogue through DRT were then interested in the analysis of the linguistic structure of discourse and of the relations that link its parts, notably by drawing on discourse analysis, which had already been exploited in computational linguistics, notably in the context of human-

computer interaction in comprehension models. This approach was interesting in the sense that it was not interested in the truth conditions of a discourse, but rather proposed an abstract model in which several elementary propositions could be grouped together to form homogeneous blocks that were related to the chaining of linguistic segments of propositional nature, thus allowing to provide a linguistically coherent hierarchization that was not limited to the simple linear connection of sentences. This approach thus allowed for differential constructions of a discourse in a tree-like manner where the leaves are the minimal segments, and the nodes the complex segments. (Grosz & Sidner, 1986; Polanyi & Scha, 1984; Webber, 1988) proposed that the hierarchical structure built iteratively from linguistic units constrains the possible attachment sites, assuming that the open segments (i.e. available for the introduction of a new discourse relation) lie on the right-hand border of the tree. To illustrate this principle, (Busquets et al., 2001) proposes the following example:

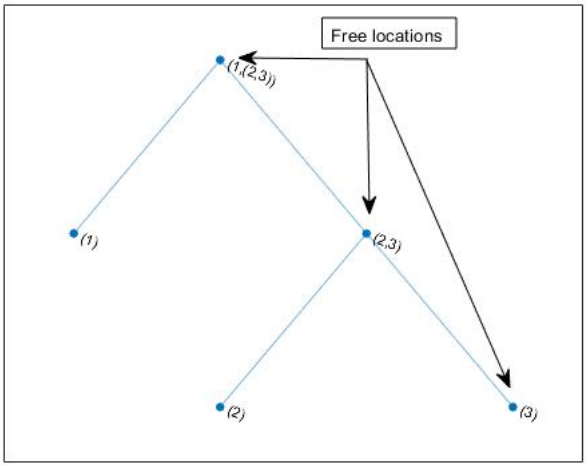

Figure 2.3: Open sites in the structure of a discourse. Adapted from (Busquets et al., 2001))

In this example, the nodes of the right boundary, which correspond to the site of open attachments. The rest is closed, unless the author produces a linguistic unit explicitly signaling the opening of a closed site.

Moreover, this theory introduces the notion of plan, interesting in our frame-

work given its possible superposition with the notion of design. (Hobbs, 1985) defines the plan in a discourse as an ultrastructure containing the content of the message, its organization (i.e. the coherence of the segments) and how the message is presented (i.e. the enunciation), also allowing access to the speakers' goals and intentions. This notion has been completed by the theory of discourse patterns (Mann & Thompson, 1988), an interesting notion because it can be superimposed on the notion of ludician chronicles, which postulates that the basic units can be grouped into groups of propositions, distinguishing between propositions carrying core or satellite properties. They propose that certain relations privilege certain segments (i.e. cores), while others are less essential, and even interchangeable between them, while remaining compatible with the communicative goal of the discourse author. Finally, (Grosz & Sidner, 1986) have shown that the structure of the collective tasks that participants seek to achieve can be deduced from the structure of the discourse, taking the view that the discourse is divided into segments, each corresponding to a subtask contributing to the satisfaction of a communicative goal. This precision makes this theory all the more interesting in our framework, since it is compatible with the notion of human-computer interaction goals, while taking into account cognitive components in its design at the linguistic (i.e. it is a sequence of utterances), attentional (i.e. focus of topics) and intentional (i.e. communicative) levels.

2.2.4.3.3 The Segmented Discourse Representation Structures Theory (SDRT)

SDRT is a dynamic representational theory of discourse which has sought to bring together the two traditions presented above and which seeks to take into account the segmentation and structural organization of discourse. It has thus extended the theoretical postulates of DRT to make explicit in a vericonditional theoretical framework the interaction approaches between the semantic content of the segments considered in a global and pragmatic structure of the discourse (Busquets et al., 2001). It was initially proposed by (Lascarides & Asher, 1993) in a form that is of particular interest to us since it takes into account the temporality of the dialogue as a variable. They proposed the SDRT as an operational theory of the semantic-pragmatic interface through deterministic methods of constructing SDRS, which represent the propositional content of

the discourse and which represent its macrostructure, whose minimal functional units are semantic in nature as in the models of (Hobbs, 1985; Polanyi Scha, 1984). Thus, SDRT represents an iterative method of constructing representations, where complex segments are constructed from compositions of simple segments, and where each new segment must be linked to a previous segment by a discourse relation, and thus respect the principle of coherence that follows from discourse analysis. The model of (Lascarides Asher, 1993) is thus superimposable on the straight boundary hypothesis of (Grosz Sidner, 1986; Polanyi Scha, 1984; Webber, 1988), with the difference that a new segment can only be attached to the last segment analyzed or to the hierarchically superior segments dominating the last segment, while abandoning the constraint that only one discourse relation connects two segments: in fact, two relations can simultaneously connect two segments of an SDRS.

An SDRS is thus a recursive structure whose elementary components are representations of propositions, labels, and discourse relations, formulated in a first-order logic language, and with an associated graphical representation allowing to facilitate their reading. Their construction is done in an incremental way, where each new elementary proposition is integrated to the already constructed SDRS (except for the first proposition that is introduced in an empty context), and through four steps (Busquets et al., 2001):
- a new elementary constituent (DRS) is constructed corresponding to the new proposition to be processed;
- we determine the possible attachment points in the existing SDRS;
- we compute the discourse relations for each considered attachment;
- we update the SDRS at the structural and propositional level (i.e. we insert the new constituent on an open site, then we specify it).

The convention in SDRT is that the arc is vertical (i.e. from top to bottom) if the relation is subordinating (i.e. likely to introduce a complex discourse segment) and horizontal (i.e. from left to right) if it is coordinating, thus allowing the SDRT to be matched with the dominance and precedence satisfaction relations of (Grosz & Sidner, 1986) (Busquets et al., 2001) proposes the following example to illustrate the hierarchization of a structure by considering the following text:
a. John went to the hospital yesterday.
b. Mary broke his nose,

c. and Paul broke his arm.

d. He was operated on right away.

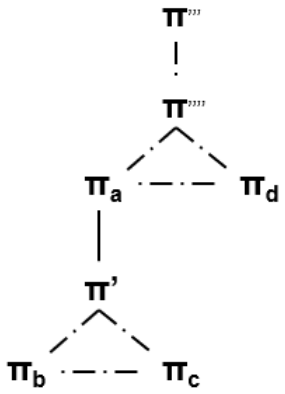

Figure 2.4: SDRT representation of the example proposed by (Busquets et al., 2001). Adapted from (Busquets et al., 2001).

Here, the continuous lines represent the attachments between the labels, the corresponding relations being attached to the lines. The dashed lines represent the hierarchy between the SDRS and their respective sub-SDRS. Here, therefore, π_b and π_c represent the labels of the universe of discourse of the sub-SDRS π', just asπ_a and π_d belong to the universe of π''. Moreover, the example shows that when a relation has a complex SDRS as its second argument, the relation is distributed over the entire discourse universe, and thus the semantics of Explanation(π_a,π') here is equivalent to the semantics of Explanation(π_a,π_b) $\wedge$ Explanation(π_a,π_c). Thus, in (a-d), (b-c) represents the segment of discourse explaining why John went to the hospital (knowing that (c) continues (b)), and then returns to the level of the explained statement with (d), making it clear that any extension will have to be attached to (d), based on the notion of a straight boundary.

This example shows us that the semantics underlying SDRS can be precisely defined in model theory thanks to the notion of embedding function (which we described in the section describing DRS) by taking into account truth conditions specific to the discourse relations linking the propositions, thus allowing

to highlight the dynamic aspects of meaning through the construction of SDRS.

2.2.5 Preliminary integration

The integration of these three models associated with these three traditions of linguistics thus allows us to circumscribe dialogue in its entirety. We understand that dialogue is situated in a topological space whose effects are measurable at the scale of interaction events, and thus in state transitions. By a cross-reading, one could imagine a combined model that would produce the topology of the exchange by using Ludician techniques, and thus via the establishment of a network of proofs allowing to organize the functional units, which would themselves be represented by the speech acts as described canonically by the authors who developed the eponymous theory. Finally, the dialogical dynamics, represented by the transitions from one position to another, would be characterizable using the rhetorical relation systems proposed by the literature of SDRT and human-computer interaction.

In the next chapter, we will present a mathematical framework allowing to unify the use of these three models, and to allow their use in combination with algebraic operations or measures of qualitatively different nature. This theoretical framework will also allow to link these three models of interaction with graph theory.

Chapter 3

Shwachman-Diamond Syndrome

3.1 History

The histopathological and phenotypic characteristics of Shwachman patients were clarified in the 1980s. Thus, research carried out on large cohorts of Shwachman-Diamond syndrome patients showed very early on a high prevalence of leukemia in Shwachman-Diamond syndrome patients (Woods et al, 1981), myocardial lesions (which can lead to death) including congenital myofibrillar necrosis (Savilahti & Rapola, 1984), and abnormal phagocytic function of polymorphonuclear leukocytes (Repo et al., 1987). Further research confirmed that exocrine pancreatic acinar dysfunction was a key feature of the symptomatology of Shwachman-Diamond syndrome, which was often associated with anemias, leukopenia and thrombocytopenia (Mack et al, 1996); as well as a wide range of immunological dysfunctions such as neutropenia, circulating and proliferating B cell defects with lack of antibody production, and T cell abnormalities (Dror & Freedman, 2001).

The autosomal recessive monogenic mode of inheritance was first elucidated in 1999 by (Ginzberg et al., 1999), with the mutation located at a locus in the centromeric region of chromosome 7 (Goobie et al., 2001). The gene involved in the emergence of the Shwachman-Diamond syndrome pathology, the SBDS gene, was then identified two years later by (Boocock et al., 2003). Skeletal features such as delayed bone age in Shwachman-Diamond syndrome were also

described early on (Aggett et al., 1979; Burke et al., 1967; Fellman et al., 1972; Ginzberg et al., 1999; Mack et al., 1996). However, it is only more recently that a radiographic study of patients with Shwachman-Diamond syndrome has shown that skeletal changes are present in all patients with the SBDS mutation, with a severity and location that varies greatly with age (Mäkitie et al., 2004)

Currently, research on Shwachman-Diamond syndrome aims to further characterize the clinical spectrum of Shwachman-Diamond syndrome by understanding the molecular and biological impairments of Shwachman-Diamond syndrome, and their relationship to the physiological and cognitive phenotype of the disease, including reasons for the significant heterogeneity in symptomatology observed in patients with the same mutation.

3.2 Epidemiology

Currently, approximately 500 cases have been described worldwide, with an estimated incidence of approximately 1/50,000 to 1/75,000 (Goobie et al., 2001). The median age at diagnosis is approximately 1 year, but the age of diagnosis varies from birth to middle adulthood. Studies in the early 2000s showed a male predominance with a male-to-female ratio of approximately 1.5:1 (M/F; (Alter, 2007)) . The median age of survival is currently about 35 years, in part because of the high probability of developing a hematologic malignancy, with an estimated cumulative probability of age-related leukemia of more than 70% *(ibid.)*.

3.3 Shwachman-Diamond and the SBDS mutation

3.3.1 Function of the SBDS gene and its product

The Shwachman-Bodian-Diamond (SBDS) gene encodes a ubiquitous 250 amino acid protein with a fundamental role in cellular physiology, given the high conservation of its sequence throughout evolution, including in archaea and eukaryotes (Boocock et al., 2003; Shammas et al., 2005). Studies in both SBDS-deficient animal models (Gijsbers et al., 2013; Provost et al., 2012; Wong et al., 2011; S. Zhang, 2009) and in patient-derived cell lines (Sezgin et al., 2013; Tulpule et al., 2013; Wong et al., 2011) have shown a critical role for SBDS in ribo-

some maturation. Indeed, these studies suggested that SBDS is required for the optimal joining of the 40S and 80S subunits to form the 80S monosome. Specifically, during translation, eIF6 (eukaryotic translation initiation factor 6) must be removed from the translation complex to allow association between the 40S subunit and the binding interface on the 60S subunit. This removal is linked to a GTPase activity of another protein, EFTuD1 (elongation factor Tu GTP-binding domain-containing protein 1) that causes a conformational change of the 60S subunits. SBDS has been shown to physically interact with EFTuD1 and affect its GTPase activity. Thus, because the GTPase activity of EFTuD1 requires SBDS, loss of SBDS function results in deficient translation due to altered subunit joining, resulting in a suboptimal 80S conformation (Gijsbers et al., 2018; S. Zhang, 2009). These observations (i.e. decreased translation) were confirmed in human embryonic kidney 293 cell lines depleted of SBDS by siRNA techniques (Ball et al., 2009).

In addition, there is a growing body of evidence that the SBDS gene may have extraribosomal functions. Indeed, studies in bone marrow cell lines derived from SDS patients have shown that the SBDS protein colocalizes with the mitotic spindle during mitosis to prevent genomic instability (K. M. Austin et al., 2008). Thus, loss of SBDS function or siRNA depletion has been shown to increase mitotic abnormalities and aneuploidy that would accumulate over time, contributing to bone marrow failure and leukemogenesis. In another study conducted in HeLA cells, (Orelio & Kuijpers, 2009) showed that SBDS protein colocalizes in human neutrophil cells with F-actin. Thus, in SBDS-mutated cell lines, it was observed that neutrophils have impaired F-actin polymerization and polarization properties, which could explain the impaired neutrophil chemotaxis in these patients.

3.3.2 Genetic basis of Shwachman-Diamond syndrome

The SBDS gene is located in the long arm of chromosome 7 at cytogenetic position 7q11 (Boocock et al., 2003) and is composed of 5 exons that encode a 1.6 kb mRNA. The gene is located in a block of duplicated sequence in two versions: the functional gene, SBDS; and its non-functional pseudogene, pSBDS, 97% identical in sequence to the functional gene. The fact is that the pSBDS gene may contain errors that can be introduced into the SBDS gene through genetic conversation (i.e. there is an exchange of genetic material between the SBDS gene and its neighboring pseudogene), thus ultimately disrupting the

production of the SBDS protein. In fact, 89% of the individuals with characterized SDS studied by (Boocock et al., 2003) had an exchange of genetic material between SBDS and pSBDS observable at meiosis, 60% of which had two converted alleles. The most frequently observed mutation was a splice site mutation with a single nucleotide change in intron 2 (258+2T>C) that alters SBDS function (hypomorphic allele). The second most frequently observed mutation in this study was 183-184TA>CT, which introduces a premature stop signal in the SBDS sequence (null allele with loss of function). Only heterozygosity for the hypomorphic/null alleles and homozygosity for the hypomorphic allele were observed for SBDS. In fact, the 183-184TA>CT mutations result in complete loss of function of the protein, so homozygosity for this allele would result in complete absence of the SBDS protein which is ubiquitous and critical in development, causing early embryonic lethality as shown in the homozygous loss of function animal model of SBDS (S. Zhang et al., 2006).

3.4 Clinical presentation of Shwachman-Diamond syndrome

Current diagnostic criteria for Shwachman-Diamond syndrome include both exocrine pancreas dysfunction and bone marrow failure, with steatorrhea and diarrhea, hematologic disorders, and recurrent infections (Cipolli et al., 1999). However, the condition is very heterogeneous and several other organs are also affected. Thus, the clinical diagnosis is validated exclusively by confirmation of the SBDS mutation, although a negative SBDS mutation does not exclude the diagnosis of Shwachman-Diamond syndrome (Shimamura, 2006), thus extending its etiological presentation.

3.4.1 Pancreatic dysfunction

Dysfunction of the exocrine pancreas is a consistent feature of SDS (Bodian et al., 1964, p. 19; Mack et al., 1996). Subsequent histological studies of pancreatic cells have demonstrated extensive fatty replacement of pancreatic acini with ductal architecture but with islets of Langerhans nevertheless preserved (Aggett et al., 1979; Bodian et al., 1964). Similarly, ductular secretion of electrolytes and fluids was shown to remain within healthy norms, but proteolytic enzyme emission was greatly diminished, resulting in steatorrhea (Mack et al., 1996).

Pancreatic dysfunction is usually identified within the first six months of life and in 90% of cases within the first year of life (Mack et al., 1996). The tests routinely used to measure it are monitoring fecal elastase 1 and serum trypsinogen and isoamylase levels; which have been shown to be predictive biomarkers of pancreatic dysfunction in Shwachman-Diamond syndrome: low trypsinogen indicating exocrine pancreatic dysfunction in patients younger than 3 years of age, and low isoamylase in patients older than 3 years of age (Ip et al., 2002).

Although all patients had a persistent deficit in enzyme secretion, it has been shown that exocrine pancreatic function improves with age in patients. For example, one longitudinal study suggested that nearly 50% of patients had improved fat absorption and near-normal fecal fat balance by age 4 years (Mack et al., 1996).

In contrast, endocrine function of the pancreas is generally unaffected in Shwachman-Diamond syndrome, although a few cases of type 1 and 2 diabetes have occasionally been reported (Dror et al., 2011; Ginzberg et al., 1999; Mack et al., 1996; Shmerling, 1969). Notably, one study reported a case with a rare form of neonatal diabetes mellitus in a patient with Shwachman-Diamond syndrome (Kamoda et al., 2005).

3.4.2 Hematology

Hematologic changes are a key feature of the symptomatology of Shwachman-Diamond syndrome. Of these, the most frequently observed feature is neutropenia, which occurs in nearly 100% of cases (Aggett et al., 1979; Ginzberg et al., 1999; Mack et al., 1996). This neutropenia may be persistent (66.6% of cases) or intermittent (33.3% of cases), with possible fluctuations from normal to low cell counts (ibid.). Similarly, thrombocytopenia occurs in 24-88% of patients with Shwachman-Diamond syndrome associated with normochromic anemia with low reticulocyte counts in 80% (Dror et al., 2011). Cytopenias affecting all cell lineages are seen in 10-65% of cases, sometimes leading to severe bone marrow aplasia (Kuijpers et al., 2004).

Bone marrow failure is also frequently reported in Shwachman-Diamond cases, but remains variable. The bone marrow is generally described as hypocellular with increased fat deposition (Aggett et al., 1979). However, several studies have reported hypercellular or normocellular bone marrow (Ginzberg et al., 1999; O. P. Smith et al., 1996). Similarly, accelerated angiogenesis with abnormal tortuous microvessels has been observed in the bone marrow of patients with

Shwachman-Diamond syndrome (Leung et al., 2006). Thus, in this population, patients are at high risk for clonal abnormalities in the bone marrow, which can lead to malignant transformation, particularly to acute myeloid leukemia (Aggett et al., 1979; Dror et al., 2011; Mack et al., 1996; O. P. Smith et al., 1996). Other studies have elaborated on this observation, including suggesting that trisomy 8 and chromosome 7 abnormalities contribute to leukemic progression in patients with Shwachman-Diamond syndrome (Dror et al., 2011).

In patients with leukemic transformation, 92% of patients are male (Dror Freedman, 2002). This transformation is associated with a poor prognosis, as patients with Shwachman-Diamond syndrome typically do not respond to chemotherapy and are highly susceptible to complications and organ toxicity in transplantation, with approximately 83% of patients dying from treatment-related complications (Dror, 2005).

3.4.3 Immunology and infections

Immunological abnormalities are also very frequently reported in SDS. In particular, studies have shown dysfunctions in the physiological functions of phagocytes (Repo et al., 1987) associated with disturbances in neutrophil migration and chemotaxis (Aggett et al., 1979; Dror et al., 2001; Ruutu et al., 1984; Stepanovic et al., 2004). In these populations, low circulating T cells, CD3+/CD4+ cells, an inverted CD4/CD8 ratio, and low numbers of natural killer cells have also been observed in Shwachman-Diamond patients. These low percentages of total circulating cells may have been associated with poor proliferative responses. Similarly, low circulating B-cell levels associated with hypoactive proliferation have been observed in patients with Shwachman-Diamond syndrome; as well as an overall decrease in proliferative capacity including an increase in the inability to produce specific antibodies against polysaccharide antigens (Dror et al., 2011).

Thus, patients with Shwachman-Diamond syndrome are at increased risk for recurrent infections of viral and bacterial origin, producing a high risk of fatal sepsis, especially near birth (Grinspan & Pikora, 2005). The authors also note that, although these vulnerabilities are related to neutropenia, these infections occur even in patient populations with normal protective neutrophil levels, showing that the severity and frequency of infections did not necessarily correlate with the degree of severity of neutropenia (Aggett et al., 1979).

The most frequently reported infections in patients with SDS are, in order,

pneumonia (33%), otitis media (29%), and skin infections and abscesses (15%). Similarly, viral infections such as measles, cytomegalovirus and parvovirus have been reported. In contrast, fungal infections (i.e. a key feature of severe neutropenia) have only been reported in connection with stem cell transplantation (Grinspan Pikora, 2005).

3.4.4 Liver

Liver dysfunction is a common feature of patients with Shwachman-Diamond syndrome, having been described in approximately 50-75% of patients from the earliest descriptions of the disease (Aggett et al., 1979; Brueton et al., 1977; Ginzberg et al., 1999; Liebman et al., 1979; Mäki et al., 1978). All of the patients concerned had mild to moderate abnormalities of the biochemical functions performed by the liver, with or without hepatomegaly, some manifestations involving massive hepatosplenomegaly associated with elevated liver enzymes have also been reported on an ad hoc basis (Wilschanski et al., 1994).

However, these liver abnormalities appear to decrease over time. For example, a longitudinal study with a six-year follow-up suggested a decrease in fatty infiltration in the liver parenchyma with increasing age (Aggett et al., 1979).

3.4.5 Kidney

In their original article, (Shwachman et al., 1964) reported mild galactosuria with healthy renal function in patients with Shwachman-Diamond syndrome. Subsequent studies, however, could not confirm the initial observation of glycosuria, but occasionally observed calciuria, nephrocalcinosis, tubular acidosis, urolithiasis, as well as renal malformations such as a duplex ureter (Aggett et al., 1979; Cipolli et al., 1999; Ginzberg et al., 1999; Mack et al., 1996).

3.4.6 Myocardium

Fatal neonatal heart failure has been reported very early in clinical reports of patients with Shwachman-Diamond syndrome (Nivelon et al, 1978; Rybojad et al, 1996). The authors of the characteristic histopathologic alterations such as myocardial necrosis or fibrosis, being or not associated with fibrosis of the left ventricle and interventricular septum, but without any evidence of myocardial inflammation or coronary artery changes (Savilahti & Rapola, 1984). A case of

progressive dilated cardiomyopathy has also been reported in a patient with the SBDS mutation (Kopel et al., 2011).

In general, subsequent work has suggested that patients with Shwachman-Diamond syndrome would be more susceptible to cardiac toxicity during stem cell transplantation (Donadieu et al., 2005; Dror, 2005; Fleitz et al., 2002).

3.4.7 Skeleton

Substandard height, resulting from longitudinal bone growth abnormalities, has always been considered a key feature of the clinical presentation of Shwachman-Diamond syndrome. Thus, patients may present with subtle growth retardation that can be clinically significant from birth (Aggett et al., 1979; Bodian et al., 1964; Cipolli et al., 2019; Ginzberg et al., 1999; Mack et al., 1996; Shwachman et al, 1964), however, deviations become more evident in early childhood and intensify with advancing age, even when patients are treated with pancreatic enzyme supplementation (Ginzberg et al., 1999).

Bone abnormalities, such as metaphyseal chondrodysplasia affecting the ribs and knees (Burke et al., 1967), and delayed skeletal maturation that may lead to thoracic dystrophy (Aggett et al., 1979; Dror et al., 2001; Fellman et al., 1972; Mack et al., 1996; McLennan & Steinbach, 1974) are frequently reported in patients with Shwachman-Diamond syndrome. Dysplasia related to Shwachman-Diamond syndrome is thus characterized by delayed formation, but with normal secondary ossification centers and variable metaphyseal enlargement, leading to an undetectable phenotype that can result in knee and hip deformities (Mäkitie et al., 2004).

Osteoporosis and generalized osteopenia have also been reported in addition to skeletal dysplasia in both children and adults with Shwachman-Diamond syndrome (Aggett et al., 1979; Mäkitie et al., 2004; Rosendahl et al., 2006).

In general, longitudinal radiographic data obtained in patients with Shwachman-Diamond syndrome confirmed that skeletal abnormalities are present in all patients with the SBDS mutation, but that the location of bone alterations can vary widely with age, even when comparing two patients with the same genotype (Mäkitie et al., 2004).

3.4.8 Oral features

It has been shown by numerous studies that patients with Shwachman-Diamond syndrome are at high risk for oral disease. Delays in tooth maturation are

common, with up to 72% of patients having tooth enamel defects that may be hypomaturative or hypoplastic with extensive caries (Aggett et al., 1979; Ho et al., 2007). Periodontal disorders (e.g. oral ulcerations or gingival bleeding) are also frequently reported in patients with Shwachman-Diamond syndrome (Ho et al., 2007).

3.4.9 Skin

From the earliest clinical descriptions, skin manifestations were observed in nearly half of the patients with Shwachman-Diamond syndrome (Aggett et al., 1979; Savilahti & Rapola, 1984). However, they vary in severity from mild scaling of the skin to severe ichthyosis. Similarly, although skin lesions are frequently observed in the perinatal period, they seem to have a tendency to diminish with advancing age, with an observable effect from the first year of life (Savilahti & Rapola, 1984).

In addition, histological studies involving ultrastructural analysis of the skin have reported cases of non-specific dermatitis in patients with Shwachman-Diamond syndrome (Liebman et al, 1979), associated with diffuse hyperkeratoses and parakeratoses of varying severity; as well as thickening of the granular layer, perivascular lymphocytic infiltration in the papillary dermis, and droplets of varying size in the cytoplasm of keratinocytes (Rybojad et al., 1996).

3.4.10 Neurological features

The neuroanatomical and neurophysiological features of SDS are just beginning to be investigated. Early reports, although suggesting cognitive impairments in SDS, did not describe neuroanatomical malformations or major neurophysiological dysfunction (Shwachman et al., 1964). However, recent research has shown neuroanatomical and neurophysiological abnormalities in individuals with SDS (Booij et al., 2013; Perobelli et al., 2015; Toiviainen-Salo et al., 2008).

With respect to gray matter, data showed greater cortical thickness in patients with Shwachman-Diamond syndrome in both the left and right hemispheres, particularly in the temporal, right parietal, and right frontal lobes; the largest increases were in the limbic cortex and left anterior cingulate cortex. In the left hemisphere, the data show thinner cortical thickness in areas BA44 and BA45 compared to controls (Perobelli et al., 2015).These two regions represent key areas of the prefrontal cortex, and that overlap both its ventrolateral and dorsolateral portions (Fuster, 1988).

With respect to white matter, diffusion tensor imaging analyses showed differences in fractional anisotropy and mean diffusivity, both of which were higher (approximately 35%) in individuals with Shwachman-Diamond syndrome compared to their control counterparts. The a resulted in increased diffusivity in the primary, secondary, and tertiary directions; this may represent a high-level abnormality in the neural connectomic pattern in the pathways underlying the fronto-temporal and occipito-parietal junctions, where very high cross-fiber densities (Perobelli et al., 2015). In general, the study observed anarchic connectivities in all regions projecting or receiving projections from the prefrontal cortex and anterior cingulate cortex, especially in their projections with the cerebellum, striatum, orbitofrontal cortex, amygdala, and temporal lobes in general ; highlighting the interest of the theoretical model of the Global Network Workspace to explain the heterogeneous cognitive pathologies resulting from the neuroanatomical and neurophysiological alterations characteristic of the Shwachman-Diamond syndrome.

3.4.11 Neuro/psychological expression of the disorder

Although the psychological features of patients with SDS were explored very quickly in early reports, there are currently very few data related to the impact of biological and neuroanatomical abnormalities on the cognition and behavior of individuals with SDS. Indeed, at present, only 7 studies have been devoted to the (partial) assessment of the psychological and social-cognitive profile of young individuals with Shwachman-Diamond syndrome.

At the intellectual level, six studies report impaired intellectual efficiency in children with SDS. These data, based on the Wechsler scales (Aggett et al., 1980), then the WISC-R (Cipolli et al., 1999; Kent et al., 1990), as well as the WISC-III (Kerr et al., 2010; Perobelli et al., 2012, 2015); and suggest that 14-33% of individuals with Shwachman-Diamond Syndrome have intellectual impairment ($QI_T < 70$). These norms differ by far from those for neurotypical individuals, where the rate of impairment is less than 2.2% of the population. However, the registers of intellectual efficiency are very heterogeneous: indeed, while some patients show deficient performance only in certain elementary cognitive modalities, others seem to be affected in a more global way, by presenting difficulties in mobilizing their higher integrative functions.

At the neuropsychological level, alterations in executive functions have already been demonstrated, notably in visual-executive (WCST; (Kerr et al.,

2010)) and attentional (in selective, divided, and sustained attention of the TEA-Ch; (Perobelli et al., 2015)). Interestingly, a dissociated profile has previously been observed regarding social cognition, with one study showing a dissociation between functional emotion recognition, and impaired theory of mind (Canton et al., 2016). The generalizability of this study remains limited, however, due to the lack of a control group matched to the group of participants with Shwachman-Diamond syndrome.

Finally, in terms of social interactions, relational difficulties have been suggested: indeed, young individuals with Shwachman-Diamond syndrome seem to have difficulties interacting with others, both in reciprocity and in general communication itself, although only two studies have reported this based on psychometric and interlocutionary logic analyses of language production (Batt et al., 2017; Canton et al., 2016). However, and again, the generalizability of this work remains limited, particularly because of the lack of a control group matched to the participants in the patient group; and because of the lack of explanation for the observed dissociation between theory of mind impairments measured in psychometrics by standardized tests, in contrast to pragmatic abilities measured in interlocutory logic, which would appear to be preserved. Indeed, the literature frequently reports joint impairments of these functions, notably in autism and schizophrenia, where these impairments can be measured psychometrically (Anagnostou et al., 2015; Green et al., 2015), and whose effects on the interactive system can be verified on dialogic material by interlocutory analysis (Gerardin-Collet, 1999; Verhaegen, 2007).

More generally, stereotypical behaviors that are poorly adapted to the environmental context have been described in the literature (Kerr et al., 2010). These anxiety-provoking interactive idiosyncrasies can thus adversely affect the quality of life of individuals, particularly in the school setting, but especially in integration with neurotypical spheres in general (Perobelli et al., 2015).

3.4.12 Other features

More sporadically, cases of Hirschsprung's disease (Burke et al., 1967), mild intestinal villous atrophy (Mack et al., 1996) and ulcerative colitis (Ginzberg et al., 1999) have been reported. Ocular disorders have also been reported occasionally, including retinitis pigmentosa, coloboma, strabismus and keratitis (Aggett et al., 1979; Ginzberg et al., 1999)

Finally, isolated cases of hypothyroidism (Shimamura, 2006), hypogonadotropic

hypogonadism (Raj et al., 2003), growth hormone deficiency (Kornfeld et al., 1995) and testicular fibrosis (Graham et al., 1980) have been reported.

Chapter 4

Material and methods

4.1 Materials

4.1.1 Subjects

Ten children (Shwachman-Diamond n=5 ; Matched Controls : n=5) from the French population participated in this study. Full measures were available for all subjects.

All participants received detailed information about the study purpose and objectives, and provided online informed consent to participate in the study. All procedures were conducted in accordance with the Declaration of Helsinki and the study protocol was approved by the Comité de Protection des Personnes Sud-Est VI (protocol number: 20.02.24.42827).

4.1.2 Semi-directive anamnesis

A semi-structured interview of approximately 30 minutes has been conducted to collect amnestic data to establish a profile of the study participants. In the case of children, the legal guardians (one parent, the other, or both) and the participant will first be met together, then the participant will be seen alone for his or her psychometric evaluation while hetero-evaluation questionnaires will be given to the legal guardians (one parent, the other, or both) in order to collect behavioural data.

4.1.3 Psychometric scales

4.1.3.1 WISC-V

The assessment of intellectual functioning has been carried out using the Wechsler Intelligence Scale for Children 5th edition (WISC-V, Wechsler).

This scale allows to identify the fundamental processes in the understanding of the general intelligence factor measured through the Total QItotal, calculated from 5 factorial indices:

- VCI (Index of Verbal Comprehension): measuring the area of verbal comprehension, verbal knowledge, application of verbal knowledge to solve problems, and processing of verbal information;
- VSI (Visuospatial Index): measures the ability to encode, analyze and manipulate objects and shapes physically or mentally to make sense of them;
- FRI (Fluid Reasoning Index): measures the domain of non-verbal reasoning, mental operations, the ability to examine logical relationships, and the ability to create and test solutions to problems;
- WMI (Working Memory Index): measures the domain of working memory, auditory processing, sequential processing and numerical skills;
- PSI (Processing Speed Index): measuring the domain of information processing speed, visual processing, scanning, psychomotor execution speed and fine motor-vision coordination.

The raw scores obtained on each WISC-V test has been converted to standardized scores ($\mu = 10$; $\sigma = 3$) based on the child's age group, using the conversion tables in the WISC-V administration manual.

Then, the standard scores has been used to calculate the different indices, using the conversion tables in the WISC-V administration manual, which in turn will be used to calculate the IQ_{total}. The scores obtained were also converted to GPI and GAI using the tables provided in the manual.

4.1.3.2 NEPSY-II

The assessment of children's neuropsychological functioning has been conducted using two subscales of the NEPSY-II (Korkman, M., Kirk, U., & Kemp, S.,

2012). Attention skills has been measured using the "Attention and Executive Function" subscale, which measures auditory attention, categorization, mental flexibility, and inhibition; and social-cognitive skills will be measured using the "Social Perception" subscale, which measures the ability to decode the expression of other people's emotions and to infer other people's mental states.

The raw scores obtained on each NEPSY-II test has been converted to standardized scores ($\mu = 10$; $\sigma = 3$) based on the child's age group, using the conversion tables in the NEPSY-II administration manual.

4.1.4 Pragmatic testing in controlled ecological environment : the TEST-ASAP

As said earlier, speech acts could represents the vector of informational transfer in human interaction, those can take the form of a request for behavioural induction by the emission of utterances that may take a direct form such as "Give me that sheet"; or an indirect form subject to gradation. For example, "Can you close the window?" and "I'm cold, there's a draught." are both invitations to close the window by indirect forms of varying degrees. The strategic use of language acts, as well as receptivity to these utterances, have already been studied as psychomarkers of cognitive psychopathology (Trognon et al., 1992).

We thus constructed a task, the TEST-ASAP (Trognon Ecological Side Task for the Assessment of Speech Act Processing), an experimental paradigm derived from the work of (Gerardin-Collet, 1999), and taking the form of a three-step ecological test allowing to evaluate the functionality of inferential pragmatic skills, by allowing to appreciate the dissociation between the cooperative disorder and the theory of mind disorder; as well as to carry out a reading of the profile of the tasks in economic terms of cost-benefit; as well as in social terms relating to the norms commonly admitted in neurotypicals.

In general, the tasks consist in inducing a cooperative action on the part of the interlocutor through the use of indirect speech acts, thus requiring the understanding of the implicit. Cooperative induction thus starts with the emission of an indirect speech act: in case of failure, a second stimulation is produced using a speech act of comparable indirectivity (thus allowing to control the attentional defect in the utterance); then, in case of a new failure, to produce a stimulation based on an explicit and direct speech act This last step thus allows the dissociation between the theory of mind disorder, where the subject will end up cooperating following induction by a language act produced in the explicit-

direct mode, as described by the work of (Gerardin-Collet, 1999) on autism; and the cooperation disorder, which will manifest itself by a failure of the task (stop rule after 3 stimulations).

We will now describe successively the three tasks that make up the TEST-ASAP, as well as the information that can be obtained by reading these three elements together.

4.1.4.1 The "Door" subtask : Inference of inter-subjective agentivity, low-cost interaction, low benefits

The first "Door" task of the ASAP-TEST proceeds as follows : when the patient is settled, the experimenter goes to distribute materials to the parents who have remained outside. On the way back, the experimenter leaves the door wide open and goes to the desk in the seat furthest from the door. Once seated, he exclaims, "Damn, I forgot to close the door!". The speech act produced and the cooperative act it seeks to induce thus requires two inferences to be made: first, that this request, beyond being a simple observation addressed "to the world", is indeed addressed to the interlocutor present in the room; and second, that this observation is a request for cooperation from the interlocutor. If the inference can be correctly made, and given the low cost of the interaction, in addition to the fact that the total cost of the action is less important for the interlocutor than for the original speaker, we should normally observe a phenomenon of cooperation if we rely on the work of (Grice, 1975).

In the case of a lack of response, a second implicit stimulus is made in the following way a few minutes later: "We really should close that door." At this level of the interaction, the request is clarified in a sense that the request no longer has to be inferred from the assertion of forgetting to close the door. The instructions are clear, but there remains the need to make the inference that the "we" presents in the request is addressed to the interlocutor present in the room, and not "to the world", nor to the initial locutor itself, as formulated previously. It thus allows us to appreciate a phenomenon of inter-subjective agentivity, which is based on the inference that when the initial speaker addresses "the world", he is in fact addressing the only person present in the room: the patient. This capacity for inter-subjective agentivity is strongly impaired in the context of autism spectrum disorders (Gerardin-Collet, 1999).

Finally, in the case of a notable absence of the effect of indirect stimuli, a direct stimulus is formulated: "Could you go and close the door, please?".

Here, the cooperative request is clearly formulated with all the instructions, and no complex inference is needed to realize and only the commitment to the interaction and the propensity to cooperate should come into play as a parameter to explain the behaviors observed at this stage of the task.

4.1.4.2 The "Pencil" subtask : Cooperation under instruction, high-cost interaction, low benefits

The second "Pencil" task of the ASAP-TEST is conducted in the following manner: during the performance of a subtest requiring the use of a pen or pencil (e.g., Drawing Fluency in the NEPSY-II; Barrage in the WISC-V). A pencil, prepared in advance and cut short so that it is functional but not optimal, is given to the patient. Then the first implicit stimulation is performed as follows: "Here, for this exercise, you need a pencil. So I'm going to give you one", then "Gee, it's badly sharpened. Well, I'll give you this sharpener, but it doesn't have a reservoir so you're going to have to go get the garbage can to sharpen the pencil." Here, task completion does not require complex inference about the action to be performed since it is clearly described. On the other hand, the achievement value is relatively low, given that the pencil is already functional as it is, and the added value of sharpening it for the use that is going to be made of it also seems relatively modest. Thus, one understands that the only reason to cooperate comes from the request of the interlocutor, who apparently goes out of his way to ensure that the evaluation takes place in the best possible conditions. We should therefore naturally imagine that the subject should cooperate if we refer to the principle of cooperation as described by (Grice, 1975). In the case of an absence of induction of cooperative action, the experimenter stimulates in the following way: "You should sharpen your pencil, you work better with a well-sharpened pencil". Here, the action is again suggested, the subject is free to cooperate or not. A priori and again, the insistence of the experimenter should induce a cooperative action. If it is still not produced, then, later in the interaction, the experimenter will pretend to have to fill out some paperwork, grab the pencil and say "Can you get me the wastebasket so I can sharpen my pencil?" Thus, the same request is formulated in the direct mode, allowing us to appreciate the cooperation deficit on a gradient when compared to other request as well.

4.1.4.3 The "Syllogism" subtask : Logical inference, low-cost interaction, high benefits at the cost of infringing social norms

Finally, the last task, "Syllogism", is based on the need for simple logical inference (inference of conclusions from simple premises). The task takes place in the framework of this protocol during the lunch break, between the two sessions of psychometric evaluations, and is formulated in the following way: "Well, this is our last test, then we'll be done." Then, "When we're done, you can go straight to your parent to get lunch." (i.e. Inference 1: End of the last test = End of the session; Inference 2: End of the session = Action to go get your parent) . Finally, at the end of the last test, the experimenter says: "That was the last test", and waits for the subject's reaction. Here, although the inference to be made is very simple, and the value to be accessed to the request is very high (end of the first session which was tiring, return to the family, sharing a meal), it still requires breaking a common social rule in asymmetric contexts: one must wait to be invited to leave the interlocution. One could thus expect the subject to present an absence of response or to ask for confirmation. In the case of an absence of response, a reminder is formulated in the following way: "That was the last test, we are finished". This reminder allows to remove a step of the inference, while insisting on the fact that nothing more will happen after the formulation of this sentence. The situation should therefore be identical to the previous one, with two possible options: a request for confirmation, or no answer. In the case of an absence of answer, the last reminder will be produced in the following way: "Since we have finished, can you go and get your parent now? It thus removes the last inference, and formulates an explicit action request that should normally be executed given the expected benefits of cooperation and the total directivity of the speech act. We thus understand that the positive behavior, that of cooperating immediately to the enunciation of the first indirect stimulus, would be a behavior that would reveal both preserved elementary logical inference capacities, but with too much weight of the expected value of producing the act in the decision to act, which can also be appreciated in a gradual way.

4.2 Method : The (A.J.)Trognon Topological and Kinetic model of interaction (2TK)

4.3 Purpose

In despite of the large number of works devoted to dialogue in all its forms in all fields, such as logic (Hamblin, 1976; Krabbe, 1985; Rahman et al., 1997; Walton et al, 2008; Walton Krabbe, 1995); social psychology (Ghiglione & Trognon, 1993; Markova, 1994; Vernant, 2008); linguistics (Caelen, 2003; Caelen & Xuereb, 2017; Labov & Fanshel, 1977, 1977; Roulet, 1987, 1995; Weigand, 2010), and in different schools, such as interactional socio-linguistics (Gumperz, 1982); conversational analysis (Sacks et al, 1974; Schegloff, 1996); and pragmatics (Gazdar, 1980; S. Levinson 1983, 2000, 2006, etc.) and even grammar), among others, there is actually very little work that has been devoted to the study of global properties of dialogue. Indeed, it appears that research has focused on the identification of the architecture or elementary components of the dialogue, but relatively little on the dialogue as a physical system, with global properties as an entity rather than as a simple summation of a set of components. For example, research on exchanges in the schools of discourse analysis has not observed dialogue as a superordinate object, although it has highlighted the properties of the takes and contents of speech turns as local phenomena. On the other hand, dialogical logics, where fundamental properties of dialogue have been described, but without characterizing the microevents.

In the last few years, research in linguistics has allowed the development of new local theories that allow us to characterize interactive processes in greater detail, especially with respect to their topological and kinetic properties. First of all, the concepts developed in the framework of Ludics (Girard 2001), by reconstructing linear logic from the notion of interaction and by relying on the concept of proof, has made it possible to characterize the topology of interactions within the dialogue (Fouqueré et al. 2018a). Since linear logic has the property of being polarizable, it allows to characterize the introduction of a thematic into the dialogue on a positive basis which will illustrate the intervention of the speaker introducing the thematic into the dialogical system, and the response associated with this intervention on a negative basis, thus allowing to connect them by a normalization process (formalized through the cut elimination theorem (Girard 2001)) as well as the construction of a semantic network

corresponding to the thematics elaborated over the successive interventions and rendering the topology of the dialogue. On the other hand, advances in the study of speech acts now allow for a fine-grained study of the kinetics of dialogue, by making it possible to characterize speech acts in their elementary properties (i.e. the type of act (Caelen 2003)) as well as in their transitional roles within the dialogue (i.e. the rhetorical relations (Asher & Lascarides 2003; Caelen & Xuereb 2017; Xuereb & Caelen 2004).

However, although these local theories allow us to analyze the dialogue in all its aspects in a scattered way, there is currently no global theory allowing to account for it in a simultaneous way

In this section, we propose an approach that allows for a global objectification of the communicative process: the 2TK model, a unifying mathematical framework that accounts for the topology and kinetics of interactive processes, based on recent developments in theoretical, pragmatic, and computational linguistics that we presented in the first section, and allowing the simultaneous use of tools derived from these respective models (i.e. Ludics for the topological elements, SDRT for the kinetic elements, and interlocutory logic for the definition of the unit elements to be characterized) ; or measurements of any other nature (electrophysiological measurement, voice recording, etc...) to allows for an account of all the objectifiable linguistic and cognitive processes involved in ordinary interactions, conversations, or interviews of any kind. The model that we will present next will allow a descriptive analysis, a graphical and formal representation of the topology and kinetics of the dialogue, preserving all its informative properties, and allowing to establish formal syntheses as well as to perform algebraic and algorithmic operations and to perform quantitative statistical operations. The data produced by this model would thus be interpretable by human experts of various disciplines, but also by artificial intelligences, which would take the form of predictive computer models of decision-making processes, based on the hypothetical inferences which could intervene in particular in the decision-making processes of evaluation (e.g. a diagnostic interview, a legal verdict, the evaluation of training systems). We will then illustrate this model with two examples taken from the literature: Faria's corpus, taken from The Count of Monte Cristo, which will illustrate the analysis of a classical interaction; Jane's corpus, a young adult with autism-spectrum disorder (Gerardin-Collet, 1999).

4.4 Definition and properties of the 2TK model

4.4.1 The interaction function

The interaction function is the foundational formula of the 2TK model. It reports the state of the dialogical system as a function of dialogical time (i.e. the statement ; the speech act ; or the indexical, depending on the resolution).

$$\Psi(\xi, \epsilon, \sigma_n) \tag{4.1}$$

With :

- ξ as the position of the statement in the dialogue depending on x and y ;
- ϵ as the dialogical time (which is iterative and relative to the structure in which it is measured and which belongs to σ) ;
- σ_n as a set of parameters that describe the system (e.g. its metric, rhetorical relation, speech act, the state of the dialogue etc....) and which depends on x, y, and ϵ.

4.4.1.1 Basic definitions and properties

The following definitions represent values that the sigma parameters can take.

Definition 9 (Dialogue) *The dialogue* Λ *represents the unit of macroscopic analysis and is defined by the set of successive planes occuring in the dialogue.*

$$\Lambda = \sum_{i=1}^{n} \Pi_i \tag{4.2}$$

With :

- Π_i *as the successive dialogical plans occuring in the dialogue.*

Definition 10 (Plans) *The plan of dialogue* Π *is the sum of the concatenations* $\mathfrak{C}$.

$$\Pi = \sum_{i=1}^{m} \mathfrak{C}_i \tag{4.3}$$

$$\tag{4.4}$$

With :

- $\mathfrak{C}_i$ *as the concatenation ;*

Definition 11 (Concatenation) *The concatenation* $\mathfrak{C}$ *is defined by the set of speech acts* κ*.*

$$\mathfrak{C} = \sum_{i=1}^{l} \kappa_i \tag{4.5}$$

Where :

- κ_i *is the speech act;*

Definition 12 (Speech act) *The speech act* κ *is defined by its information, and its type* k*.*

$$\kappa = (q, k) \tag{4.6}$$

Where :

- q *is the information considered for the speech act. It can represent a character string, a quantity of information measured in bits, keywords (which can be keywords present in the sequence as formulated by an interlocutor or keywords from perlocutionary description systems). In order to simplify the construction of models, it is possible to approximate speech act by the reduction of its measure to its type as* $\kappa \approx (k)$*.*

- k *is the type.*

Property 12.1 (Polarity) *The polarity* δ *of a speech act* κ *is defined by its provability within the dialogical structure to which it is compared.*

$$\delta = \begin{cases} 1 \Leftrightarrow \kappa(\epsilon_{n+i}) \vdash \kappa(\epsilon_n) \\ 0 \Leftrightarrow \neg(\kappa(\epsilon_{n+i}) \vdash \kappa(\epsilon_n)) \end{cases} \tag{4.7}$$

Property 12.2 (Decisivity) *The decisivity* d *of a speech act* κ *is assumed by the informational uniqueness of its speech act in the kinetic dynamics of discourse.*

$$d = \begin{cases} 1 \Leftrightarrow \exists! \kappa_n = I_{\kappa_n} \\ 0 \Leftrightarrow \exists I_{\kappa_n} \equiv I_{\kappa_{n+i}} \end{cases} \tag{4.8}$$

Definition 13 (Act type) *The act type k is defined by the grammatical form of the statement.*

$$k = \begin{cases} DO \\ MK \\ DMK \\ DC \\ DM \end{cases} \tag{4.9}$$

With:

Act (2TK)	Act (Caelen, 2003)	Searle equivalent (Searle, 1969)	Meaning (Caelen, 2003)
DO	F^A	Declarative	Do or carry out an action (in verbal or non verbal)
MK	F^S	Assertive or expressive	(make-known) communicate an information
DMK	F^{FS}	Directive	(do make-known) ask for an information
DC	F^P	Promissive with delegation	(do can) give a choice, make an invite
DM	F^D	Directive	(do must) oblige without giving an alternative

Table 4.1: Characterization of speech acts in the 2TK model and relationship with their source models.

Definition 14 (Address) *The address ξ is defined by its topological coordinates x and y.*

$$\xi = (x, y) \tag{4.10}$$

Property 14.1 (Scaffolding address) *Any speech act formulated by one of speakers implies the creation of an address that remains a scaffolding address until it has been exploited.*

$$\kappa_n \implies ?\xi_n \tag{4.11}$$

Property 14.2 (Exploited address) *An address is said to be exploited when a subsequent speech act is attached to it or when the speech act that defines it is the last of its concatenation.*

$$?\xi = \xi \Leftrightarrow (\kappa_{n+1} \vdash \kappa_n) \tag{4.12}$$

Property 14.3 (Derived addressing) *Any speech act κ deriving the dialogue plan Π_n to a contextually relevant derived plan Π'_n in regards to the addresses*

created by either speaker creates a derived address ξ'_{n+1} adjacent to the point of derivation.

$$\kappa \supset \Pi'_n \Leftrightarrow ?\xi'_{(x+1,y+1)} \tag{4.13}$$

Property 14.4 (Incidental addressing) *Any speech act κ corrupting the dialogue plan Π_n to a non relevant incidental plan $\Pi^{\emptyset}_n$ in regards to the addresses created by either speaker creates an incidental address $?\xi^{\emptyset}_n$ on the point of incidence.*

$$\kappa \supset \Pi^{\emptyset}_n \Leftrightarrow \xi^{\emptyset}_{(x+0,y+0)} \tag{4.14}$$

Definition 15 (Rhetorical relation) *The rhetorical relation ρ is defined as the translation vector connecting an element ξ_n to another element ξ_m:*

$$With:\ \rho = \begin{cases} dElab \Leftrightarrow (x+1, y+1)\ \textit{at the position of}\ (x_{max}, y=0) \\ pElab \Leftrightarrow (x+1)\ \textit{at a given position} \\ cElab \Leftrightarrow (x+1)\ \textit{at a given position} \\ QSub \Leftrightarrow (y+1)\ \textit{at a given position} \\ QSubClar \Leftrightarrow (y+1)\ \textit{at a given position} \\ QSubPre \Leftrightarrow (y+1)\ \textit{at a given position} \\ QSubCor \Leftrightarrow (y+1)\ \textit{at a given position} \\ Elab \Leftrightarrow (y+1)\ \textit{at a given position} \\ ElabClar \Leftrightarrow (y+1)\ \textit{at a given position} \\ ElabPre \Leftrightarrow (y+1)\ \textit{at a given position} \\ ElabCor \Leftrightarrow (y+1)\ \textit{at a given position} \\ QAP \Leftrightarrow (y+1)\ \textit{at a given position} \\ IQAP \Leftrightarrow (y+1)\ \textit{at a given position} \\ PQAP \Leftrightarrow (y+1)\ \textit{at a given position} \\ RAP \Leftrightarrow (y+1)\ \textit{at a given position} \\ IRAP \Leftrightarrow (y+1)\ \textit{at a given position} \\ C \Leftrightarrow (y+1)\ \textit{at a given position} \\ D \Leftrightarrow (x+1, y+1)\ \textit{at a given position, moving to derived plane} \\ I \Leftrightarrow (x+0, y+0)\ \textit{at a given position, moving to incidental plane} \end{cases}$$

Definition 16 (State of dialogue) *The state of dialogue is a stable state containing the measures describing the system and that is only transformed by the next speech act.*

$$D_i = D_{i+1} \Leftrightarrow \kappa_{i+1} \tag{4.15}$$

Property 16.1 (State of dialogue transition) *Any speech act κ formulated by one of the speakers implies the transformation of the the state of dialogue D_i to its next state D_{i+1} which will be a function of the type of speech act k, its direction, its polarity δ, and the rhetorical relation ρ associated with the previous*

address ξ_{n-1}.

$$D_i + \kappa_{i+1} \xrightarrow[k_B^A,\ \delta]{\rho} D_{i+1} \tag{4.16}$$

4.4.1.2 State of the dialogical system : overview of some possible values for the internal parameters σ

Definition 17 (The Vergence (V)) *The vergence is a measure of interlocutor convergence to an object represented by the ratio between the number of positively polarized speech acts present in the dialogue or in the section of dialogue and the total number of speech acts. It is defined as follow :*

$$V = \frac{\sum \kappa_{i,\delta(1)}}{\sum \kappa_i} \tag{4.17}$$

Property 17.1 (The maximal convergence) *The maximal convergence of the dialogue or the section of dialogue is achieved if and only if all speech acts present in the dialogue or in the section of dialogue are positively polarized.*

$$V = V(Max) \Longleftrightarrow V = 1 \tag{4.18}$$

Property 17.2 (The convergence) *In a dialogue or a dialogue section, there is convergence between the interacting elements if and only if* $V > 0.5$.

Reciprocal 17.1 (The divergence) *In a dialogue or a dialogue section, there is divergence between the interacting elements if and only if* $V \leq 0.5$.

Definition 18 (The Goal Completion (G)) *Goal Completion is the ratio between the number of goals or sub-goals resolved and the total number of goals or sub-goals emitted during the dialogue or a section of dialogue. It is defined as follow :*

$$G = \frac{\sum \dagger \gamma_i}{\sum ? \gamma_i} \tag{4.19}$$

Definition 19 (The Topological Exploitation (E)) *Topological Exploitation is the ratio between the number of addresses exploited added to the addresses closing a theme and the number of addresses created during the dialogue or dialogue*

section. It is defined as follow :

$$E = \frac{(\sum \xi_i + \sum \dagger\xi_i)}{\sum ?\xi_i} \tag{4.20}$$

Definition 20 (Celerity (C)) *The Celerity of a dialogue or a section of dialogue is the ratio between the number of speech acts needed to solve a goal and the number of speech acts produced to solve the goal. The example used corresponds to a concatenation. It is defined as follow :*

$$C = \frac{\sum \kappa_{i,d_{(1)}}}{\sum \kappa_i} \tag{4.21}$$

4.4.2 Applications

4.4.2.1 In a free cooperative task

4.4.2.1.1 The "Faria" case : classical rules with return to a previous address, formalization and metrics calculation

Locutor	Enunciation	ϵ	x	y	Act type	Polarity	Decisivity	ρ
Faria	What was your life at that time?	1	1	1	DMK	1	1	pElab
Edmond	I was going to become captain of the Pharaoh	2	1	2	MK	1	1	QAP
Edmond	I was going to marry a beautiful girl.	3	2	2	MK	1	1	cElab
Faria	Was there anyone who had a vested interest in you not becoming captain of the Pharaoh?	4	1	3	DMK	1	1	QSub
Edmond	[...] only one man [...]	5	1	4	MK	1	0	iQAP
Faria	What was his name?	6	1	5	DMK	1	0	QSubPre

Continued on next page

Table 4.2 – continued from previous page

Locutor	Enunciation	ϵ	x	y	Act type	Polarity	Decisivity	ρ
Edmond	Danglars	7	1	6	MK	1	1	ElabPre
Faria	So... now tell me about this beautiful young lady...	8	2	3	DMK	1	1	QSubPre

Table 4.2: Sample of dialogue taken from (Fouqueré et al., 2018). The corpus was written by Alexandre Dumas, arranged by (Fouqueré, 2018), and categorized using the 2TK model.

4.4.2.1.1.1 Analysis of the dialogue kinetics :

Faria's corpus begins in the middle of a conversation. So we initialize D_0 from a previously established plan located in ξ_x, aiming to establish the reasons and the person who would like to see Edmond disappear.

So we have : $D_0 \in \Pi_1$

A first speech act is produced by Faria of the "do make-know" type and of positive polarity and decisivity (it advances the dialogue plan while providing new information). It aims to establish the reasons that would suggest that Edmond's life is in danger. It is therefore a plan elaboration (pElab). This speech act opens a new concatenation within the plan that explores the previous parameters of Edmond's life. It is associated with a goal of the same nature. All these acts and goals are encoded in Edmond's memory (working memory concerning the exchange, episodic memory concerning the spatio-temporal characteristics of the exchange).

This speech act was created from an address $\in \xi_x$ located in pre-corpus events and which created a new address $?\xi_{x=1,y=1}$ by exploiting the common ground. The dialogical state D_0 is thus transformed by the speech act κ_1 to the dialogical state D_1. We can thus note:

$$D_0 + \kappa_{1,\xi_x} \xrightarrow[DMK_E^F,\ \delta(1)\mathrm{d}(1)]{\text{pElab}} D_1$$

$$\Longrightarrow \mathrm{D}_1 \equiv DMK_E^F \supset \begin{cases} ?\mathfrak{C}_1 \\ ?\gamma_1,\mathfrak{C}_1 \end{cases}$$
$$\wedge \xi_x \supset \left\{ ?\xi_{1(x=1,y=1)} \right.$$

Then, Edmond replies to Faria on the concatenation that she initiated from her speech act κ_1. He produces two successive adapted answer to the question by emitting two MK-type speech acts, positively polarized and decisive. Firstly, it produces an answer adapted to the question (QAP). It can be said there that the statement located at $\xi_{1(x=1,y=1)}$ produced an address $?\xi_{1.1(x=1,y=2)}$ by its exploitation. We can therefore note:

$$D_1 + \kappa_{2,\xi_1} \xrightarrow[MK_F^E,\ \delta(1)\mathrm{d}(1)]{\text{QAP}} D_2$$

$$\Longrightarrow \mathrm{D}_2 \equiv MK_F^E \left\{ \uparrow \gamma_1,\mathfrak{C}_1 \right.$$
$$\wedge\ \xi_1 \supset \left\{ ?\xi_{1.1(x=1,y=2)} \right.$$

Then, Edmond completes his intervention by elaborating the concatenation with a new sub-theme (cElab), provable both by the previous intervention as well as by the theme that motivated it. We can also say that Edmond advanced the common goal. However, it cannot be said that his previous intervention was exploited, as this was not the direct motivation for this specific speech act. We can therefore note:

$$D_2 + \kappa_{3,\xi_{1.1}} \xrightarrow[MK_F^E,\ \delta(1)\mathrm{d}(1)]{\text{cElab}} D_3$$

$$\Longrightarrow \mathrm{D}_3 \equiv MK_F^E \Big\{ \uparrow \gamma_1, \mathfrak{C}_1$$
$$\wedge\ \xi_1 \supset \Big\{ ?\xi_{1.2(x=2,y=2)}$$

Then, Faria bounces back on one of Edmond's two under-statements, asking him if anyone had any interest in not seeing him invested as captain of the Pharaoh, so producing a DMK-type, positively polarized speech act that can be characterized as a Subordinate Question (QSub). Here Goal 1 is elaborated by creating a sub-Goal 1.1 to find out if the threats to Edmond came from his promotion as captain. Edmon encoded in memory the statement and the associated implications.

Thus, we can say that the exploitation of the Edmond's statement in $\xi_{1.1(x=1,y=2)}$ allowed the creation of the address $?\xi_{1.1.1(x=1,y=3)}$ corresponding to the "Pharaoh" theme.

$$D_3 + \kappa_{4,\xi_{1.2}} \xrightarrow[DMK_E^F,\ \delta(1)\mathrm{d}(1)]{\text{QSub}} D_4$$

$$\Longrightarrow \mathrm{D}_4 \equiv DMK_E^F \begin{cases} \uparrow \gamma_1, \mathfrak{C}_1 \\ ?\gamma_{1.1}, \mathfrak{C}_1 \end{cases}$$
$$\wedge\ \xi_{1.1(x=1,y=2)} \supset \Big\{ ?\xi_{1.1.1(x=1,y=3)}$$

Then Edmond produces an incomplete adapted response to the question (iQAP - as the identity of the man remains unknown) by producing an MK-type, positively polarized speech act, but cannot be characterized as decisive ($d = 0$). Indeed, Faria's intervention "Is there anyone (...)" already contains the request for identification of a single individual; Edmond's response "(...) only one man (...)" seems informatively redundant: if a single person was indeed identifiable by Edmond at this state of dialogue, then he could have given the information directly. However, the sub-goal 1.1 still progresses by the Edmond's mention to a man (whose identity is still unknown) who might not have wanted him to become captain of the Pharaoh.

We can therefore say that Faria's statement in $?\xi_{1.1.1(x=1,y=3)}$ allowed the creation of a $?\xi_{1.1.1.1(x=1,y=4)}$ by its exploitation. We note :

$$D_4 + \kappa_{5,\xi_{1.1.1}} \xrightarrow[MK_F^E,\ \delta(1)\mathrm{d}(0)]{\text{iQAP}} D_5$$

$$\begin{aligned}\Longrightarrow \mathrm{D}_5 \equiv MK_F^E\Big\{&\uparrow \gamma_{1.1},\mathfrak{c}_1 \\ &\wedge\ \xi_{1.1.1(x=1,y=3)} \supset \Big\{?\xi_{1.1.1.1(x=1,y=4)}\end{aligned}$$

Then, Faria again produces a question heading to precise Edmond's statement (QSubPre) by producing a DMK, positively polarized speech act, asking Edmond to elaborate on his statement, advancing goal 1.1. However, the speech act cannot be considered decisive: indeed, if Edmund had not produced his non-decisive speech act earlier, the present would also not have taken place. We can therefore say that the exploitation of Edmond statement $?\xi_{1.1.1.1(x=1,y=4)}$ allowed the creation of a scaffolding $?\xi_{1.1.1.1.1(x=1,y=5)}$ address. So we note:

$$D_5 + \kappa_{6,\xi_{1.1.1.1.1}} \xrightarrow[\mathrm{D}MK_E^F,\ \delta(1)\mathrm{d}(0)]{\text{QSubPre}} D_6$$

$$\begin{aligned}\Longrightarrow \mathrm{D}_6 \equiv DMK_E^F\Big\{&\uparrow \gamma_{1.1},\mathfrak{c}_1 \\ &\wedge\ \xi_{1.1.1.1(x=1,y=4)} \supset \Big\{?\xi_{1.1.1.1.1(x=1,y=5)}\end{aligned}$$

Then Edmond produces a relative answer to the question which elaborates his previous statement, in relation to the question that motivated it (ElabPre), through the production of a positively polarized and decisive MK speech act (as the information is unique within the dialogue). This speech act advances goal 1 by closing subgoal 1.1 (a threatening individual having been identified).

It can therefore be said that Faria's statement in $?\xi_{1.1.1.1.1(x=1,y=5)}$ allowed the creation of an address $?\xi_{1.1.1.1.1.1(x=1,y=6)}$ by its exploitation. So we note:

$$D_6 + \kappa_{7,\xi_{1.1.1.1.1.1}} \xrightarrow[MK_F^E,\ \delta(1)\mathrm{d}(1)]{\text{ElabPre}} D_7$$

$$\Longrightarrow \mathrm{D}_7 \equiv MK_F^E \begin{cases} \dagger\ \gamma_{1.1},\mathfrak{C}_1 \\ \uparrow \gamma_1,\mathfrak{C}_1 \end{cases}$$
$$\wedge\ \xi_{1.1.1.1.1.1(x=1,y=5)} \supset \left\{ ?\xi_{1.1.1.1.1.1.1(x=1,y=6)} \right.$$

Finally, Faria produces a subordonate question about the common ground, producing a DMK-like (could be rated as DMK or MK as well), positively polarized and decisive speech act that emits subgoal 1.2 (exploring the parameters of Edmond's marriage ; QSubPre).

Here, the Faria statement in $?\xi_{1.2.1}$ is exploiting the $\xi_{1.2}$ address created by Edmond in ϵ_3, thus ratifying the closure of the previous concatenation $\mathfrak{C}_1$ in $\xi_{1.1.1.1.1.1}$, and thus ratifying the creation of a new concatenation $\mathfrak{C}_2$ at $\xi_{1.2}$.

$$D_7 + \kappa_{8,\xi_{1.1.1.1.1.1.1}} \xrightarrow[MK_E^F,\ \delta(1)\mathrm{d}(1)]{\text{QSubPre}} D_8$$

$$\Longrightarrow \mathrm{D}_8 \equiv DMK_E^F \begin{cases} C_E\epsilon_8 \\ \uparrow \gamma_1,\mathfrak{C}_1 \\ ?\gamma_{1.2},\mathfrak{C}_2 \end{cases}$$
$$\wedge\ \xi_{1.1.1.1.1.1.1(x=1,y=6)} \supset \begin{cases} \xi_{1.2(x=2,y=2)} \\ ?\xi_{1.2.1(x=2,y=3)} \\ \dagger\xi_{1.1.1.1.1.1.1(x=1,y=6)} \Longleftrightarrow \dagger\mathfrak{C}_1 \end{cases}$$

4.4.2.1.1.2 Metrics calculation for the whole dialogue

Calculating the Vergence (V)

We know that : $V = \dfrac{\sum \kappa_{i,\delta(1)}}{\sum \kappa_i}$

Here, we have :
- $\sum \kappa_{i,\delta(1)} = \kappa_1 + \kappa_2 + \kappa_3 + \kappa_4 + \kappa_5 + \kappa_6 + \kappa_7 + \kappa_8 = 8$

$-\sum \kappa_i = \kappa_1 + \kappa_2 + \kappa_3 + \kappa_4 + \kappa_5 + \kappa_6 + \kappa_7 + \kappa_8 = 8$

So : V= $\dfrac{\sum \kappa_{i,\delta+}}{\sum \kappa_i} = \dfrac{8}{8} = 1 \implies V_\lambda = V_\lambda(Max)$

We can then conclude that both locutors are convergent as V=V(Max).

Calculating the Goal Completion (G)

We know that : $G = \dfrac{\sum \dagger\gamma_i}{\sum ?\gamma_i}$

Here, we have
- $\sum \dagger\gamma_i = \dagger\gamma_{1.1,\mathfrak{e}_1} = 1$
- $\sum \gamma_i = \gamma_{1.1,\mathfrak{e}_1} + \gamma_{1.2,\mathfrak{e}_2} = 2$

So : $G = \dfrac{1}{2} = 0,5$

In this corpus sample, only half of the total goals were completed. We can therefore conclude that there is a partial resolution of the dialogical goals pursued in this dialogue.

Calculating the Topological Exploitation (E)

We know that : $E = \dfrac{(\sum \xi_i + \sum \dagger\xi_i)}{\sum ?\xi_i}$

Here, we have
- $\sum \xi_i + \sum \dagger\xi_i = \xi_1 + \xi_{1.1} + \xi_{1.2} + \xi_{1.1.1} + \xi_{1.1.1.1} + \xi_{1.1.1.1.1} + \dagger\xi_{1.1.1.1.1.1} = 7$
- $\sum ?\xi_i = ?\xi_1 + ?\xi_{1.1} + ?\xi_{1.2} + ?\xi_{1.1.1} + ?\xi_{1.1.1.1} + ?\xi_{1.1.1.1.1} + ?\xi_{1.1.1.1.1.1} + ?\xi_{1.2.1} = 8$

So : $E = \dfrac{7}{8} = 0.875$

We can therefore conclude that in this corpus sample, the addresses are partially exploited, as there are as more addresses created as there are addresses exploited.

Calculating the Celerity (C)

We know that : $C = \frac{\sum \kappa_{i,d_{(1)}}}{\sum \kappa_i}$

Here, we have :
- $\sum \kappa_{i,d_{(1)}} = 8 - 2 = 6$
- $\sum \kappa_i = 8$

So : $C = \frac{6}{8} = 0.75$

We can therefore conclude that in this corpus sample, the celerity is partial, as the dialogue could have progressed more quickly. In fact, given that in response to Faria's question about the identification of the threatening man, Edmond replies "only one man", then the man was already identified by Edmond and he could have given his identity directly. Since the information "only one man" is encompassed in the formulation of a single name, then the previous sequence becomes unnecessary, and so does the subsequent request for reformulation by Faria.

4.4.2.1.1.3 Dialogue summary

$\Lambda = \Pi_1$

$\Pi_1 \vDash (\mathfrak{C}_1 \xi_{1.1} \equiv \dagger \gamma_{1.1,\mathfrak{C}_1}) + (\mathfrak{C}_2 \xi_{1.2} \equiv \gamma_{1.2,\mathfrak{C}_2})$

$$\mathrm{C}_1\xi_{1.1} := \begin{cases} \kappa_1(\xi_1, \epsilon_1, \delta(1)d(1), DMK) \\ \kappa_2(\xi_{1.1}, \epsilon_2, \delta(1)d(1), MK) \\ \kappa_4(\xi_{1.1.1}, \epsilon_4, \delta(1)d(1), DMK) \\ \kappa_7(\dagger\xi_{1.1.1.1.1.1}, \epsilon_7, \delta(1)d(1), MK) \\ \% \begin{cases} \kappa_5(\xi_{1.1.1.1}, \epsilon_5, \delta(1)d(0), MK) \\ \kappa_6(\xi_{1.1.1.1.1}, \epsilon_6, \delta(1)d(0), DMK) \end{cases} \end{cases}$$

$$\rho^{F->E}_{\mathfrak{C}_1\xi_{1.1}} \equiv \begin{bmatrix} 1pElab & 0pElab \\ 1QSub & 0QSub \\ 0QAP & 1QAP \\ 0iQAP & 1iQAP \\ 1QSubPre & 0QSubPre \\ 0ElabPre & 1ElabPre \end{bmatrix}$$

$$\mathrm{C}_2\xi_{1.2} := \begin{cases} \kappa_1(\xi_1, \epsilon_1, \delta+, DMK) \\ \kappa_3(\xi_{1.2}, \epsilon_3, \delta+, MK) \\ \kappa_8(\xi_{1.2.1}, \epsilon_8, \delta+, (D)MK) \end{cases}$$

$$\rho^{F->E}_{\mathfrak{C}_2\xi_{1.2}} \equiv \begin{bmatrix} 1pElab & 0pElab \\ 0cElab & 1cElab \\ 1QSubPre & 0QSubPre \\ 0QAP & 1QAP \end{bmatrix}$$

4.4.2.1.1.4 Metrics-based analysis

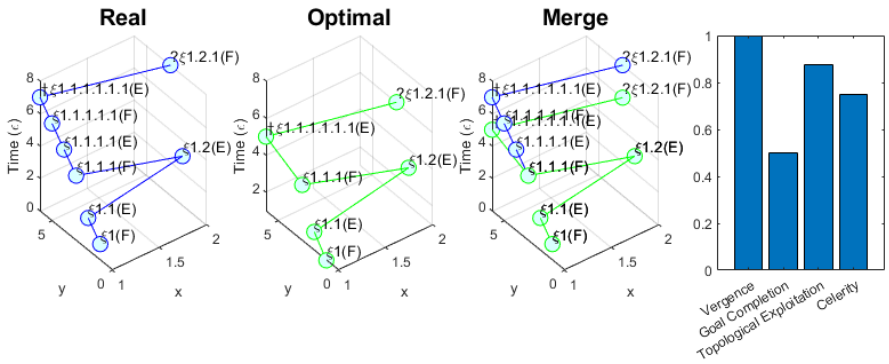

Figure 4.1: Topology (left) and metrics (right) concerning the Faria-Edmond dialogue. The "Real" plot represents the topology of the dialogue as it took place and the "Optimal" plot represents the topology of the dialogue without the inserted sequences.

We have reproduced with the model the main properties of the Faria-Edmond

dialogue, which consists of a plan made up of concatenations (Fig. 1.5, Left) made up of 6 and 3 speech acts respectively.

At the level of the whole dialogue, the convergence between the interlocutors is maximal (V=1, Right), as all speech acts produced by the two interlocutors are of positive polarity and advance the goals pursued in the sequence. However, in this section, the goals are only partially completed (G=.5; Right) and the addresses are only partially exploited (E=.875; Right). This metric, however, represents only an artefact related to the cutting of the corpus, which stops just after the opening of a new goal and a potentially exploitable address (with the addition of additional sequences from the original work, these last two metrics would have a calculated value of 1). Finally, and given the presence of two sequences inserted within this dialogue (corresponding to the slowdown observed for the identification of the man who might have wished Edmond not to become captain of the Pharaoh), the celerity is not maximal (C=.75; Right), thus highlighting that the dialogue could have progressed more rapidly (Fig. 1.5 ; Left).

However, the metric profile of the two concatenations present in this section is heterogeneous. For the first concatenation, all the goals are completed (G=1) and the plan is fully exploited (E=1), but the celerity remains low (C=.6). Concerning the second concatenation, the celerity is high (C=1; given the absence of inserted non-decisive sequence), but the resolution of the goals is null (G=0) and the plan is only partially exploited (E=.5)

Concerning the speech acts produced within the dialogue as a whole, we can observe a bimodal profile according to the interlocutor: Faria produced 4 speech acts of the "do make-know" (DMK) type and Edmond 4 speech acts of the "make-know" (MK) type, which allows us to conclude that Faria held the role of "investigator" within the dialogue, unlike Edmond who held the role of "investigated". This data is consistent with the measured rhetorical relations, where Faria produced mostly subordinate questions, while Edmund produced mostly responded to them.

4.4.2.1.2 The "Jane" case : measuring the effectiveness of a cooperative task in Autism Spectrum Disorder, formalization and metrics calculation

Locutor	Enunciation	ϵ	x	y	Act type	Polarity	Decisivity	ρ
Jane	Eh ! The radio !	1	1	1	MK	1	1	pElab
Psychologist	What did you say, Jeanne?	2	1	2	DMK	1	0	QSubClar
Jane	The radio... side again...	3	1	3	MK	1	0	ElabClar
Psychologist	What ?	4	1	4	DMK	1	0	QSubClar
Jane	Side.	5	1	5	MK	1	0	QAP
Psychologist	The side ?	6	1	6	DMK	1	0	QSubClar
Jane	The side.	7	1	7	MK	1	0	QAP
Psychologist	The side.	8	1	8	MK	1	0	C
Jane	The music.	9	1	9	MK	1	0	Elab
Psychologist	What do you want, Jane ?	10	1	10	DMK	1	1	QSubClar
Jane	The music.	11	1	11	MK	1	0	QAP
Psychologist	The music ?	12	1	12	DMK	1	0	QSubClar
Jane	(Jane points to the radio while moving towards)	13	1	13	DO	1	1	QAP
Jane	(Jane points at the tapes)	14	1	14	DO	1	1	Elab

Continued on next page

Table 4.3 – continued from previous page

Locutor	Enunciation	ϵ	x	y	Act type	Polarity	Decisivity	ρ
Jane	(Jane points at the tapes)	15	1	15	DO	1	1	RAP
Jane	(Jane points at the tapes)	16	1	16	DO	1	0	C

Table 4.3: Sample of dialogue taken from (Gerardin-Collet, 1999, dir. Alain Trognon)

4.4.2.1.2.1 Analysis of the dialogue kinectics

Jane's corpus begins in the middle of a conversation. So we initialize D_0 from a previously established plan located in ξ_x, where both interlocutors are listening to the radio.

So we have : $D_0 \in \Pi_1$

Then, a first speech act is produced by Jane of the "make-know" type and of positive polarity (it elaborates the dialogue plan) and decisive. All we know at this moment is that there is a concatenation congruent with the previously established plan with associated goals that we don't know yet. The psychologist encodes it in memory.

This speech act was created from an address $\in \xi_x$ located in pre-corpus events and which created a new scaffolding address $?\xi_{1(x=1,y=1)}$ by the exploitation of the common ground. The dialogical state D_0 is thus transformed by the speech act κ_1 to the state of dialogue D_1. It is arbitrarily considered as decisive since it is the first speech act considered. We can thus note:

$$D_0 + \kappa_{1,\xi_x} \xrightarrow[MK_P^J,\ \delta(1)\mathrm{d}(1)]{\text{pElab}} D_1$$

$$\Longrightarrow \mathrm{D}_1 \equiv MK_P^J \supset \begin{cases} ?\mathfrak{C}_1 \\ ?\gamma_{1,\mathfrak{C}_1} \end{cases}$$
$$\wedge\ \xi_x \supset \left\{ ?\xi_{1(x=1,y=1)} \right.$$

Then, the psychologist answers to Jane about the concatenation she initiated and thus produces an adapted answer to the question, but heading to clarify Jane's statement (QSubClar) using a DMK-type speech act, but that is not decisive. Thus, the psychologist open a new sub-goal corresponding to the identification of the meaning of Jane's statement. Jane's encodes it in memory.

We can thus note :

$$D_1 + \kappa_{2,\xi_{1.1}} \xrightarrow[DMK_J^P,\ \delta(1)\mathrm{d}(0)]{\text{QSubClar}} D_2$$

$$\Longrightarrow \mathrm{D}_2 \equiv DMK_J^P \supset \begin{cases} \uparrow\gamma_{1,\mathfrak{C}_1} \\ ?\gamma_{1.1,\mathfrak{C}_1} \end{cases}$$
$$\wedge\ \xi_{1(x=1,y=1)} \supset \left\{ ?\xi_{1.1(x=1,y=2)} \right.$$

Then, Jane answers to the psychologist attempting to clarify her previous statement by precising it (ElabClar). She then produces an adapted speech act which is positively polarized. The psychologist encodes this information in memory.

We can thus note :

$$D_2 + \kappa_{3,\xi_{1.1.1}} \xrightarrow[MK_P^J,\ \delta(1)\mathrm{d}(0)]{\text{ElabClar}} D_3$$

$$\Longrightarrow \mathrm{D}_3 \equiv MK_P^J \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1.1(x=1,y=2)} \supset \Big\{ ?\xi_{1.1.1(x=1,y=3)}$$

Then, the psychologist answers to asking Jane to clarify even more her statement (QSubClar) using a DMK-type speech act, positively polarized. Thus, the psychologist advances his own sub-goal corresponding to the identification of the meaning of Jane's statement. Jane's encodes it in memory.

We can thus note :

$$D_3 + \kappa_{4,\xi_{1.1.1.1}} \xrightarrow[DMK_J^P,\ \delta(1)\mathrm{d}(0)]{\text{QSubClar}} D_4$$

$$\Longrightarrow \mathrm{D}_4 \equiv DMK_J^P \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1.1.1(x=1,y=3)} \supset \Big\{ ?\xi_{1.1.1.1(x=1,y=4)}$$

Then, Jane answers to the psychologist attempting to reformulate her previous statement by emphasizing the section of its statement containing the information that would resolve the meaning of that statement (QAP). She then produces an adapted speech act which is positively polarized. The psychologist encodes this information in memory.

We can thus note :

$$D_4 + \kappa_5, \xi_{1.1.1.1.1.1} \xrightarrow[MK_P^J,\ \delta(1)\mathrm{d}(0)]{\text{QAP}} D_5$$

$$\Longrightarrow \mathrm{D}_5 \equiv MK_P^J \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1.1.1.1(x=1,y=4)} \supset \Big\{ ?\xi_{1.1.1.1.1(x=1,y=5)}$$

Then, the psychologist answers again to asking Jane to clarify more her statement (QSubClar) using a DMK-type speech act, positively polarized. Thus, the psychologist advances his own sub-goal corresponding to the identification of the meaning of Jane's statement.

We can thus note :

$$D_5 + \kappa_6, \xi_{1^6} \xrightarrow[DMK_J^P,\ \delta(1)\mathrm{d}(0)]{\text{QSubClar}} D_6$$

$$\Longrightarrow \mathrm{D}_6 \equiv DMK_J^P \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1.1.1.1.1(x=1,y=5)} \supset \Big\{ ?\xi_{1^6(x=1,y=6)}$$

Then, Jane answers to the psychologist by confirming the psychologist' previous statement by repeating the the information that would resolve the meaning of that statement (C). She then produces an adapted speech act which is positively polarized, but still not decisive. The psychologist encodes this information in memory.

We can thus note :

$$D_6 + \kappa_7, \xi_{1^7} \xrightarrow[MK_P^J,\ \delta(1)\mathrm{d}(0)]{\text{QAP}} D_7$$

$$\Longrightarrow \mathrm{D}_7 \equiv MK_P^J \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^6(x=1,y=6)} \supset \Big\{ ?\xi_{1^7(x=1,y=7)}$$

Then, the psychologist answers to Jane asking to confirm it understanding of Jane's statement meaning using a MK-type speech act, positively polarized by repeating the information given by Jane (C). Thus, the psychologist advances his own sub-goal corresponding to the identification of the meaning of Jane's statement. Jane's encodes it in memory.

We can thus note :

$$D_7 + \kappa_8, \xi_{1^8} \xrightarrow[DMK_J^P,\ \delta(1)\mathrm{d}(0)]{\text{C}} D_8$$

$$\Longrightarrow \mathrm{D}_8 \equiv DMK_J^P \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^7(x=1,y=7)} \supset \Big\{ ?\xi_{1^8(x=1,y=8)}$$

Then, Jane answers to the psychologist by elaborating her previous statement to resolve the current goal (Elab). She then produces an adapted speech act which is positively polarized. The psychologist encodes this information in memory.

We can thus note :

$$D_8 + \kappa_{9,\xi_{1^9}} \xrightarrow[MK_P^J,\ \delta(1)\mathrm{d}(0)]{\text{Elab}} D_9$$

$$\Longrightarrow \mathrm{D}_9 \equiv MK_P^J \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^8(x=1,y=8)} \supset \Big\{ ?\xi_{1^9(x=1,y=9)}$$

Then, the psychologist answers again to asking Jane to clarify more her statement (QSubClar) using a DMK-type speech act, positively polarized. Thus, the psychologist advances his own sub-goal corresponding to the identification of the meaning of Jane's statement. However, we will consider this speech act as decisive, since it asks for additional information than what was initially asked (i.e. the result of Jane's action request).

We can thus note :

$$D_9 + \kappa_{10,\xi_{1^{10}}} \xrightarrow[DMK_J^P,\ \delta(1)\mathrm{d}(1)]{\text{QSubClar}} D_{10}$$

$$\Longrightarrow \mathrm{D}_{10} \equiv DMK_J^P \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^9(x=1,y=9)} \supset \Big\{ ?\xi_{1^{10}(x=1,y=10)}$$

Then, Jane answers to the psychologist by emphasizing the section of its statement containing the information that would resolve the meaning of that statement (QAP). She then produces an adapted speech act which is positively polarized (it advances the sub-goal of the psychologist and thus the dialogue plan). This intervention is not considered decisive since it is a repetition of the intervention that took place with the psychologist's production.

We can thus note :

$$D_{10} + \kappa_{11}, \xi_{1^{11}} \xrightarrow[MK_P^J,\ \delta(1)\mathrm{d}(0)]{\text{QAP}} D_{11}$$

$$\Longrightarrow \mathrm{D}_{11} \equiv MK_P^J \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^{10}(x=1,y=10)} \supset \Big\{ ?\xi_{1^{11}(x=1,y=11)}$$

Then, the psychologist answers to Jane asking to confirm it understanding of Jane's statement meaning using a DMK-type speech act, positively polarized by repeating the information given by Jane (QSubClar). Thus, the psychologist advances his own sub-goal corresponding to the identification of the meaning of Jane's statement.

We can thus note :

$$D_{11} + \kappa_{12}, \xi_{1^{12}} \xrightarrow[DMK_J^P,\ \delta(1)\mathrm{d}(0)]{\text{QSubClar}} D_{12}$$

$$\Longrightarrow \mathrm{D}_{12} \equiv DMK_J^P \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^{11}(x=1,y=11)} \supset \Big\{ ?\xi_{1^{12}(x=1,y=12)}$$

Then, Jane answers to the psychologist by doing a pointing action aimed at clarifying his or her point visually rather than linguistically. It is thus rated as a QAP, and not as a RAP, since the psychologist's initial request was not formally a request for action. She thus produces an adapted speech act of DO-type which is positively polarized. The psychologist encodes this information in

memory. The speech act is still not decisive since it is a gestural repetition of the information given at $\epsilon = 1$

We can thus note :

$$D_{12} + \kappa_{13}, \xi_{1^{13}} \xrightarrow[DO_P^J,\ \delta(1)\mathrm{d}(0)]{\text{QAP}} D_{13}$$

$$\Longrightarrow \mathrm{D}_{13} \equiv MK_P^J \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^{12}(x=1,y=12)} \supset \Big\{ ?\xi_{1^{13}(x=1,y=13)}$$

Then, Jane elaborates her current statement (i.e. her previous speech act in the same statement) doing a pointing action aimed to resolve the meaning of her initial statement (Elab). She thus produces an adapted speech act of DO-type which is positively polarized (it advances the sub-goal of the psychologist and thus the dialogue plan). This intervention is considered decisive since it directly clarifies the request, and also gives meaning to some of its other interventions (e.g. $\epsilon = 3$ that could rightly be considered decisive, even if this is not the choice we made for the example.

We can thus note :

$$D_{13} + \kappa_{14}, \xi_{1^{14}} \xrightarrow[DO_P^J,\ \delta(1)\mathrm{d}(1)]{\text{Elab}} D_{14}$$

$$\Longrightarrow \mathrm{D}_{14} \equiv MK_P^J \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^{13}(x=1,y=13)} \supset \Big\{ ?\xi_{1^{14}(x=1,y=14)}$$

Then, the psychologist answers to Jane by producing an action (she helps Jane return the tape) that she thinks is relative to the meaning of Jane's initial statement (RAP). The psychologist thus produces a decisive DO-type speech act, positively polarized. Thus, the psychologist advances his own sub-goal corresponding to the identification of the meaning of Jane's statement.

We can thus note :

$$D_{14} + \kappa_{15}, \xi_{1^{15}} \xrightarrow[DO_J^P,\ \delta(1)\mathrm{d}(1)]{\text{RAP}} D_{15}$$

$$\Longrightarrow \mathrm{D}_{15} \equiv DMK_J^P \supset \Big\{ \uparrow \gamma_{1.1,\mathfrak{C}_1}$$

$$\wedge\ \xi_{1^{14}(x=1,y=14)} \supset \Big\{ ?\xi_{1^{15}(x=1,y=15)}$$

Jane closes the exchange by going back to sit down and dancing again in her chair (C). She thus produces a positively polarized, DO-type speech act. In this way, this statement resolves the psychologist's sub-goal (which is now fixed on the meaning of the initial statement of the exchange), thus making this sequence decisive.

We can thus note :

$$D_{15} + \kappa_{16}, \xi_{1^{16}} \xrightarrow[DO_P^J,\ \delta(1)\mathrm{d}(1)]{\text{C}} D_{16}$$

$$\Longrightarrow \mathrm{D}_{16} \equiv MK_P^J \supset \begin{cases} \dagger \gamma_{1.1,\mathfrak{C}_1} \\ \dagger \gamma_{1,\mathfrak{C}_1} \end{cases}$$

$$\wedge\ \xi_{1^{15}(x=1,y=15)} \supset \begin{cases} ?\xi_{1^{16}(x=1,y=16)} \\ \dagger \xi_{1^{16}(x=1,y=16)} \end{cases}$$

4.4.2.1.2.2 Metrics calculation for the whole dialogue

Calculating the Vergence (V)

We know that : $V = \frac{\sum \kappa_{i,\delta(1)}}{\sum \kappa_i}$

Here, we have :
- $\sum \kappa_{i,\delta(1)} = 16$
$- \sum \kappa_i = 16$

So : V= $\frac{\sum \kappa_{i,\delta(1)}}{\sum \kappa_i} = \frac{16}{16} = 1 \implies V = V(Max)$

We can then conclude that both interlocutors are convergent toward the resolution of the goals.

Calculating the Goal Completion (G)

We know that : $G = \frac{\sum \dagger\gamma_i}{\sum ?\gamma_i}$

Here, we have
- $\sum \dagger\gamma_i = \dagger\gamma_{1,\mathfrak{C}_1} + \dagger\gamma_{1.1,\mathfrak{C}_1} = 2$
- $\sum \gamma_i = \gamma_{1,\mathfrak{C}_1} + \gamma_{1.1,\mathfrak{C}_1} = 2$

So : $G = \frac{2}{2} = 1$

In this corpus sample, all of the goals pursued by the speakers were completed. We can therefore conclude that there is a total resolution of the dialogical goals pursued in this dialogue.

Calculating the Topological Exploitation (E)

We know that : $E = \frac{(\sum \xi_i + \sum \dagger \xi_i)}{\sum ? \xi_i}$

Here, we have
- $\sum \xi_i + \sum \dagger \xi_i = 15 + 1 = 16$
- $\sum ? \xi_i = 16$

So : $E = \frac{16}{16} = 1$

We can therefore conclude that in this corpus sample, the addresses are fully exploited, as there are as more addresses created as there are addresses exploited.

Calculating the Celerity (C)

We know that : $C = \frac{\sum \kappa_{i,d_{(1)}}}{\sum \kappa_i}$

Here, we have :
- $\sum \kappa_{i,d_{(1)}} = 5$
- $\sum \kappa_i = 16$

So : $C = \frac{5}{16} = 0.3125$

We can therefore conclude that in this corpus sample, the celerity is partial, as the dialogue could have progressed more quickly, if Jane had pointed directly at the tape at the time of her interlocutor's request for clarification.

4.4.2.1.2.3 Dialogue summary

$\Lambda = \Pi_1$

$\Pi_1 \vDash (\mathfrak{C}_1 \xi_1 \equiv \dagger \gamma_{1,\mathfrak{e}_1} + \gamma_{1.1,\mathfrak{e}_1})$

$$
\mathrm{C}_1\xi_1 := \begin{cases}
\kappa_1(\xi_1, \epsilon_1, \delta(1)d(1), MK) \\
\kappa_{11}(\xi_{1^{13}}, \epsilon_{13}, \delta(1)d(1), DO) \\
\kappa_{14}(\xi_{1^{14}}, \epsilon_{14}, \delta(1)d(1), DO) \\
\kappa_{15}(\xi_{1^{15}}, \epsilon_{15}, \delta(1)d(1), DO) \\
\kappa_{16}(\dagger\xi_{1^{16}}, \epsilon_{16}, \delta(1)d(1), DO) \\
\% \begin{cases}
\kappa_2(\xi_{1^2}, \epsilon_2, \delta(1)d(0), DMK) \\
\kappa_3(\xi_{1^3}, \epsilon_3, \delta(1)d(0), MK) \\
\kappa_4(\xi_{1^4}, \epsilon_4, \delta(1)d(0), DMK) \\
\kappa_5(\xi_{1^5}, \epsilon_5, \delta(1)d(0), MK) \\
\kappa_6(\xi_{1^6}, \epsilon_6, \delta(1)d(0), DMK) \\
\kappa_7(\xi_{1^7}, \epsilon_7, \delta(1)d(0), MK) \\
\kappa_8(\xi_{1^8}, \epsilon_8, \delta(1)d(0), MK) \\
\kappa_9(\xi_{1^9}, \epsilon_9, \delta(1)d(0), MK) \\
\kappa_{10}(\xi_{1^{10}}, \epsilon_{10}, \delta(1)d(0), DMK) \\
\kappa_{12}(\xi_{1^{11}}, \epsilon_{11}, \delta(1)d(0), MK) \\
\kappa_{13}(\xi_{1^{12}}, \epsilon_{12}, \delta(1)d(0), DMK)
\end{cases}
\end{cases}
$$

$$
\rho^{J->P}_{\mathfrak{C}_1\xi_1} \equiv \begin{bmatrix}
1pElab & 0pElab \\
4QAP & 0QAP \\
0RAP & 1RAP \\
2Elab & 0Elab \\
0QSubClar & 5QSubClar \\
1ElabClar & 0ElabClar \\
1C & 1C
\end{bmatrix}
$$

4.4.2.1.2.4 Metrics-based analysis

We reproduced with the model the main properties of the dialogue between Jane (J), a young adult with autism in her twenties, and a psychologist (P), which consists of a single concatenation (Fig. 1.6), made up of 16 speech acts. The results suggest partially preserved pragmatic abilities as well as some theory of mind skills, with the presence of intact cooperative skills.

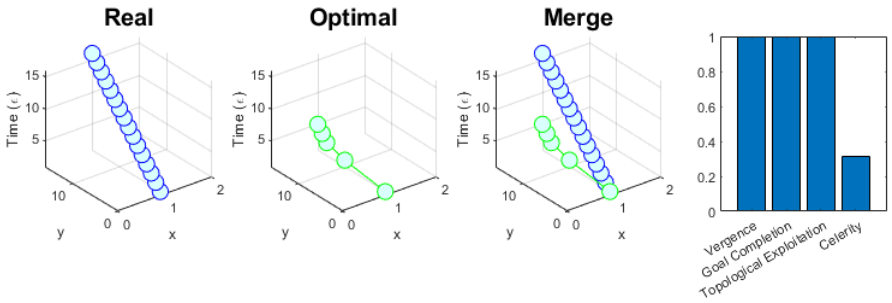

Figure 4.2: Topology (left) and metrics (right) concerning the Jane-Psychologist dialogue. The "Real" plot represents the topology of the dialogue as it took place and the "Optimal" plot represents the topology of the dialogue without the inserted sequences.

At the level of the whole dialogue, the convergence toward the goal is maximal (V=1, Fig. 2), as all speech acts produced by both interlocutors are of positive polarity and advance the goals pursued in the sequence. Moreover, the goals are fully completed (G=1; Fig. 2) and the plan is fully exploited (E=1; Fig. 2). However, we can observe a massive degradation of the celerity (C=.3125; Fig. 1; Fig. 2) due to the presence of inserted sequences (i.e. non-decisive speech act) corresponding to the numerous reformulations and clarifications of the initial request which slow down the progression of the goals.

Concerning the speech acts produced within the dialogue, we can observe that the construction of the cooperative action takes place first in an assertive mode (majority of MK-type acts), then in a declarative mode (majority of DO-type acts) which allows the resolution of the goal in progress to be unlocked. The associated rhetorical relations are mostly represented by requests for clarification and associated responses (5 QSubClar; 1 ElabClar and 4 QAP), highlighting Jane's difficulties in making herself understood by the psychologist, despite her good understanding of the mental state of her interlocutor by Jane (through the numerous reformulations and refocus she produces as well as the change in the mode of communication from assertive to declarative).

Here, the course of the dialogue shows a certain difficulty for Jane in making oneself understood when expressing a request by declaring a constituent (i.e. a nominal group) in its formulation. However, Jane's utterances constitute a communicative intention given the numerous attempts to clarify her request which she makes through repetition or by focusing on linguistic elements of her interlocutor (Bretherton & Bates 1979). Moreover, Jane is fully aware of her

purpose,as she persists in the face of her interlocutor's misunderstanding by repeating her act of indirect request by moving from a verbal request (MK) to a pointing out action (DO), thereby initiating the action she had requested from her interlocutors and enabling the progress of the action to be unblocked. She produced intentional behaviour in the sense of (Searle & Vanderveken 1985) by representing the conditions for the satisfaction of her utterance, and showed optimal capacities for cooperation, given her communicational abilities. The sequence thus shows at least partially retained theory of mind abilities, as Jane is able to infer the difficulties of understanding that her interlocutor experiences. These data are consistent with the observations of (Kissine et al. 2015, 2016), who suggested that ASD individuals exhibit capacities for contextual understanding and production of indirect requests.

Chapter 5

Disciplinary contributions and results

5.1 Towards a computational psychology: proof of concept

5.1.1 Viability of computational approaches to perform common psychometric operations

The validation of scales to discriminate between clinical populations is a relatively common procedure in psychology and medicine. The current validity framework postulates that validity corresponds to the level of evidence and theoretical justification that supports the interpretation and use of scores given by a scale. Thus, it is not the scale itself that is formally validated, but rather the interpretation of the scores it generates (Gonzalez et al., 2021; Messick, 1989; Schmeiser et al., 2006).

The concept of validity generally cuts across three major aspects: construct validity, content validity, and criterion validity. Construct validity is a central concept in psychology that identifies the extent to which the proposed test identifies the construct being measured, is generally obtained by correlating the measure with a number of other measures, and whose correlation patterns are theoretically predictable (Westen & Rosenthal, 2003). In contrast to construct validity, content validity provides a check on the representativeness of the items on a given instrument with respect to the construct under study, and an esti-

mate of the representativeness of the items comprising the instrument for the measurement of the construct under study. (Shi et al., 2012). Finally, criterion validity aims to measure the performance predicted by the measurement tool. In particular, it is underpinned by predictive validity, which aims to verify the performance of the test with respect to the criterion taken as the object of study, for example by predicting a diagnosis from the set of variables (i.e. items) considered (Taherdoost, 2016).

Computational approaches, such as machine learning, have shown dramatic results on many numerical problems. Thus, a growing number of research fields are beginning to use these types of strategies to analyze data, such as in physics (Moreno et al., 2021), chemistry (Schütt et al., 2019), ecology (Howell et al., 2019), and neuroscience (Just et al, 2014, 2017), where machine-learning techniques have been applied to distinguish a normally difficult-to-identify clinical population (suicide ideators) from neurotypical individuals, using neural signatures of conceptual representations captured in fMRI and following the presentation of valence-bearing words on a screen.

We postulate in the present work that machine learning strategies may represent a promising avenue for solving psychometric problems, or, more generally, may allow for an additional layer of evidence in scale validity assessment approaches.

In general, machine learning methods consist of two phases: a first phase that aims to create a model from a finite number of available data (i.e., observations), and then evaluate the power of the model by solving a practical task, such as estimating a probability density or assigning a class to an observation, on a different sample than the one used to build the model (Serdyukov, 2017).

With respect to construct validity in particular, regressive approaches seem to be particularly appropriate for solving this type of task. From a mathematical point of view, regression is a particular category of analysis that allows one variable to be approximated by a set of other variables that are correlated to it (Maulud & Abdulazeez, 2020). In a construct validation approach, we could transpose this approach by verifying the capacity of a regression model to reconstruct the variance observed in a sample on a scale measuring a construct, from samples coming from other scales measuring other constructs that are correlated to it.

Similarly, concerning criterion validity, and in particular predictive validity, we believe that supervised classification approaches could represent a candidate of choice. In machine learning, supervised classification is defined as an algo-

rithmic categorization of objects, allowing to assign a class to each observation of a sample based on statistical data (Michie et al., 1994). In a criterion validity approach, we could transpose this approach by verifying the ability of a classification model to correctly identify a clinical group on the basis of subjects' self-reported answers to a questionnaire.

We conducted two experiments on these data: first, we assessed construct validity using regression techniques, as described above, by attempting to reconstruct the observed variance in responses to the Fenigstein & Vanable scale from the available responses in the other scales (i.e., RC6; NEGE-r; and RBS) and observed the differential performance of the respective scale-based algorithms in this task. We then assessed criterion validity using classification techniques, as described above, by attempting to automatically predict the clinical category associated with the observations (i.e., psychotypic or paranoid), based on the different scales available, and again observing the differential predictive abilities of these tools.

For each of these experiments, artificial control experiments were performed. The control experiments ensure that the observed results are not random events, thus distinguishing the signal from the background.(Torday Baluška, 2019). In general, a positive control is a group that is known to respond with certainty when exposed to a stimulus, while the negative control is a variable for which no response is expected when exposed to a given stimulus, thus providing a baseline value for background noise.(Ghosh et al., 2014). In these experiments, we used the MMPI-2-Rf paranoia scale as a positive control. Indeed, being based on the same construct as the Fenigstein & Vanable scale, it should be able to reconstruct the variance of the Fenigstein & Vanable scale in the regression experiment. Similarly, given that the diagnosis of paranoia is made on the basis of the MMPI-2-Rf T-scores, one would expect a ceiling effect to be reached when the diagnosis is predicted with this scale (i.e., the maximum performance that can be expected). More generally, this step verifies the possibility of the operation. In addition, we used two parameters as negative controls: age and gender of the respondent. Indeed, these variables should not be able to reconstruct the variance of the Fenigstein & Vanable scale, as these data are not informative about the paranoid construct in the regression experiment; nor should they be able to provide the information necessary to correctly identify paranoid individuals in the sample. More generally, this step will allow us to note the impossibility of performing accurate discrimination in the absence of sufficient information about the measured construct.

5.1.1.1 Performing construct validity using Random Forest Regression

5.1.1.1.1 Material and method

5.1.1.1.1.1 Subjects

Four hundred and seventy-five unscreened adults (mean age = 25.33 years, SD = 11.22; men n = 145; women n = 330) from the general French population participated in this study. The screening of participants was performed entirely online, and ethical consents were obtained in accordance with the Declaration of Helsinki. Complete measurements were available for all subjects. The data are from the University archives and were collected as part of a Master's thesis conducted by Loïs Demange and Cassandra Guernier at the University of Lorraine (Demange & Guernier, 2017).

5.1.1.1.1.2 Psychometric material

MMPI-2-RF: The Minnesota Multiphasic Personality Inventory-2 Restructured Form (MMPI-2-RF) is a standardized psychological instrument for the comprehensive assessment of psychopathology and/or personality that evaluates the subject's psychological dynamics (e.g., psychopathological disorders, behavioral tendencies, etc.). We used the French version of this tool which consists of 51 clinical scales including a paranoia diagnostic scale (Restructured Clinical 6 - RC6) consisting of questions on moral self-righteousness, interpersonal sensitivity and distrust. This tool was used as a positive control, as it measures the same construct as the Fenigstein & Vanable scale. Additionally, and given that paranoia is equated in the clinical literature with delusions of anticipation of a threat or negative future events (Freeman & Garety, 2004), and the existence of Bayesian reasoning bias in the cognitive science literature (Moutoussis et al., 2011; Rossi-Goldthorpe et al, 2021), these scales were cross-referenced with two other clinical scales: the Neuroticism Scale-Revised (NEGE-r - MMPI-2-Rf), which measures negative emotions such as anxiety, insecurity, worry, as well as a general tendency toward dramatization and negative anticipation (Tellegen et al., 2003); and the Response Bias Scale (RBS - MMPI-2-Rf), which is designed to detect symptoms associated with cognitive response bias (Gervais et al., 2007).

Fenigstein & Vanable's Paranoia Scale (1992): This paranoia scale was designed to detect symptoms related to paranoia in non-clinical populations examining paranoid thoughts (Fenigstein & Vanable, 1992), through the identification of perceptions of suspicion, external control loci, feelings of resentment and ill will, distrust, etc...; and occurring in daily life (Fenigstein & Vanable, 1992). This instrument, initially produced and validated in the English language, was translated into French by the original authors of the work (Demange & Guernier, 2017).

5.1.1.1.1.3 Machine learning model: Random-Forest regressor

The machine-learning approach is to train a model on a subset of the dataset, and then test that trained model on another subset of the dataset that was not used to train the model. The data that is presented in the test condition is therefore unseen, and the performance measured in this condition represents the best possible approximation of the generalizability of the model on a single collection of data. In this study, we used a Random Forest regression model to assess the differential predictive power of participants' responses to different clinical subscales of the MMPI-2-Rf. The objective was to reconstruct the variance of participants' responses to the Fenigstein & Vanable scale from participants' responses to one or more other scales. The Random Forest is considered a "meta-estimator" that fits a number of decision trees to several subsamples of the data set in parallel. It then averages these decision trees to improve its predictive accuracy and control overfitting (Breiman, 2001; Geurts et al., 2006). In this study, only the number of trees generated and the loss-function were defined by the experimenter, while the other hyperparameters were used in their default configuration (i.e., they were not explicitly defined by the experimenter) in order to measure a baseline functionality, such as the one currently expected in statistical methods available from code libraries and embedded in software like RStudio or Spyder. The number of generated trees was set to 10000 in accordance with experiments conducted by (Oshiro et al., 2012) and for the loss-function, we used the root mean square error as the metric.

5.1.1.1.1.4 Procedure

Data were collected online by (Demange & Guernier, 2017) through word of mouth and social media. The dataset a then that they left available at the University of Lorraine archives was randomly divided to form an independent training set (n=380) and a test set (n=95) using the scikit-learn library in Python. To assess the differential performance of participants' response matrices to the different clinical scales (RBS and NEGE; including all items), we used machine-learning regressors, assuming that the concepts underlying these scales share useful and informative dimensions that will allow automatic inference of participants' responses to the Fenigstein & Vanable scale. In addition, we used similar regressors to compare our results to those of two control factors: inferring participants' responses to the Fenigstein & Vanable scale from the MMPI-2-Rf RC6 scale, which is designed and validated to measure the concept of paranoia (i.e., this experiment measures process feasibility); and inferring participants' responses to the Fenigstein Vanable scale from their age and gender (i.e., two variables). This was done under the assumption that these two factors should explain the majority of the variance in participants' responses when they are not paranoid. In other words, we evaluated predictions in six conditions: RC6 alone, RBS alone, NEGE alone, RBS and NEGE together. We performed this assessment for a reduced version (10 random items each) to fit the number of items to the Fenigstein & Vanable; and Age+Gender scale.

To calculate the similarity between the predicted responses of the full Fenigstein & Vanable participant (all 20 items) and the observed responses, we constructed a cosine similarity matrix for all conditions. In this way, each predicted item is compared to its actual counterpart and the similarity between the two response matrices is represented using a scale between 0 and 1. Subsequently, we performed a Kruskal-Wallis test ($similarity \sim predictionsource$; due to the non-normal distribution of the data) to assess whether the predictive power varies as a function of the source scale that made the predictions; followed by a non-parametric Dunn-Bonferroni post-hoc procedure to analyze the interactions between the variables. Finally, we performed six two-way ANOVAs ($score \sim source * item$; i.e., one ANOVA for each prediction source) with respect to value source (two levels: predicted or observed) and item (one level per Fenigstein & Vanable item). This was done to statistically assess the differential performance of the different scales in reconstructing the variance of the Fenigstein Vanable scale. The hypothesis here is that the ability of a machine learning algorithm to predict the observed variance of a sample of participants' responses to a questionnaire can be inferred from responses to other question-

naires that provide a sufficient amount of information about the construct under study to infer its properties. The different interactions between the variables under study were analyzed using the Tukey procedure, the machine-learning models were coded in Python using functions from the scikit-learn library and using Spyder v3.7 as the interpreter; and the statistical analyses were coded in R using RStudio v1.0.143 as the interpreter.

5.1.1.1.2 Results and discussion

The results of the cosine similarity matrix analysis can be seen in Figure 5.1 and Table 5.1; and the results concerning the analysis of variance are presented in Table 5.2.

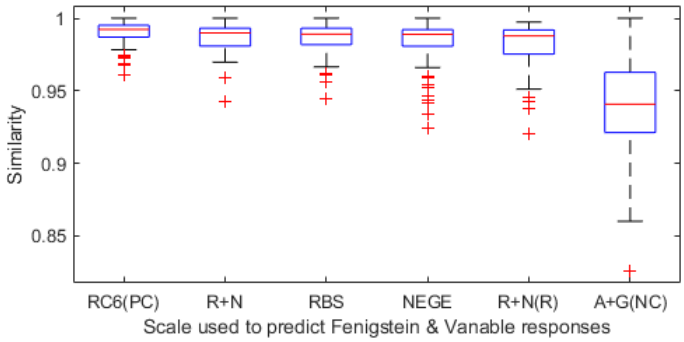

Figure 5.1: Average similarity between actual and predicted matrices for predictions of participants' responses to the Fenigstein & Vanable scale from RC6 (positive control), RBS & NEGE (combined), RBS, NEGE, RBS + NEGE (reduced), and Age+Gender (negative control)

5.1.1.1.2.1 Similarity

For the prediction of RC6 to Fenigstein & Vanable, the mean similarity was .99 (SD±.008), with minimum similarity at .961 and maximum similarity at 1, indicating perfect prediction of participants' self-reported values by the algorithm. Then, from NEGE+RBS to Fenigstein & Vanable, the mean similarity was .99 (SD±.009), with minimum similarity at .94 and maximum similarity at 1. Then, from RBS to Fenigstein & Vanable, the mean similarity was .98 (SD±.01), with minimum similarity at . Next, from NEGE to Fenigstein & Vanable, the mean similarity was .98 (SD±.01), with minimum similarity at .92 and

maximum similarity at 1. Then, from the reduced version of NEGE+RBS, the mean similarity was .98 (SD±.01). Finally, from age and gender to the Fenigstein & Vanable scale, the mean similarity was .94 (SD±.03) with a minimum similarity of .82 and a maximum similarity of 1.

Scale	RC6 (PC)	RBS+NEGE	NEGE	RBS	R+N(R)	A+G
RC6 (PC)	-	***p<.001***	***p<.001***	***p<.001***	***p<.001***	***p<.001***
RBS+NEGE	***p<.001***	-	n.s.	n.s.	***p<.001***	***p<.001***
NEGE	***p<.001***	n.s.	-	n.s.	n.s.	***p<.001***
RBS	***p<.001***	n.s.	n.s.	-	n.s.	***p<.001***
R+N(R)	***p<.001***	***p<.001***	n.s.	n.s.	-	***p<.001***
A+G	***p<.001***	***p<.001***	***p<.001***	***p<.001***	***p<.001***	-

Table 5.1: Results of the Kruskal-Wallis test. [n.s. : not significant; RC6 (PC) : Restructured Clinical 6 (Positive Control); NEGE : Neuroticism Scale; RBS : Responses Biases Scales; R+N(R) : RBS+NEGE (reduced); A+G (NC) : Age+Gender (Negative Control)]

These results suggest that when the same dimensions are measured in two scales (e.g., between RC6 and Fenigstein & Vanable), the similarity between the actual and predicted matrices will be high with a low standard deviation. Furthermore, if one or more dimensions are shared between two or more scales (e.g., between Fenigstein & Vanable and RBS+Nege; Fenigstein & Vanable and RBS; Fenigstein & Vanable and NEGE), the similarity between the actual and predicted matrices will remain high with a low standard deviation, with a positive association between the number of shared dimensions and predictive power (which may be suggested by the significant differences between the RBS+NEGE and NEGE predictions alone). Furthermore, predictive power will be higher when more items measure a shared dimension between two constructs, as shown by the significant difference between RBS+NEGE (full) and RBS+NEGE (reduced). Notably, these results also suggest that when the factor associated with the clinical condition is controlled, only age and gender produce variation in participants' responses.

5.1.1.1.2.2 Analysis of variance of predicted responses

The results of the analysis of variance are available in Table 5.2. The data suggest that all scales sharing common dimensions with paranoia are capable of reconstructing the variance of participants' responses to the Fenigstein & Vanable scale.

Scale	Item	Source	Item:Source
RC6 (PC)	***F(19,3640)=61.6, p<.001***	*F(1,3640)=1.49,p=.22*	*F(19,3640)=.13,p=1*
RBS+NEGE	***F(19,3640)=55.67,p<.001***	*F(1,3640)=1.38,p=.24*	F(19,3640)=.19,p=.999
RBS	***F(19,3640)=55.27,p<.001***	*F(1,3640)=17.82,p=.26*	F(19,3640)=.17,p=.999
NEGE	***F(19,3640)=54.64,p<.001***	*F(1,3640)=.004,p=.95*	F(19,3640)=.17,p=.999
R+N(R)	***F(19,3640)=55.67,p<.001***	*F(1,3640)=1.38,p=.24*	F(19,3640)=.19,p=.999
A+G (NC)	***F(19,3640)=71.35,p<.001***	***F(1,3640)=7.75,p=.0054***	F(19,3640)=1.005,p=.45

Table 5.2: Results of analysis of variance (ANOVA) tests. [n.s. : not significant; RC6 (PC) : Restructured Clinical 6 (positive control); NEGE : Neuroticism Scale; RBS : Responses Biases Scales; R+N(R) : RBS+NEGE (reduced); A+G (NC) : Age+Gender (negative control)].

These results suggest that all regressors constructed from scales that share dimensions with the paranoid construct are able to automatically reconstruct the observed sample variance on the Fenigstein & Vanable scale. In contrast, the only variable that failed to do so was the negative control (Age+Gender), which behaved in the opposite way to all other conditions (whose regressors' behavior instead matched the pattern observed in the artificial positive control experiment). We therefore postulated that this highlighted difference could be interpreted as a factor that does not depend on age or gender, and that the algorithm is not able to capture: it lacks the underlying dimensions of paranoia. We also believe that predictability remains high when predictions are made using the "age+sex" factor since, if the "paranoia" factor is removed, only age and sex will vary participants' responses (i.e., these factors can predict neurotypical participants' responses).

5.1.1.1.3 Preliminary conclusions

In summary, the main results of this experiment indicate that when two scales assess the same dimensions, a prediction from one to the other will result in a high similarity matrix between actual and predicted values, with a low standard deviation. In addition, when two or more scales share dimensions, the similarity between the matrices will remain high, but to a lesser extent and with a higher standard deviation, and with a relationship that the fewer dimensions shared between the scales, the less similarity there will be and the higher the standard deviation will be (see the "Similarity" section). Similarly, the more dimensions shared between scales, the better the algorithm will be able to reproduce the original variance of the sample (see section "Analysis of variance of predicted responses") and its intrinsic characteristics.

5.1.1.2 Performing criterion validation using Random Forest classification

5.1.1.2.1 Material and method

5.1.1.2.1.1 Subjects

A subset (paranoids: n=131; controls: n=131) of the original sample was used for this experiment. We assumed that in the classification study, the experimenters would have initial knowledge of the clinical conditions and would perform the classification using two balanced groups. They were matched automatically using the MatchIt code library, coded in R, and interpreted by RStudio v1.0.143.

5.1.1.2.1.2 Psychometric materials

MMPI-2-RF: We used the same Restructured Clinical 6 (RC6) to test the criterion validity of the Fenigstein & Vanable scale.

Fenigstein & Vanable's Paranoia Scale (1992) We used the same paranoia scale translated into French by (Demange & Guernier, 2017)

5.1.1.2.1.3 Machine-learning model: the Random Forest classifier

To assess whether the Fenigstein Vanable scale is sufficient to diagnose paranoia, we constructed a Random Forest classifier. The classification performed in this study consists of predicting the diagnosis of MMPI-2-Rf paranoia (i.e. T-score of the MMPI-2-Rf paranoia scale > 80, using a binary variable: 0 or 1) using only the participants' responses to the Fenigstein Vanable scale. In this study, only the number of trees generated and the criterion were set by the experimenter, while all other parameters were set by default. 10000 trees were used (according to (Oshiro et al., 2012)) and the criterion used was entropy (i.e. the optimal tree division being chosen according to the principle of minimum entropy).

5.1.1.2.1.4 Procedure

The MMPI-2 was assessed automatically using a Python program to avoid human error. Normative data were encoded in Python to automate the transformation of the raw data into a T score and then from the T score into a diagnosis, according to the MMPI-2-Rf threshold (Paranoia T ¿ 80). Next, 131 control individuals were selected by matching using the MatchIt library in R to form two equivalent groups of 131 individuals (i.e., $n_{paranoiac}$=131 and $n_{controls}$=131). The dataset was then randomly divided to form a training dataset independent (n=209) from the test dataset (n=53). A k-Fold cross-validation (with k = 10) was performed to assess the differential performance of the scales in automatically assigning participants' class from the participants' responses to the respective scales; and measures of accuracy, specificity, and sensitivity were generated for all conditions.

Finally, two ANOVAs were performed: first, a one-way ANOVA ($accuracy \sim scale$), to test whether significant differences in performance exist as a function of the scale used to perform the classification task (4 levels: RC6 (positive control); F&V; RBS+NEGE; A+G (negative control)). Then, a 2-way ANOVA ($score \sim scale * metric$) was performed to control for differential scale performance in terms of sensitivity and specificity. All significant interactions were controlled using a Tukey post-hoc procedure. Machine-learning algorithms were coded in Python using the Sci-Kit Learn libraries and statistical analyses were coded in R and interpreted in RStudio v1.0.143.

5.1.1.2.2 Results and discussion

The cross-validation results for all conditions are shown in Figure 5.2.

Random Forest classifiers trained on Fenigstein and Vanable scale data from 209 of the 262 participants identified the home group of the remaining participants with a mean accuracy of .81(±.4), a mean sensitivity of .85(±.15), and a mean specificity of .93(±.05) (Figure 5.2). In contrast, classifiers trained on the positive control data (RC6) had a mean accuracy of .92(±.03), with a mean sensitivity of .78(±.13) and a mean specificity of .96(±.05); whereas classifiers trained on the negative control data (Age+Gender) had a mean accuracy of .67(±.04), with a mean sensitivity of .37(±.2) and a mean specificity of .93(±.06).

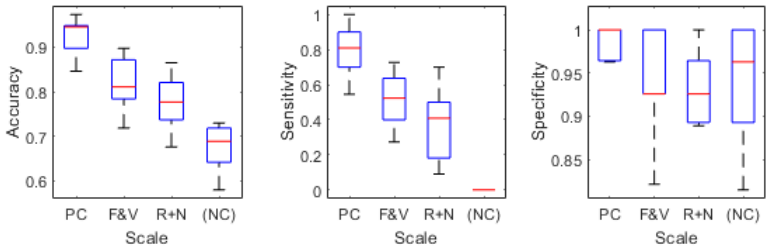

Figure 5.2: Average similarity between actual and predicted matrices for predictions of participants' responses to the Fenigstein & Vanable scale from RC6 (positive control : PC), RBS & NEGE (combined ; R+N), and Age+Gender (negative control : NC)

5.1.1.2.2.1 Accuracy

The results of the accuracy measures are presented in the left panel of Figure 5.2 and in Table 5.3. The scales showed differential performance in identifying participants' class of membership.

Scale	RC6 (PC)	F&V	R+N	A+G (NC)
RC6 (PC)	-	***p<.001***	***p<.001***	***p<.001***
F&V	***p<.001***	-	*p=.39*	***p<.001***
R+N	***p<.001***	*p=.39*	-	***p<.001***
A+G (NC)	***p<.001***	***p<.001***	***p<.001***	-

Table 5.3: Tukey post-hoc test results for accuracy. [RC6 (PC): Restructured Clinical 6 (Positive Control); FV: Fenigstein Vanable; R+N: RBS+NEGE (Combined); A+G (NC): Age+Gender (Negative Control)]

Regarding accuracy, the one-way ANOVA ($accuracy \sim scale$) revealed a significant effect of the scale used to perform the automatic classification of the participants' category of belonging [$F_{(3,36)}$=36.45, $p < .001$]. Subsequent post-hoc analysis revealed differential performance across all conditions (Table 5.3, Figure 5.2 (Left)), except between the F&V and R+N conditions, which showed similar performance.

5.1.1.2.2.2 Sensitivity and specificity

The results for the detection metric measures are shown in Table 5.4 and Figure 5.3 (middle-left). The scales showed differential performance in identifying

patients, but similar performance in identifying control subjects.

Metric	Sensitivity				Specificity			
Scale	RC6	F&V	R+N	A+G	RC6	F&V	R+N	A+G
RC6	-	***p<.001***	***p<.001***	***p<.001***	-	*p=.96*	*p=.96*	*p=.97*
FV	***p<.001***	-	*p=.10*	***p<.001***	*p=.96*	-	*p=1*	*p=1*
R+N	***p<.001***	*p=.10*	-	***p<.001***	*p=.96*	*p=1*	-	*p=1*
A+G	***p<.001***	***p<.001***	***p<.001***	-	*p=.97*	*p=1*	*p=1*	-

Table 5.4: Tukey's post hoc test results for sensitivity and specificity. [RC6 (PC): Restructured Clinical 6 (Positive Control); F&V: Fenigstein & Vanable; R+N: RBS+NEGE (Combined); A+G (NC): Age+Gender (Negative Control)]

Regarding the detection measures, the two-way ANOVA ($score \sim scale * metric$) revealed a significant effect of scale [$F_{(3,36)}$=51.21, $p < .001$] and metric [$F_{(3,72)}$=487.54, $p < .001$], with a significant interaction between the scale used to generate the prediction and the type of metric used to measure the performance [$F_{(3,36)}$=41.20, $p < .001$]. Subsequent analysis by Tukey's post-hoc procedure revealed significant differences between all scales regarding sensitivity measures, except between the F&V and R+N conditions (Table 5.4, Figure 5.3 - Middle); but no differences between different conditions regarding specificity measures (Table 5.4, Figure 5.3 - Right).

5.1.1.2.2.3 Preliminary conclusions

These results show that only the scales specifically measuring the paranoia construct are able to correctly attribute the clinical condition to paranoid participants, whereas all are able to correctly identify control individuals. However, a significant difference was observed between the performance of classifiers trained on the RC6 scales and those trained on the Fenigstein & Vanable scales. This observation could be explained by the fact that the patients' diagnosis was produced from the normative data of the MMPI-2-Rf, of which the RC6 scale is part. This bias should thus give it an advantage in performing the classification task. However, it should not be a problem in future work, given that in clinical trials, the assignment of clinical condition to participants is done by medical and/or psychological diagnosis prior to the administration of the scales; thus, the control experiments will be able to play their role in a more objective and less biased manner.

5.1.1.3 General discussion

Using machine-learning approaches, we were able to perform two common validation operations in psychometrics, namely construct validity and criterion validity.

First, we performed a construct validation operation using a Random Forest regression algorithm, showing that it was possible to reconstruct the observed variance of participants' responses to a questionnaire from responses to a questionnaire measuring the same constructs, or from responses to a set of questionnaires measuring constructs sharing dimensions with the construct of interest. We then performed a predictive criterion validation using a Random Forest type classification algorithm, and showed that it was possible to automatically identify the class to which participants belonged, relative to two clinical groups (i.e. paranoid and neurotypical), from scales specifically measuring the construct of interest, or from a set of scales sharing dimensions with it.

To the best of our knowledge, and although machine learning paradigms have already been employed to discriminate between different clinical groups using Likert scales and classification algorithms (Duda et al., 2017), we believe this work is the first to investigate the viability of these approaches within the overall framework of the clinical scale validation approach. As such, it could provide a proof of concept that computational approaches could be applied to solve psychometric problems, and allow for an additional layer of evidence when employed in concert with traditional validation approaches.

Finally, we believe that beyond the validation setting, and even beyond the general clinical setting, these types of approaches could have interesting prospects in research fields. Indeed, pre-trained classification models on clinical populations could perform automatic predictions on new and much more massive unlabeled datasets, and thus allow large-scale multidimensional psychometric studies. One could also imagine linking dimensions of different nature, for example by performing predictions of psychophysical data from cognitive and/or psychometric measures, thus allowing the creation of synthetic datasets to train theoretical models, or allowing the linking of measures obtained in different exploratory paradigms by training multi-layer models and relying on transfer-learning. Further research will therefore be needed to better evaluate the potential of these approaches in the research setting and especially in terms of clinical translation possibilities.

5.1.2 From the 2TK model to the computational psychology of interaction: the example of schizophrenia

As described earlier, schizophrenia is generally characterized at the cognitive level by difficulties integrating local cues into a global context (Talamini et al., 2010). In the context of language, the sentence carries a representation in a context, and this contextual representation, which falls under pragmatics, is particularly impaired in the schizophrenic context.

Thus, the debate between Chaika and Fromkin in the early 1970s (Chaika, 1974; Fromkin, 1975) when linguists were interested in the properties of schizophrenic language taught us that all the discourse inconsistencies produced by schizophrenics exist in the speech of all speakers, with the exception of inconsistencies in the sequentiality of speech, which represents the higher level of language use, and which therefore requires the global integration of linguistic markers. Indeed, the study of schizophrenic dialogue dysfunctions has a long tradition at the School of Nancy, initiated by (Trognon, 1987, 1992) and extended by (Musiol & Rebuschi, 2007; Musiol & Trognon, 2000) and then by (Musiol & Verhaegen, 2014; Verhaegen, 2007).

Since then, linguists and psycholinguists have been able to show this phenomenon of conversational disruption (or disengagement; incidence; depending on the terminology used) many, many times, through almost the entirety of the models available in linguistics and psycholinguistics; in particular, in interlocutionary analysis, in Ludics, and in SDRT (Fouqueré et al, 2021a; Musiol, 2009; Musiol & Rebuschi, 2007; Musiol & Trognon, 2000; Musiol & Verhaegen, 2014; Rebuschi Amblard Musiol, 2014; Verhaegen, 2007), all of which highlight the same phenomenon.

However, and if we place ourselves in the debate that opposed Elaine Chaïka and Victoria Fromkin, we realize that the subsequent research that followed this fundamental work (including outside the field of linguistics, notably in the field of mathematics that investigated schizophrenic discourse using graph theory (Spencer et al, 2021)), have focused on the only point of agreement between the two authors, the conversational break, leaving aside all the other properties of schizophrenic language highlighted by Elaine Chaïka, considered by contemporary authors to be properties shared between neurotypical speakers and schizophrenics.

One might thus question the reasons for abandoning this work on these shared properties, especially in a discipline such as psychology, whose develop-

ments have led to the emergence of numerous disciplines that allow for the establishment of psychological metrics, notably differential psychology, psychometrics, cognitive psychology and neuropsychology. Indeed, if we reason by transposition, working memory, for example, is also a function shared by schizophrenics and neurotypical individuals. The sharing of this capacity does not, however, negate the interest in measuring the differential performance of these two groups of individuals in a wide variety of tasks, which is why this cognitive function is still being studied in this population in comparison with control subjects, more than six decades after the first descriptions of this impairment (Rogasch et al., 1968). It is thus easy to understand that the findings of an alteration, a dysfunction, or the existence of shared processes are insufficient in the pathological characterization, and also limit the fundamental predictions that can be formulated from the clinical observations that have been measured; and that it is rather in the measurement of the magnitude of the difference, and in the identification of the variables that make it possible to predict this difference, that the maximum of inferences will be able to be drawn from the experimental or clinical data. Thus, in the present work, we advocate the position that the analysis of acquired processes as functional provides a degree of additional information to the simple measurement of a similarity or difference; all the more so if one relies on the data of the literature of cognitive remediation, whose theoretical basis has rested since its first definitions on the hypothesis that a given function can be realized in a great diversity of possible functional combinations (Ben-Yishay & Prigatano, 1990).

Thus, the present experiment proposes to explore the dimensions shared between schizophrenics and neurotypicals, by analyzing corpora of schizophrenic patients and controls taken from the work of (Verhaegen, 2007). However, and in contrast to the work we mentioned earlier, we will focus exclusively on long corpora (i.e. more than 30 speech acts) without any impact: the differences measured thus account for the effect of schizophrenic pathology in interactive functions that have been assumed to be functional since the 1970s.

5.1.2.1 The paradigm of topological deviation as a model of the coherence of thought

The topological deviation paradigm, derived from the 2TK model, and used in this study is illustrated in Figure 5.3 and in Table 5.5. This paradigm was designed to take into account the difficulties in obtaining homogeneous discourse

data in a free dialogue situation, and consists in comparing the real dialogue with two theoretical versions of it: a hyperlemmatized version (taking into account all the speech acts, and organized from the premises to the conclusions, the so-called "optimized" version) and an alemmatized version (taking into account only the speech acts that have significantly advanced the exchange, i.e. with no inserted sequences in the sense of Levinson(S. C. Levinson, 2006), or without repetition or continuation if we rely on categorization in terms of rhetorical relations (Caelen & Xuereb, 2017)). The latter two versions having been rearranged to highlight the semantic topology of the information exchanged during the conversation (thematic organization) rather than the kinetic topology, which corresponds to the actual information exchange.

Real (Observed)	**Optimized (Hyperlemmatized)**	**Optimal (alemmatic)**	ϵ
I have a car	I have a car	I have a car	1
A Ford	A Ford	It's a Ford Fiesta	2
It is red	It's a Ford Fiesta	It is magenta	3
Finally, to be more accurate	It is red	-	4
It is magenta	Finally, to be more accurate	-	5
It's a Ford Fiesta	It is magenta	-	6

Table 5.5: Examples of theoretical reorganization of the "Car" exchange.

In this ad-hoc example created for the occasion (Table 5.5), we observe exactly what we would observe in a classical interaction. We have a man who claims to have a car, and who describes its properties: its make and its color.

However, we can observe, in real conditions (Table 5.5, Col.1), that the dialogue is not very well organized. In particular, we observe a return to a theme that could have been closed earlier (real condition at $\epsilon = 6$ with a return to the theme of the brand): we could very well imagine a more organized version of this dialogue, where each speech act would be correctly attached to its theme and where all the information related to it would be given before the closure of the theme, thus allowing us to produce the optimized version of the exchange (Table 5.5, Col.2).

Moreover, we could also imagine a shorter version: indeed, here, we can observe that the speech act "Ford Fiesta", already contains the information "Ford"; and similarly, that the precision "magenta" supplants the previous information "red". From the point of view of information theory (Shannon, 1948), we could therefore have the same amount of information in three turns of speech,

thus producing the optimal theoretical version of the dialogue (Table 5.5, Col.3).

If we topologically organize this exchange from the encoding rules in 2TK, then we can project it onto a three-dimensional (x, y, ϵ) plot, in 3 versions (Figure 5.3).

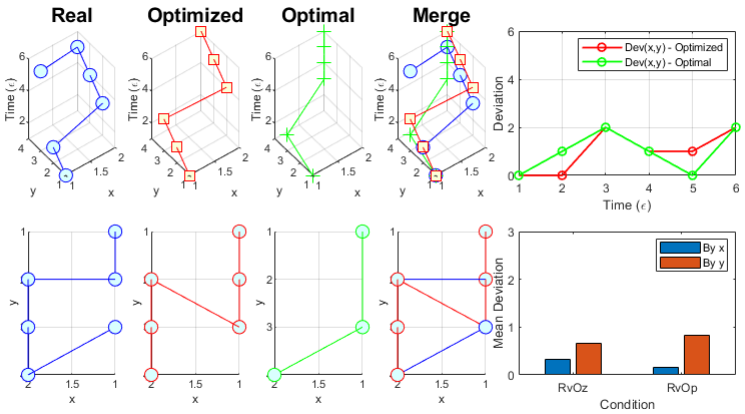

Figure 5.3: Topological-kinetic dynamics of the exchanges shown in Table 5.5 The first four figures on the left represent the topological-kinetic dynamics under all conditions (top) and the connection profile of the sequences (bottom), respectively. The curves at the top right represent the total deviations measured for each condition and for each time unit. The corresponding total dialog-scale quantization is shown in the bottom right figure.

In this figure, we can observe from left to right: the real exchange, where we can observe first the change of theme, from brand to color, then the development of the color theme, and finally the return to the brand theme; then the optimized exchange (i.e. reordered), with a more fluid exploitation of the themes; then, the optimal exchange, where the exchange of information is identical, to a certain extent, but with a higher celerity; and finally, we can observe the superimposition of the graphs in order to visually appreciate their differences.

In addition, and from the topological coordinates of each of the versions of the exchange, it is possible to calculate a specific metric to measure the difference between the dynamics of an exchange such as it has taken place in comparison with other developments that it would have been theoretically possible to observe: the topological deviation. Thus, the topological deviation corresponds for each unit of time (i.e. a speech act; an iteration of epsilon) to the vector distance between the real topological position of the exchange compared to the theoretical topological position of one of the exchanges that

has been optimized. For example, and using the Euclidean distance (easily computed with a bare hand), the total topological deviation is thus given to us by the following equation, which could also be represented for each unit of time (Figure 5.3. Right-Top):

$$Dev(x,y) = \sqrt{\sum_{\epsilon=1}^{n}(x_{T_t} - x_{R_t})^2} + \sqrt{\sum_{\epsilon=1}^{n}(y_{T_t} - y_{R_t})^2} \tag{5.0}$$

With :
- T : Theoretical observation (optimized or optimal) ;
- R : Real observation ;
- ϵ = dialogical time (iterated for each speech act).

However, although the total deviation represents the summation of the deviations according to the x and y parameters, in this study, the deviation is calculated separately, by parameter (Figure 1. Right-Bottom). The corpus were therefore analyzed according to their deviation according to the y parameter (which corresponds to the stages of elaboration of a given theme) and according to the x parameter (which can correspond either to the elaboration of a theme into a sub-theme or to the transition to a new theme).

The precision of the method presented above could be improved by subtracting the effect of the deviation of y on x, or by using other types of distances (e.g. Minkowski distances), but the analysis was carried out in order to be entirely replicated in a handwritten way (i.e. potentially in a clinical context, directly in the office), including encoding and calculations, and in a rapid way.

5.1.2.1.1 The y parameter

In the 2TK model, from which the topological deviation paradigm is derived, the y-parameter corresponds to the development of a given topic in a vertical axis. Thus, an iteration in the y-parameter can either correspond to the introduction of information completing a given theme (i.e. which makes the exchange progress); or to the introduction of an inserted section (which will suspend the progression of the exchange).

Depending on the type of iteration characterizing the parameter y, the impact on the topological deviation will be differentiable: in the case of an iteration

that makes the exchange progress, no deviation will be introduced when comparing the real and theoretical topologies, since the sequence will be preserved both in the optimized versions (which preserve all the sequences of the exchange) and in the optimal versions (which preserve only the sequences that have made the exchange progress). On the other hand, in the case of an iteration that does not advance the exchange (i.e. an inserted sequence, a repetition, a continuation), the iteration will produce a deviation between the real and the optimal topologies (because the sequence will be deleted), but not between the real and the optimized topologies (because the sequence will be kept), thus creating a differential deviation.

5.1.2.1.2 The x parameter

In the 2TK model, the parameter x corresponds to the elaboration of a theme of a dialog element by sub-elements. Thus, an iteration in the parameter x can either correspond to the elaboration of a theme into sub-themes (e.g. Car $\Longrightarrow$ Brand + Color), or to the creation of a new theme.

In the topological deviation paradigm, the parameter x can thus be used to measure the organization of thought. Indeed, the frequent jumps from one theme to another as well as the returns will produce important deviations, in all theoretical and real comparisons, but particularly between the optimized and real versions where the effect will be the most marked (given the absence of interference from the effect of the sequences inserted in the analysis).

5.1.2.2 Topological deviation tested against acquired data: a cases studies

5.1.2.2.1 Material

The corpuses of fifteen participants were taken from the archival data of the University of Lorraine and produced in the framework of Frédéric Verhaegen's doctoral work (Verhaegen, 2007). Three groups of participants were constituted (healthy controls: n=5; untreated schizophrenics: n=5; treated schizophrenics: n=5). The research was conducted in accordance with legislative standards in effect in the year of data collection and the Declaration of Helsinki. Written consents were obtained from all participants or their legal guardians, if applicable.

5.1.2.2.2 Analysis of corpuses from (Verhaegen, 2007)

5.1.2.2.2.1 An example of a control corpus : N02

The analysis concerning the control subject used as an example is available in Figure 5.4. The data showed a strong organization of thought in this subject, despite a slight punctuated and localized thematic disorganization in the range of $\epsilon = [20 - 35]$.

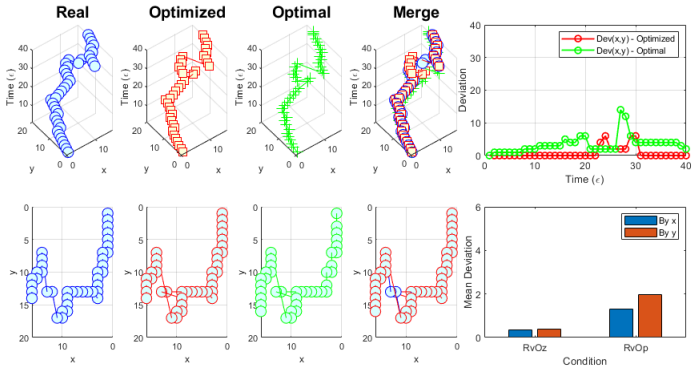

Figure 5.4: Topological deviation model of the N02 corpus (control group). The first four figures on the left represent the topological-kinetic dynamics under all conditions (top) and the connection profile of the sequences (bottom), respectively. The curves at the top right represent the total deviations measured for each condition and for each time unit. The corresponding total dialog-scale quantization is shown in the bottom right figure.

Concerning the kinetic analysis of the dialogue (Figure 2, Right-Top), we can observe a weak deviation between the real exchange and the optimized exchange, suggesting a strong tonic coherence of the thought organization, as shown by the quantification (Real vs. Optimized, deviation in x: $RvOz_x$=.33; Real vs. Optimized, deviation in y: RvOzy=.33, Fig.2, Right-down).

Similarly, a small deviation between the actual and optimal exchange was measured (Actual vs. Optimal, deviation in x: RvOpx=1.3; Actual vs. Optimal, deviation in y: RvOpy=1.9). It is however stronger than the deviation corresponding to the comparison of the real and optimized exchanges, suggesting the presence of inserted sequences. The dialogue could therefore have taken place with a higher speed (i.e. a shorter exchange is possible).

5.1.2.2.2.2 An example of a schizophrenic corpus : MAY

The analysis concerning the schizophrenic subject used as an example is available in Figure 5.5. The data showed an important disorganization of thought in this subject, highlighting a non-ordered sequentiality and a strong thematic confusion producing an anarchic pragmatic connectivity.

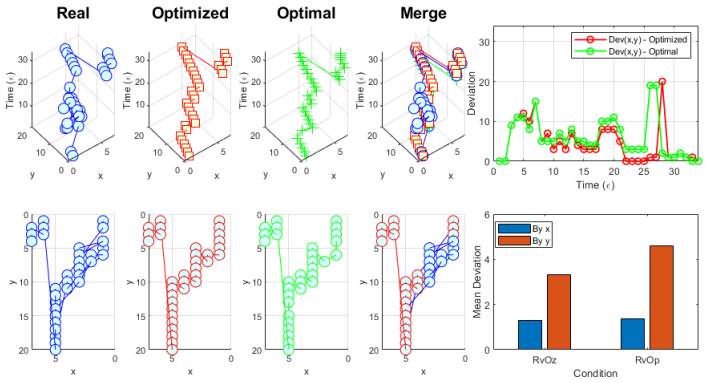

Figure 5.5: Topological deviation model of the MAY corpus (untreated schizophrenia group). The first four figures on the left represent the topological-kinetic dynamics under all conditions (top) and the connection profile of the sequences (bottom), respectively. The curves at the top right represent the total deviations measured for each condition and for each time unit. The corresponding total dialog-scale quantization is shown in the bottom right figure.

Concerning the kinetic analysis of the dialogue (Figure 3), we observe a strong deviation between the real and the optimized exchange, testifying to the number of operations necessary to observe the pragmatic coherence of the exchange, and thus suggesting an important lability of the organization of thought, as shown by the quantification (Real vs. Optimized, deviation in x : $RvOz_x$=1.24; Real vs. Optimized, deviation in y: $RvOz_y$=3.34, Fig.3, Right-Low) and the superposition of the interaction plots (Fig.3, Left) which shows a nodification of the progression of themes.

Similarly, a strong deviation between the actual and optimal exchange was measured, especially in the theme elaboration axis (Actual vs. Optimal, deviation in x: $RvOp_x$=1.34; Real vs. Optimal, deviation in y: $RvOp_y$=4.59), highlighting the ubiquity of sequences inserted into the dialogue and the difficulty of achieving effective interaction.

5.1.2.2.2.3 Group study

The analysis conducted at the group level is presented in Figure 5.6. The results showed a strong impact of schizophrenia on the organization of thought and the optimization of discursive elaboration.

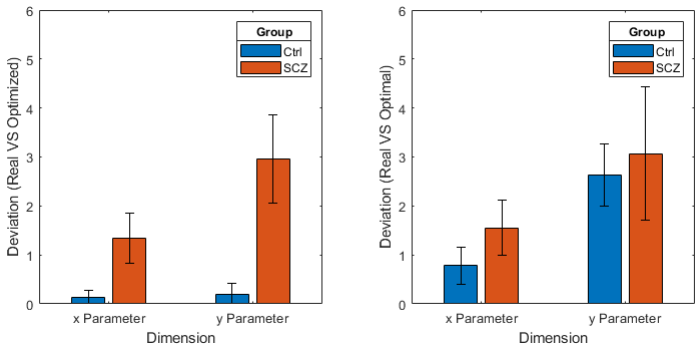

Figure 5.6: Topological deviations measured at the group level and for each parameter.

Three-way ANOVA revealed a strong effect of group [$F_{(1,32)}$=34.67, p<.001], theoretical model considered [$F_{(1,32)}$=15.23, p<.001] and parameter considered [$F_{(1,32)}$=32.86, p<.001], with a significant interaction between the group and the theoretical model considered [$F_{(1,32)}$=9.93, p=.003] as well as between the group, the theoretical model considered, and the parameter considered [$F_{(1,32)}$=4.67, p=.03]

A subsequent Tukey test showed a significant difference between schizophrenics and controls regarding the parameters x [p=.01], and y [p<.001], and generally showed a notable significant difference between the two groups regarding the deviations measured in the Real vs. Optimized condition (Figure 5.6), which assess thought organization.

These results suggest a significant impairment in the expression of thought organization in schizophrenic individuals. This result is consistent with results originally obtained in interlocutionary analysis and SDRT and conducted in the doctoral work from which the data were derived (Musiol & Verhaegen, 2014; Verhaegen, 2007).

5.1.2.2.2.4 Measuring the effect of antipsychotic treatment on the organization of thought

The results regarding the measurements of topological deviations in the Real vs. Optimized condition for parameter x in the different experimental groups are presented in Figure 5.7. The data showed a significant impact of antipsychotic treatment on the expression of thought organization.

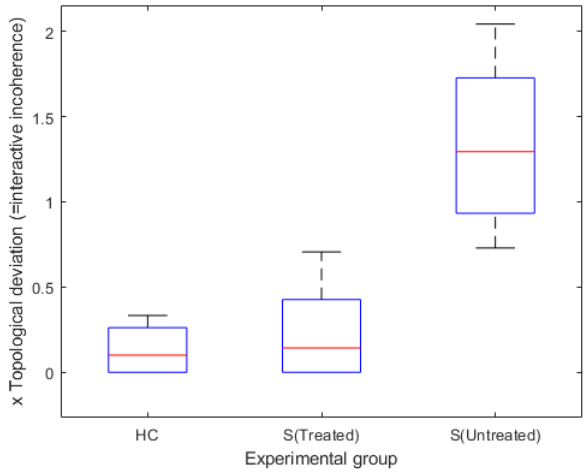

Figure 5.7: Effect of antipsychotic treatments on topological deviation measures (real vs. optimized) for parameter x.

One-way ANOVA (deviation group) revealed a significant effect of experimental group [$F_{(2,12)}$=17.77, p<.001].

Subsequent post-hoc analysis using the Tukey procedure showed a significant difference between untreated schizophrenics and controls [p<.001], as well as between untreated schizophrenics compared with their matched treated counterparts [p<.001], but not between controls and schizophrenics treated with an antipsychotic molecule [p=.89].

These results suggest that antipsychotic treatments allow for an improvement in thought organization, as evidenced by the regularization of topological deviations in x at levels statistically equivalent to control subjects.

These observations are all the more interesting as they were performed on non-incidental corpuses of everyday speech (e.g. when interlocutors introduce themselves).

5.1.2.2.2.5 Computational diagnosis of schizophrenia using topological-kinetic parameters: first evidences

We subsequently developed a deep convolutional neural network model (Lecun et al., 1998; LeCun et al., 2015), and trained it based on image bands representing the topological-kinetic properties of the exchange. Two examples of data that were used to train the neural network are shown in Figure 5.8.

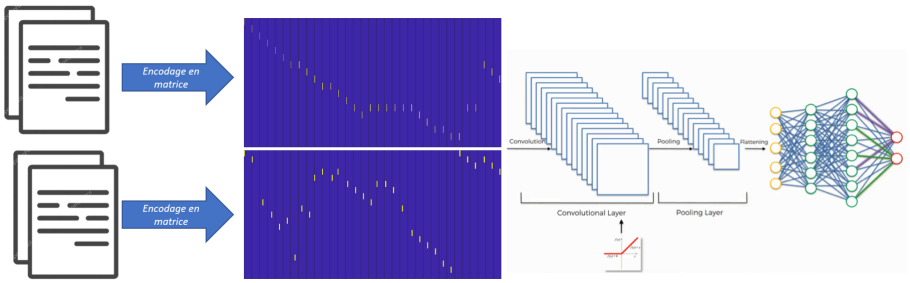

Figure 5.8: Training data generation procedure and architecture of the neural network used [Top: N02 (Control group); Bottom: MAY (Schizophrenic group)]. Adapted from (Eremenko & de Ponteves, 2022) with written permission from the authors.

The neural network was trained on the basis of the non-incidental corpora of 3 control subjects and 3 schizophrenic subjects, was able to correctly identify the remaining 4 subjects and belonging to the two previous groups (accuracy=1,sensitivity=1,specificity=1). In subsequent tests performed on the corpora of schizophrenic subjects treated with antipsychotic molecules, the neural network classified half of the subjects (n=2) as controls; and the other half (n=3) as schizophrenic, even though the topological deviation scores of these subjects were within the neurotypical norms. This observation opens up several possible explanatory hypotheses, such as a differential response to the treatment, the existence of an additional dimension that was not considered when the procedure was established, or simply the existence of a bias in the model, due to the small number of observations used to train it. In general, this experiment can only be considered as the first step in the construction of a proof of concept, since this type of architecture usually requires a massive amount of data. We could also consider that, as these models are usually trained on highly dimensionalized data, that reducing the information to elementary properties of the interaction would reduce the amount of data needed to build these decision models.

5.1.2.3 Contributions of interactional computational psychology to the discipline: conclusions

Using the topological deviation paradigm, derived from the 2TK model, we were able to perform a measure of coherence of thought at the dialogical scale, and showed that this measure not only allowed us to discriminate between neurotypical and schizophrenic individuals, but could also allow us to evaluate the impact of an antipsychotic treatment on coherence of thought from a measure performed at the scale of a dyadic interactive system and directly obtainable under minimal experimental or clinical settings (e.g. paper-pencil).

First, we showed that the populations could discriminate from the analysis at the scale of an individual, in particular at the graphical analysis of the combination of the three projections (i.e. real and theoretical) by observing a nodification of the themes, relative to the disorders of sequentiality described consensually, including in the diagnostic criteria of the fields of psychiatry (American Psychiatric Association, 2013) and a significant topological deviation between the real and optimized models.

We then confirmed these findings at the group level, comparing deviation measures in untreated schizophrenic subjects and controls, and showed that schizophrenics not only exhibited weaker coherence in discourse sequentiality; but also produced more inserted sequences, significantly slowing down the actual progression of dialogue.

To our knowledge, and even if schizophrenic dialogue has been massively investigated since the initial works of (Chaika, 1974; Fromkin, 1975), and in all disciplines of linguistics and psycholinguistics (Fouqueré et al, 2021a; Musiol & Rebuschi, 2007; Musiol & Trognon, 2000; Musiol & Verhaegen, 2014; Verhaegen, 2007), including in atheoretical and unsupervised computational linguistics (Mota et al., 2012, 2017; Spencer et al, 2021), we believe that this work is the first to investigate the impact of coherence of thought on the interactive system in free dialogical situations on non-incidental sequences, and the effect of antipsychotic treatments on the same system; as well as to realize the measurement of the effect magnitude of dimensions that have been assumed to be shared between schizophrenics and neurotypical individuals since the first linguistic descriptions of schizophrenic speech; notably through methods that can be implemented directly on paper in experimental or clinical conditions.

Finally, we believe that in the light of these experiments, and in the context of clinical studies based on these results, these approaches could present

particularly interesting perspectives: for example, in the realization of dialogical measures on anamnestic data, and in comparing the obtained metrics to tables such as those that could be observed in psychometric factorial tables; or in their cross-analysis with cognitive or psychometric measures, using analytical statistics or computational methods.

5.2 Psychological diagnosis of Shwachman-Diamond syndrome

5.2.1 Intellectual efficiency

5.2.1.1 Intellectual Quotient

The results for both experimental groups on intelligence quotient scores measured on the WISC-V are showed in Figure 5.9. Shwachman-Diamond syndrome appears to have an impact on intellectual efficiency.

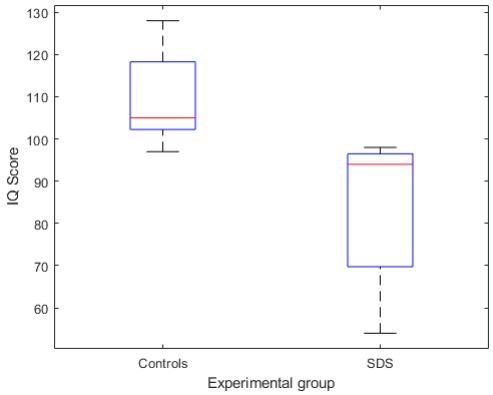

Figure 5.9: Total intelligence quotient for each experimental group

Two-way ANOVA revealed a significant effect of experimental group [$F_{(1,6)}$=6.1, p<.05], but no significant interaction was found.

These results suggest an impairment of intellectual efficiency in Shwachman-Diamond syndrome subjects independent of the patient's biological sex.

5.2.1.2 Composite scores

Results for both experimental groups on composite scores measured on the WISC-V are presented in Figure 5.10. Shwachman-Diamond syndrome appears to have an impact on intellectual skills, but not on cognitive skills.

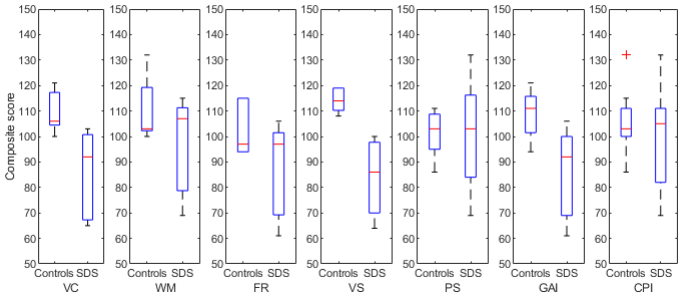

Figure 5.10: Composite scores measured with the WISC-V for both experimental groups.

Three-way ANOVA revealed a significant effect of the group [$F_{(1,40)}$=15, p<.001], as well as a marginal interaction between experimental group and measured dimension [$F_{(1,40)}$=3.3, p=.07].

Post-hoc analysis performed on the marginal group:dimension interaction using Tukey's test revealed a significant difference between the experimental groups for the general ability index [p<.001], but not for the cognitive competence index [p=.72].

These results suggest an impairment of intellectual abilities in Shwachman-Diamond syndrome subjects, but that cannot be attributed to global cognitive dysfunctions.

5.2.1.3 Unitary scores

The results for both experimental groups regarding unitary scores measured on the WISC-V are presented in Figure 5.11. Shwachman-Diamond syndrome seems to have an overall, but heterogeneous, impact on performance on the proposed tests.

The three-way ANOVA revealed a significant effect of the experimental group [$F_{(1,80)}$=23, p<.001], but no significant interaction was found.

These results suggest that Shwachman-Diamond syndrome produces a global impairment of intellectual functions, but with an heterogeneous presentation,

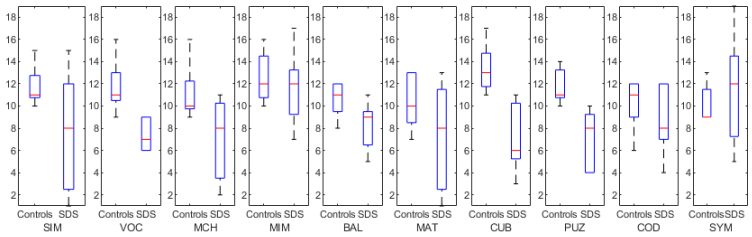

Figure 5.11: Unitary scores on the WISC-V tests for the two experimental groups.

suggesting a differential impairment depending on the patients or social setting.

5.2.2 Neuropsychological functioning

5.2.2.1 Attention and executive functions

The results for the two experimental groups regarding the attention and executive function scores measured at the NEPSY-II are presented in Figure 5.12. Shwachman-Diamond syndrome appears to have an overall, but heterogeneous, impact on performance on the proposed tests; as well as a differential and gender-related expression in the proposed attention tests.

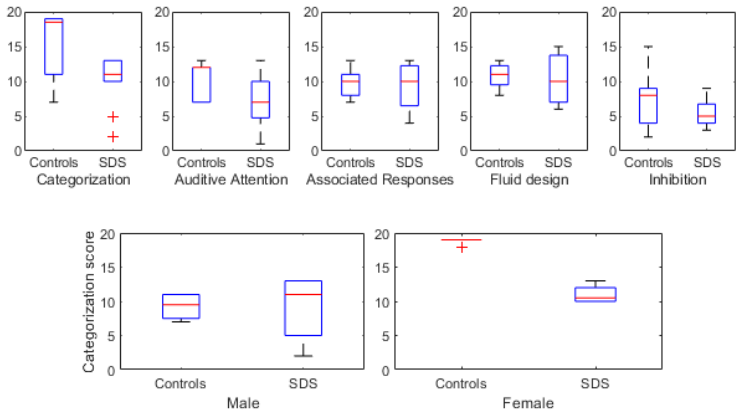

Figure 5.12: Results for the "Attention and Executive Functions" scale (NEPSY-II). [Top: Composite scores of each task for each group. Bottom: Scores on the "Categorization" test for each gender]

The three-way ANOVA ($score \sim group * gender * task$) revealed a signifi-

cant effect of experimental group [$F_{(1,76)}$=17.4,p<.001], and task [$F_{(1,76)}$=13.2, p<.001], as well as significant interactions between experimental group and subject gender [$F_{(1,76)}$=8.6, p=.004], task and subject gender [$F_{(1,76)}$=4.7, p=.001], and between task, group, and subject gender [$F_{(1,76)}$=3, p=.02].

Subsequent post-hoc analysis using Tukey's test showed an overall significant difference between the performance of female SDS subjects compared to their control counterparts [p<.001]; but not between male SDS subjects compared to their control counterparts [p=.94]. It did, however, show a homogeneous deficit performance in both genders and for the SDS group on the Categorization test, compared to the control counterpart group [p<.001].

These results suggest that the SDS pathology produces a heterogeneous impairment of attentional and executive functions, with a presentation that seems ubiquitous on all the proposed tests in the females, but remains circumscribed to the level of the Categorization test for the male subjects.

5.2.2.2 Social perception

5.2.2.2.1 Emotion recognition

The results for both experimental groups regarding emotion recognition scores measured at the NEPSY-II are presented in Figure 5.13. Shwachman-Diamond syndrome patients do not appear to have a deficit in facial emotion recognition.

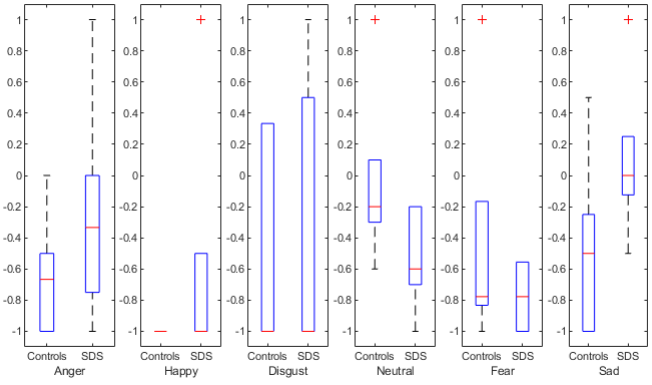

Figure 5.13: Error rates by emotion regarding the NEPSY-II "Emotion Recognition" subtest. Data were rescaled to a range of [-1;1] to allow for relevant statistical analysis and graphical observation.

The three-way ANOVA ($score \sim group * gender * emotion$) showed a significant effect of the emotion considered [$F_{(1,36)}$=2.8, p=.031], not associated with any other significant effect, nor with any significant interaction between the variables considered.

These results suggest that performance in emotion recognition varies according to the emotion considered, but that this difference is homogeneous between the two groups, which present similar performances on all the emotions considered.

5.2.2.2.2 Theory of Mind

5.2.2.2.2.1 Psychometric data

The results for both experimental groups regarding theory of mind scores measured on the NEPSY-II are presented in Figure 5.14. Shwachman-Diamond syndrome patients do not appear to have an overall deficit in theory of mind when compared to control subjects.

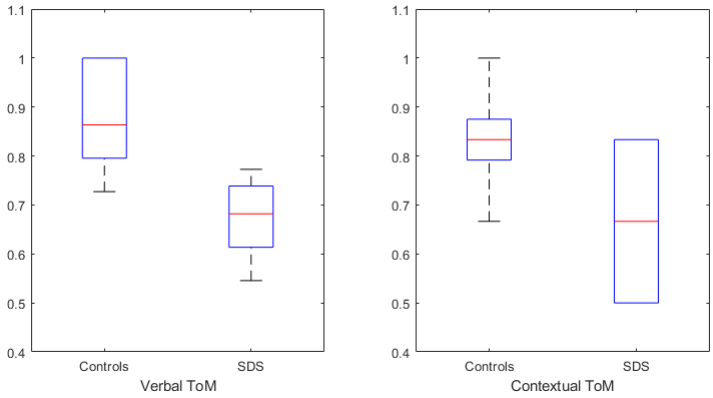

Figure 5.14: Subjects' performance on theory of mind tasks. Data were rescaled to an interval of [0;1] to allow for relevant statistical analysis and graphical observation.

The three-way ANOVA ($score \sim group*gender*scale$) revealed a significant effect of the experimental group [$F_{(1,36)}$=9.4, p=.009], not associated with any other significant effect, nor in the interaction between the variables considered.

These results suggest that theory of mind performance is impacted by patients with Shwachman-Diamond syndrome, homogeneously between verbal and

contextual dimensions.

5.2.2.2.2.2 The particular case of second-order mentalization

We will focus here on a particular item of the theory of mind battery and part of the "Seeing is knowing (False-belief)" category (Pratt & Bryant, 1990). In particular, it describes the ability of children, from the age of 3, to understand the well-known smartie box task, where if a person observes what is in a closed box, he or she will be able to know the contents, and to infer the impossibility of producing this knowledge for anyone who does not handle the box. Children with autism spectrum disorders are thus deficient in this type of task, and in all tasks involving higher levels of theory of mind (Baron-Cohen, 2000, 2001; Baron-Cohen et al., 1985; Baron-Cohen et al., 1986, p.; Lord et al., 2020; Swettenham, 1996).

The following figure (5.15) represents performance on this specific first-order mentalization task two conditions : the first condition (top) is a simulation generated from the above literature data, with the simulated control subjects exhibiting 100% of the time a correct response to this type of task; and simulated autistic subjects who would act randomly (with the two possible responses equiprobable) when exposed to these stimuli involving first-order theory of mind functions; the second condition (bottom) presents the performance of the two groups of subjects studied in the present work. The analysis showed similar performance between Shwachman-Diamond subjects and controls, which contrast with the simulated theory of mind condition as described in the literature.

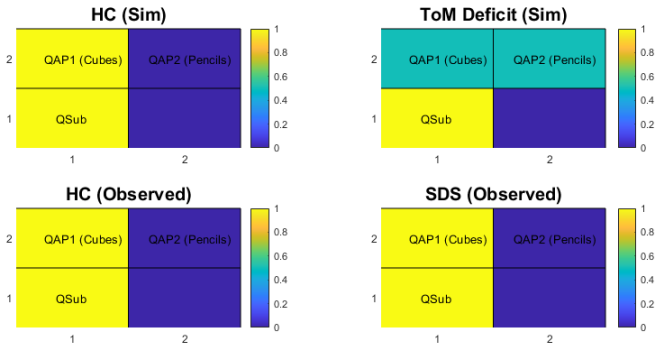

Figure 5.15: 2TK matrix representation of the exchange run probabilities regarding the NEPSY-II item discriminating first-order theory of mind. [Top: Simulation experiment. Bottom: data observed. Experimenter's question corresponds to position (x=1,y=1); correct response corresponds to position (x=1,y=2); and incorrect response corresponds to position (x=2,y=2)].

It can be observed in Figure 5.15 that control subjects showed similar performance to that predicted by the simulation, with 100% of the responses produced being on the $(x = 1, y = 2)$ locus. Interestingly, Shwachman-Diamond syndrome individuals, yet described as severely affected in theory of mind in the literature (Canton et al., 2016), showed similar performance to controls and discriminable from the pattern that theory of mind deficient patients should have exhibited.

These results are even more interesting if we focus on the second item of this sub-battery and presented as follows (Table 5.6):

Corpus
Remy and patrick wanted to ride the Ferris wheel
Audrey and Sabine didn't want to go on the Ferris wheel.
They decided to take a ride instead.
When the boys arrived at the Ferris wheel, the line was too long.
So instead they went to the haunted house.
When Audrey and Sabine's ride ended.
They went to get the boys.
Where should they go to get them: the haunted house or the Ferris wheel?

Table 5.6: Presentation of the second-order theory of mind item of the "Theory of Mind - Verbal Task (False belief)" subscale of the NEPSY-II "Social Perception" scale.

In this task, to produce the correct response, one must make the correct inference that Audrey and Sabine could not pick up the boys at the haunted house, since they do not have access to the information (available in the narrative) that the line was too long at the Ferris wheel, motivating the boys' decision to go to the haunted house instead.

The following figure (5.16) represents performance on this specific first-order false-belief task two two conditions: the first condition (top) is a simulation generated from data available in the literature and concerning this specific item, with simulated control subjects exhibiting 100% of the time a correct response to this type of task; and simulated autistic subjects who would act randomly (with the two possible responses equiprobable) when exposed to these stimuli involving second-order theory of mind functions in a false-belief situation; the second condition (bottom) presents the performances of the two groups of subjects studied in the present work.

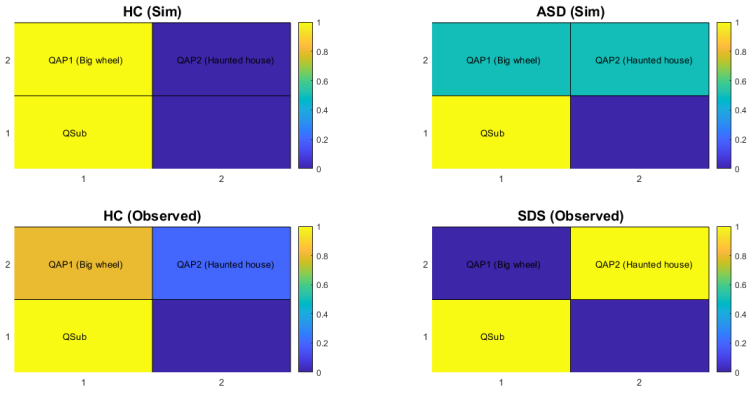

Figure 5.16: 2TK matrix representation of the exchange run probabilities regarding the NEPSY-II item discriminating second-order theory of mind in the false-belief condition. [Top: Simulation experiment based on data from (Loukusa et al., 2018). Bottom: observed data in the present study on control (left) and SDS (right) subjects. Experimenter's question corresponds to position (x=1,y=1); correct answer corresponds to position (x=1,y=2); and incorrect answer corresponds to position (x=2,y=2)].

It can be seen in Figure 5.16 that all the experimental conditions contrasted with each other with different patterns, including in the comparison of the control subjects with the simulation that had been performed. One control indeed produced an incorrect response, but this could be explained by primary atten-

tional difficulties, as supported by the joint analysis of this patient's results in the "Social Perception" and "Attention and Executive Functions" batteries, as suggested by the NEPSY-II manual. Similarly, subjects with Shwachman-Diamond syndrome presented a clearly discriminable response pattern to controls, with 100% of patients producing incorrect responses, thus showing a homogeneous feature in the presentation of Shwachman-Diamond syndrome, with a second-order theory of mind in false belief situations homogeneously dysfunctional, and contrasting with a first-order theory of mind homogeneously functional.

5.2.3 SDS versus negative control status: subjects' performance on cognitive tasks in comparison with artificial intelligence

5.2.3.1 Epistemological situation of the experience

By placing ourselves in a framework of understanding in terms of Global Network Workspace, current technologies could allow us to open new ways of understanding human pathologies: for example, by going through theoretical simulations, as done previously, to confront the experimental data acquired with models that attempt to generalize them, and then by confronting them with data acquired later in other settings. Current technologies now allow us to perform other types of simulation, and in particular simulations of pathological speech using artificial neural network models of language interaction such as GPT-3 (Floridi & Chiriatti, 2020) or Goofer (Winters et al., 2019).

Indeed, these language models are built according to a connectionist model on very large databases and whose responses are constructed probabilistically by predicting the most likely following characters relative to the intrinsic exposure context of the stimulus (T. B. Brown et al., 2020). Thus, based on the Workspace model, a framework in which the integrative abilities of humans are explained by the properties of the two computational hubs of the dorsolateral prefrontal cortex, and the anterior cingulate cortex; as described above ; one could make the prediction that by exposing this type of algorithm with a quasi-infinite knowledge base to verbal tasks requiring integration of the context to produce an adapted response, one would observe the same response pattern as that which could be observed in pathological contexts whose etiology is explained in part or in totality by dysfunctions in these two integrating centers.

Since patients with Shwachman-Diamond syndrome are affected at the level of these two computational hubs, it seems relevant to compare their performance with artificial neural network models that do not have these integrative cognitive properties. They could thus serve as a negative control allowing to observe the interactive presentation of the total dysfunction of these capacities, thus creating a performance gradient whose interval would range from the performances of the artificial neural networks (not possessing these capacities and thus creating a negative baseline) to the performances of the neurotypical subjects (supposed to carry these capacities).

5.2.3.2 Procedure

The experiment conducted in the control and SDS subjects and concerning the production of the two psychometric scores obtained from verbal data were replicated on the GPT-3 API in its most elaborate "Da Vinci" version. The "Similarities" and "Information" subtests of the WISC-V were administered to produce the verbal comprehension index; and the Theory of Mind-Verbal Modality subscale subtests of the NEPSY-II were administered to GPT-3. Each of these measures was administered 5 times (once per subject pair Controls/Shwachman-Diamond) in a simulated human-human interaction condition. In this experiment, the experimenter performed the test with the help of another experimenter who was an accomplice and whose function was to record the sequences produced by the evaluating experimenter; then to read the responses provided by GPT-3 in the most natural way possible, in order to reproduce the evaluation situation as well as possible.

5.2.3.3 Results

5.2.3.3.1 Psychometrics

The results for the four experimental groups on the Verbal Comprehension (WISC-V) and Theory of Mind - Verbal tasks (NEPSY-II) composite scores are presented in Figure 5.17. The results showed differential performance between the three groups specifically for Theory of Mind.

Concerning the verbal comprehension index (Figure 5.17, Left), the two-way ANOVA ($score \sim group * test$) showed no significant effect, indicating a homogeneous performance relative to the group and the test considered.

In contrast, regarding the performance on the theory of mind and verbal

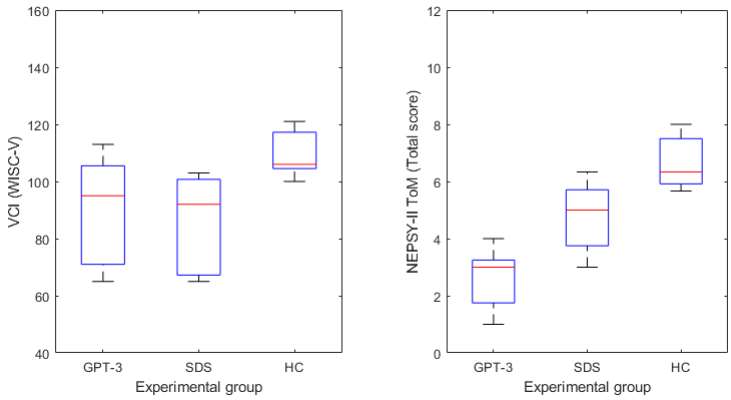

Figure 5.17: Differential performance of experimental groups on verbal comprehension (WISC-V; Left) and theory of mind (NEPSY-II; Right) tasks.

modality tests, the one-way ANOVA (score group) showed a significant effect of the experimental group [$F_{(2,12)}$=15.79, p<.001]. Subsequent post hoc analysis using the Tukey procedure revealed differences between all experimental groups, namely between GPT-3 and SDS [p<.001]; GPT-3 and Control [p<.001]; and between Shwachman-Diamond syndrome patients and Control as well [p<.001].

These results support an explanation of the pathological presentation of Shwachman-Diamond syndrome in Global Workspace terms, by suggesting an effect of the presence and functionality of the computational hubs of the Global Network Workspace in producing appropriate responses in theory of mind tasks.

These observations also present interesting clinical perspectives: indeed, one might conclude from these data that success on the Verbal Comprehension Index tests is not predictive of specifically human intellectual abilities, and whose measured performance would reflect the extent of semantic knowledge rather than the ability to apply verbal knowledge in a novel integrative context.

5.2.3.3.1.1 The particular case of second-order mentalization : second round

The following figure (5.18) represents the performance obtained by the three experimental groups on the two items measuring inference abilities in false-belief situations. All three groups showed highly discriminable and task-dependent performance.

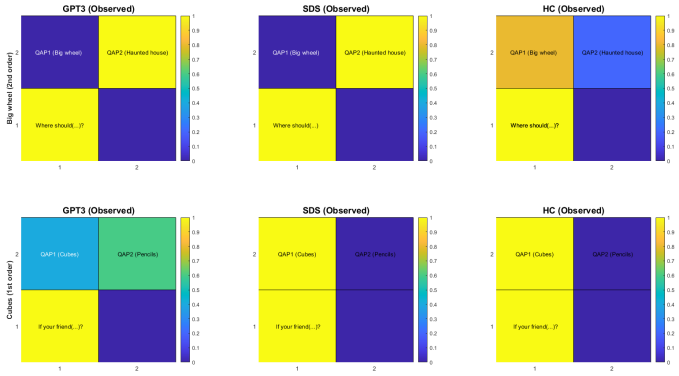

Figure 5.18: 2TK matrix representation of the probabilities of exchange progress regarding the NEPSY-II item discriminating theory of mind in false-belief situations. [Top: 2nd order; Bottom: 1st order. Experimenter's question corresponds to position (x=1,y=1); correct answer corresponds to position (x=1,y=2); and incorrect answer corresponds to position (x=2,y=2)].

Regarding the "Cube" item measuring 1st order theory of mind abilities, it can be observed that subjects with Shwachman-Diamond syndrome show similar performance to control subjects, where all participants from both groups answered the question correctly. In contrast, participants from the GPT-3 group showed near chance level performance, with a majority (60%) of incorrect answers.

On the other hand, and very interestingly, 2nd order theory of mind performance in the false belief condition was distributed differently across the groups. In this experimental condition, subjects with Shwachman-Diamond syndrome show similar performance on the artificial neural network in a homogeneous manner, differentiating them from the control group where only one error was measured at the group level.

Both of these group-wide measures are even more interesting when the results are polarized. These data suggest that, when performing the task involving 1st order functions, a decision based on lexical data leads in half of the cases to an erroneous response (Figure 5.18, Bottom Left). These data suggest that an additional inferential process is indeed necessary to succeed in this task, and that this inferential process is correctly performed by subjects with Shwachman-Diamond syndrome. In contrast, we understand that when performing the task involving 1st order functions, a decision based on lexical data will lead to an

incorrect answer 100% of the time (Figure 5.18, Top-Left). The similar performance measures observed in the GPT-3 and SDS groups thus suggest that the implementation of 2nd order functions requires a different integrative process than the 1st order theory of mind, suggesting the need for a differential contextualization of the different elements of the problem, whose integration could be located in one of the integrative centers of the Global Network Workspace, dysfunctional in subjects with Shwachman-Diamond syndrome, and absent from the GPT-3 artificial neural network; thus highlighting that subtle neuroanatomical perturbations at the level of these integrating centers are sufficient to produce a loss of this second-order inference function, in false-belief tasks.

5.2.4 Interactive functioning

5.2.4.1 Pragmatic functioning

5.2.4.1.1 Modeling and simulations of the TEST-ASAP "Basket" test

In addition to its analytical capabilities, the 2TK model can also be used to model tasks in experimental situations, as well as to perform simulations to make predictions. Here, we can observe the model of a task we have built, the TEST-ASAP, based on the work of (Gerardin-Collet, 1999, dir. Alain Trognon), an allowing to check the functionality of the pragmatic system in children. This task consists in trying to make the child perform a cooperative action by inducing him using indirect speech act, requiring the understanding of the implicit meaning. It thus consists in inducing cooperative action by an indirect speech act ; then in case of failure, to carry out another implicit stimulus ; and then in case of a new failure, to carry out an explicit stimulus, to control the factor of cooperativity. Thus, this task is making it possible to dissociate the deficit of the theory of mind (no access to indirection) and the disorder of cooperation (total refusal to cooperate). This particular "Pencil" task consists to give a pencil with lead cut to raz and sharpener without tank to the subject, and induce a behavior were the patient goes to get the papertrash using indirect speech-act. Three inductive sentences were prepared, from the most indirect "I give you this pencil and this sharpener, but there is no tank, so we need the papertrash to sharp it" to the most direct enunciation "Can you get the papertrash, please?", in order to know the level of induction which is needed to induce this cooperative behavior. The theoretical graph of the task is shown in

Figure 5.19.

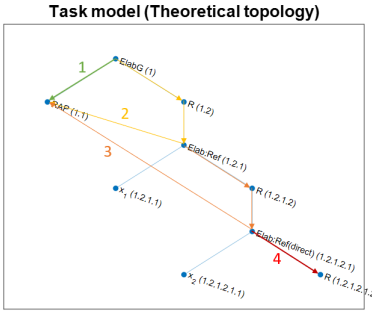

Figure 5.19: Theoretical topology of the TEST-ASAP "Pencil" subtask. (1): Success in 2 rounds. ; (2): An implicit restatement is necessary. ; (3): An explicit retry is necessary (theory of mind deficit). ; (4): Failure of the task (cooperative deficit).

We then performed simulations based on this theoretical model of the task, considering 4 possible groups: control group (n=100), theory of mind deficit group (n=100), cooperation deficit group (n=100), SDS group (n=100), based on data from (Batt et al. 2017). Simulations are shown in Figure 5.20.

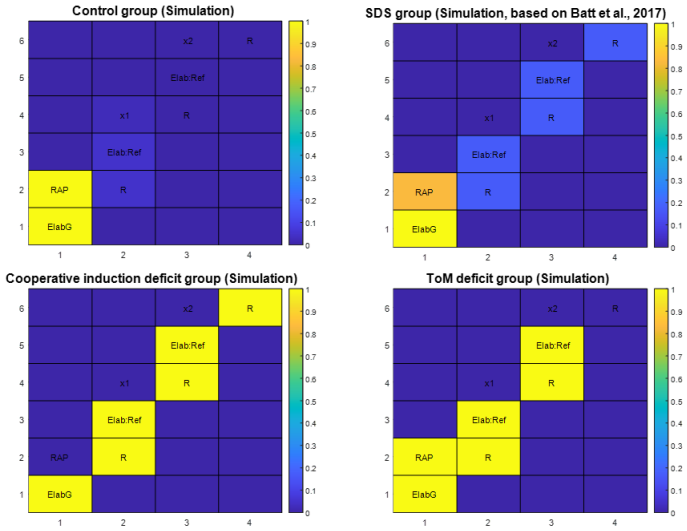

Figure 5.20: Matrix representation of the TEST-ASAP "Pencil" subtask. Each pair of coordinates corresponds to the probability of being at a given position at least at one stage in the interaction, according to the theoretical experimental group

We considered that the controls would access the request directly 95% of the time, with a 5% chance that an event would occur during the induction and produce an attentional break requiring a single restart. On the other hand, it was considered that in the case of a deficit in the theory of mind, one would need to go to the explicit direct request before the realization of the cooperative action in 100% of the cases, thus prolonging the duration of the interaction before the realization. In the case of the cooperative deficit, it was estimated that the task would fail 100% of the time, also prolonging the interaction. Given that the task was designed to be performed in Shwachman-Diamond Syndrome subjects, the topic of my thesis, the results were simulated from the data of (Batt et al. 2017), although the data were collected in a simpler setting, and where 83% of the subjects responded directly to the implicit stimulus and 17% who presented a total refusal. The results obtained in an autistic subject (Gerardin-Collet, 1999, dir. Alain Trognon) and in a Shwachman-Diamond syndrome subject (evaluated during this thesis), are presented in Figure 1.9.

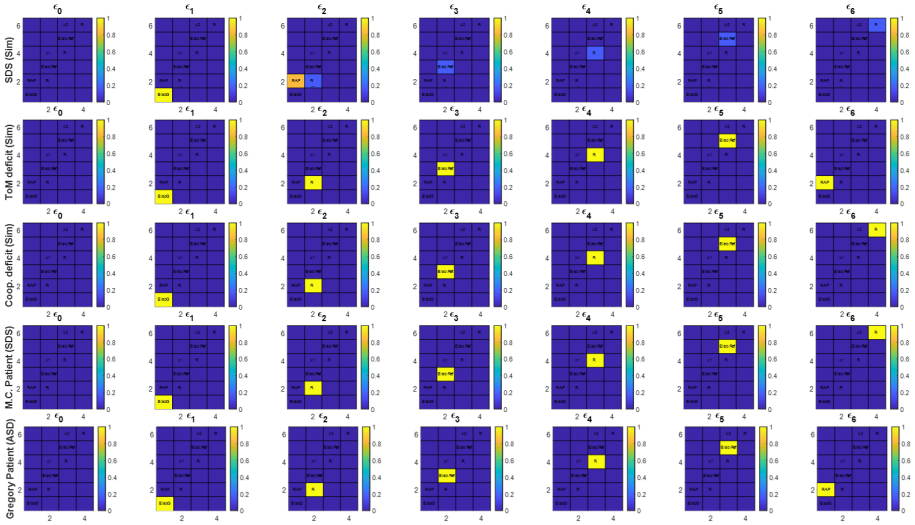

Figure 5.21: Matrix representation of the TEST-ASAP "Pencil" subtask. Each matrix is one unit of time representing the probability of being at a given position at one given unit of time. From the top to the bottom : SDS (Simulation) ; Theory of Mind Deficit (Simulation) ; Cooperation Deficit (Simulation) ; M.C. Patient (SDS - Real Observation) ; Gregory Patient (ASD - Real Observation)

We can see here that the real observations were all cases predicted in the model. The superposition of the simulations and the observations allows us to

conclude that there is a deficit in the theory of mind in the autistic subject (which is already well accepted in the literature, (see Baron-Cohen, 2000)), and that there is a deficit in cooperation in this SDS subject, who thus showed a typical Shwachman-Diamond syndrome trait predicted by the simulation as well.

5.2.4.1.2 Insights from the TEST-ASAP

The results concerning the topological-kinetic measurements of the TEST-ASAP and concerning the two groups are available in Figure 5.21. The data showed discriminable behavior between the two groups, with more homogeneous behavior in the Shwachman-Diamond syndrome group.

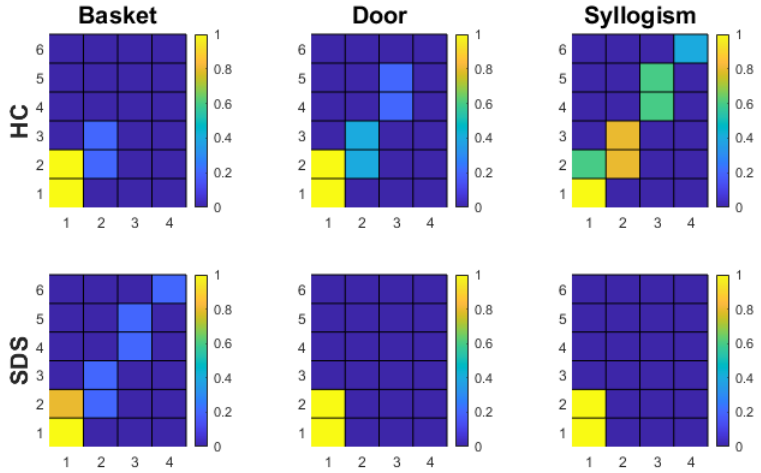

Figure 5.22: Results of the TEST-Asap and concerning the two groups in 2TK projected in matrices. Each cell of the matrix represents a topological position and the associated color gradient corresponds to the probability of passing over this position at least once during the interaction.

Regarding the "Basket" subtest, the two groups showed differentiable performance, but this could be predicted by the simulation performed. 4 out of 5 controls immediately satisfied the indirect language act of fetching the trash can, and one of them made the request to repeat the instruction (had not listened). The SDS group behaved similarly, with the exception of one particular male patient who completely refused to perform the task, even after a direct prompt, showing a notable refusal to cooperate.

Concerning the "Door" subtest, the two groups showed almost opposite behaviors: while in the SDS group, the patients systematically got up to go and close the door after the indirect induction, in the control group, it was necessary to almost systematically reiterate the request in the indirect mode, inducing then a question from the child of the type "Do you want me to go and close the door?"

Finally, the "Syllogism" subtest showed opposing patterns in its entirety: whereas in the SDS group, the subjects got up instantly as soon as the end of the task was announced to go and get their parents to go and eat, the control subjects tended to remain inhibited and to wait for further instructions from the experimenter, even going as far as a total refusal to satisfy the speech act, even though it was successful, as the control child remained waiting to be escorted by the experimenter into the waiting room.

The triple dissociation made possible by the TEST-ASAP makes it possible to assess the granularity of SDS cooperation: as a reminder, the subtask "Bin" makes it possible to assess the propensity for cooperation when the cooperation procedure is clearly explicit, but its realization is not a necessary condition for solving the goal associated with the subgoal of sharpening pencils (i.e., using the pencil in its poorly sharpened pencil state). Thus, there is no direct benefit to cooperating for the patient, other than to satisfy the experimenter's request. In contrast, the "Door" subtask assesses the propensity to cooperate when the cooperative procedure is implicit but requires only one level of inference to process the indirection (i.e. who the inductive act is directed to) and produces benefits for both interlocutors (i.e. there is no longer a draft), in addition to satisfying a social norm (i.e. the door is closed when with a health care professional). Finally, the subtask "Syllogism" allows to assess the cooperation propensity when the cooperation procedure is explicit, and the benefits are only at the patient's level (i.e. the patient will take a break, will go eat and relax). On the other hand, in this test, the immediate satisfaction of the speech act, the conclusion of the pre-induced premises (i.e. 1. "when this test is over, you can get up to go get your parent and go eat"; 2. "there, we finished this test!") requires to transgress a social rule (i.e. one does not get up before having the agreement of the health professional). Thus, in the cross-reading of these three tests, we understand that the behaviors of SDS patients are spectral and should depend on the interactive context when the benefits are low for the subject; with a propensity to cooperate that increases as a function of the expected benefits for the subject. On the other hand, the performances do not seem to depend on

the level of indirection and thus seem to be only related to the economic aspect of the interaction; all the more so as the value of the perceived benefits seems to be higher than that of the social norms in use, as evidenced by the lifting of the social inhibition observed in the "Syllogism" subtest

5.2.4.2 Pragmatics and dialogical strategy: towards an economic perspective

The case of the young AG is interesting because it illustrates the difficulties that parents may encounter in certain interaction situations, such as the completion of homework. Indeed, the completion of homework is often a source of intra-family conflict in the context of Shwachman-Diamond syndrome, with parents often evoking ill-willed behavior. Just before the start of this sequence, which represents the completion of the first nine items of the WISC-V "Comprehension" subtest, the patient expressed her disappointment that an additional exercise separated her from the break she was going to have for lunch (Table 1.7):

Locutor	ϵ	**Enunciation**
AG	-5	Hey hey hey so we have one more and then we're almost done
AG	-4	Oh no!
Exp	-3	Yeah that's good
Exp	-2	In any case with the tablet we will have finished...
AG	-1	No! And I don't have one left, I have several!

Table 5.7: Exchange that preceded the initiation of the "Comprehension" subtest of the WISC-V.

5.2.4.2.1 Convergence of interlocutors

The results for the dialogue backed by the "Comprehension" subtest and concerning vergence for interlocutor and the task are presented in Figure 5.23. They illustrate how envy and motivation translate into dialogue management, especially in the context of Shwachman-Diamond syndrome.

The performance of the subtest "Comprehension" was particularly delicate because of the numerous spontaneous comments made by the patient and related in a more or less pragmatic way to the thematic contents of the items. Indeed, from the first item of the subtest, a very large quantity of spontaneous

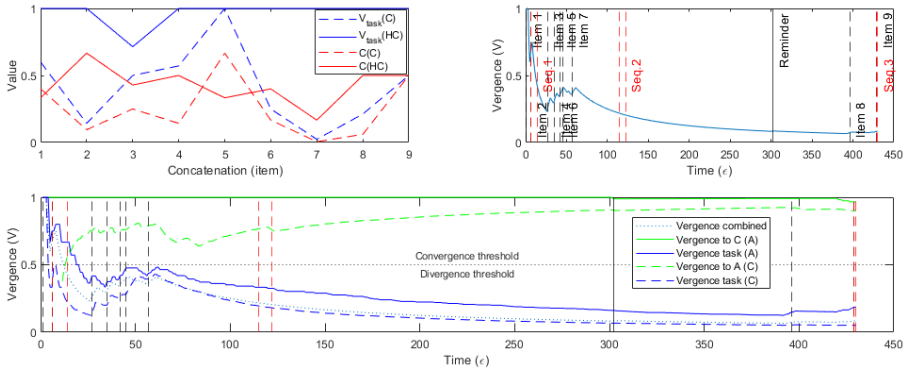

Figure 5.23: Kinetic analysis of the Experimenter-AG interaction during the WISC-V Comprehension subtest in 2TK. The top left figure presents the vergence and celerity values obtained for each item (encoded as a concatenation) in the patient (hatched line) and in her matched control (solid line). The top right figure presents the interaction-wide vergence measure for subject AG and denotes the clipped sequences. The bottom figure represents the vergence according to two parameters: the vergence to the task (i.e. if the speech act is directed towards its resolution: in blue); and the vergence to the interlocutor (i.e. if the speech act allows to prove the last concatenation ratified by the interlocutor) ; in full line for the experimenter and in dashed line for the subject.

comments were formulated after ratification of the answer formulated by the subject, making the vergence of the first concatenation fall to 0.6 (i.e. 40% of the acts were not directed towards the resolution of the task), then to 0.15 for the second concatenation, thus showing an important divergence of the dialogical system towards the task in progress (Figure 5.23, Left and Right, Seq.1 on Table 5.8) :

Locutor	ϵ	Enunciation
Exp	6	Why can't you pet a dog you don't know?
AG	7	Otherwise it bites you if it is mean
Exp	8	Yeah that's good
AG	9	Because otherwise it bites your cheek
AG	10	That's what daddy when he was young if he had seen a dog that was very bad
Exp	11	Yeah
AG	12	And he wanted to pet it
AG	13	And then he had his cheek bitten

Continued on next page

Table 5.8 – continued from previous page

Locutor	ϵ	Enunciation
AG	14	And so we sewed him up

Table 5.8: Corpus associated with Seq.1 in Figure 1.23.

Thereafter, the experimenter tried to close immediately the subtopics opened by the patient, which made it possible to raise the vergence to an optimal level of convergence at the level of the 5th item (V=1, Fig.5.23, Left). However, this level could not be maintained during the next question where the vergence dropped again significantly (V=.25, Fig.5.23, Left). Moreover, at the level of the next item, the patient was able to connect a personal anecdote to the thematic field of the question (i.e. the emergency numbers), which she exploited from one step to the next in order to monopolize the dialogic system, up to a point where the patient was totally unaware of the interventions of her interlocutor (Figure 5.23, Right, Seq.2, Table 5.9).

Locutor	ϵ	Enunciation
CG	115	then we have Marie Helene she called late
CG	116	and then twice the EMS
CG	117	EMS and the second time they say
CG	118	"but what is actually going on"
CG	119	we said "no no it's fixed".
Exp	120	Hey, hey, hey, hey, come on, we've got five minutes left, let's do the ones that are left?
CG	121	so it's normal that Claire goes no more on the table
CG	122	Marie-Hélène does it but only on the scale

Table 5.9: Corpus associated with Seq.2 in Figure 5.23.

Subsequently, the patient was so engaged in the elaboration of her ancillary themes that she completely forgot about performing the task (Fig 5.23, Right, Seq.3, Table 5.10), thus breaking the communicative link and motivating the abandonment of the task performance by the experimenter to set up the lunch break.

Locutor	ϵ	Enunciation
Exp	429	so why is it good for kids to help with chores [trad : tâches ménagères] around the house?
CG	430	uh what about the shelf [trad : étagère]?

Table 5.10: Corpus associated with Seq.3 in Figure 5.23.

The comparison with the matched control subject is even more stringent, especially when the information provided by celerity is brought to the analysis. Indeed, celerity measures only the performative aspect of the task, through the measurement of the sequences that were decisive in the resolution of the task (i.e. the expected question-answer pair, without the other sequences). The vergence measures the directionality of the speech act towards an element of the dialogical system, in this case the resolution of the task in progress (i.e. it keeps the additional elaborations, provided that they have been formulated before ratification of the correct answer). In fact, we observe that in the case of CG (C), decreases in speed are almost always accompanied by a decrease in vergence (Figure 5.23, Full Lines), because of two types of occurrence: additional elaborations that took place after ratification of the given answer, and therefore after closure of the concatenation in progress (i.e. the item; Seq.1); or divergences that have no connection other than semantic with the task in progress (Seq.2).

In the case of the control subject (HC), the vergence towards the task is almost always at its optimal level (V=1), except at the level of the 3rd concatenation where the interlocutors diverged: indeed, the experimenter ratified the subject's response prematurely, which led to an interruption of his next speech

act (due to topic closure, thus producing a first divergence between speakers), which subsequently again ratified topic closure following the subject's lack of utterance completion (and thus producing a second divergence between speakers, Seq. HC1). It is important to note that celerity was already low in this sequence and at this concatenation (Figure 5.23, Top-Left, Concatenation 3) due to an environmental element (noise) that disrupted the utterance of the question, and likely disrupted the rest of the sequence (Table 5.11).

Locuteur	**Epsilon**	**Enunciation**
Exp	10	why do we use calendars?
HC	11	[noise is heard in the room] well... why what?
Exp	12	why do we use calendars?
HC	13	well to know what day it is
Exp	14	mhm
HC	15	and...
Exp	16	ok

Table 5.11: Corpus associated with concatenation 3 and obtained from control subjects. All speech acts are represented.

However, and in general for the other concatenations, the additional elaborations were produced before ratification of the correct answer by the experimenter, thus showing a high convergence between the interlocutors. Subsequent tests of correlation between vergence and celerity measurements were performed given all concatenations and for both subjects. Vergence and celerity were found be strongly correlated over the Shwachman-Diamond subject [$r_{(7)}$=.87, p<.001] ; but not in the control subject [$r_{(7)}$=.008, p=.98]

5.2.4.2.2 Strategic management of the dialogue and training of the experimenter outside the framework of the current task

The sequence is all the more interesting as it also shows how AG managed to strategically use the dialogic system to precipitate the termination of the task at hand. Indeed, from the first concatenation, we observe that AG's vergence towards the task and towards his interlocutor pass the divergence threshold at ϵ=5 (Figure5.23 ; Below). Furthermore, and even though the vergence towards the experimenter was able to rise to the convergence threshold at ϵ=14, the vergence towards the task was never able to pass this threshold again, thus

showing a deficit of cooperation towards the resolution of the current task. Moreover, AG succeeded in dragging the experimenter into this divergence: indeed, the experimenter being in a listening role and looking for discursive elaboration, he always tried to remain convergent with his interlocutor (as shown by the vergence of the experimenter towards AG which remained almost entirely constant at the value of V=1, except when he tried to refocus the subject towards the task). This maintenance of the dialogical link, and thus of the convergence between the interlocutors, was done at the cost of the experimenter's vergence towards the task, which passes the divergence threshold at ϵ=21 (i.e. as early as the second concatenation), which he will never manage to bring back up to the convergence threshold, in spite of several attempts which are identifiable by the subtle decreases of the experimenter's vergence towards AG.

In the dialogical game that took place, the intrinsic context of the experimenter was, among other things, a temporal constraint (the time for the subjects to take the tests was very limited due to the schedule of a train to be taken), so we can imagine that he did, during this sequence, everything in his power to focus the subject on the task, which he had to complete in a minimum of time. He failed in this endeavor, however, getting drawn into the patient's digressions in an attempt to maintain the dialogic link, ultimately leading to the premature termination of the task, and thus the success of the subject's abstraction from its completion.

5.2.4.2.3 The effect of the relaunch: empirical evidence of the divergence between the goals of the interlocutors

Here we will focus on a very short section of this dialogue. The 7th concatenation (i.e., item 7) was highly charged with the patient's personal anecdotes, producing very little convergence (Figure 5.23, Left). During this concatenation, a reminder was given to the patient, indicating that the experimenter was in a particular hurry, and that there was a need to speed up the pace by refocusing the interaction on the task (Figure 5.23, Right, ϵ=302).

Locuteur	**Epsilon**	**Enunciation**
Exp	302	We really need to finish now because I'm gonna take the train.

Table 5.12: Speech act produced at ϵ=302 (Reminder on the Fig.5.23)

Normally, this statement should have produced a particular effect on the

dialogic system because of its form, which may allow the statement to be interpreted as a reprimand; as well as because of the final justification, which should have increased the patient's cooperativeness according to Gricean principles.

In order to verify this claim from a computational point of view, an artificial neural network (Recurrent Neural Network) was trained specifically on this interaction in order to predict the vergence of the interlocutors on time series. The neural network was trained by the dynamics of this single interaction, from the first speech act (ϵ=1) to the reminder (ϵ=302), and then it was asked to predict the continuation of the interaction, allowing it to correct itself every three speech acts (Figure 5.24).

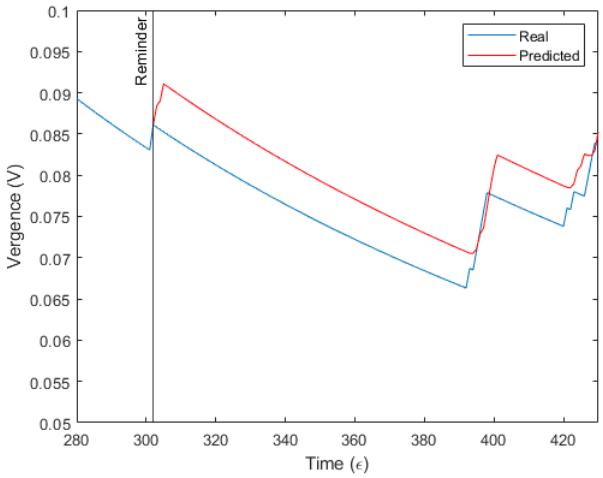

Figure 5.24: Prediction of the effect of reminder by a trained Recurrent Neural Network on the vergence values of the first 302 speech acts.

In Figure 5.24, we can clearly see that after induction, the reminder should have allowed refocusing on the task by producing an increase in vergence (Figure 5.24, red curve). However, we can clearly observe that it had no effect on vergence (Figure 5.24, blue curve), which continued to decrease significantly, suggesting a strong divergence between the goals pursued by the interlocutors and an absence of cooperativity from the patient.

5.2.4.3 Cooperation and interactive engagement: the effect of cost

The second unitary case that we present here, MC, also helps to illustrate the difficulties encountered by Shwachman-Diamond syndrome patients caregivers and

teachers in situations of cooperative interactions with an unequal benefit/cost balance between the interlocutors. This example also allows us to illustrate in a more detailed way the effect of the difficulties of integration of the elements of the context by the Shwachman-Diamond syndrome patient to produce adapted responses. In general, all the elements highlighted in this subject can be explained by economic parameters in terms of cognitive cost and motor cost. We present in Figure 5.25 the results obtained during three sections of interaction: the interaction that took place during a cooperative task (the basket, not cognitively costly and requiring active motor cooperation); the interaction that took place during a cognitive task (the performance of the subtest "Image Memory", cognitively costly but not requiring cooperation); and the interaction that took place in a free dialogue situation (i.e., a control situation, not cognitively costly)

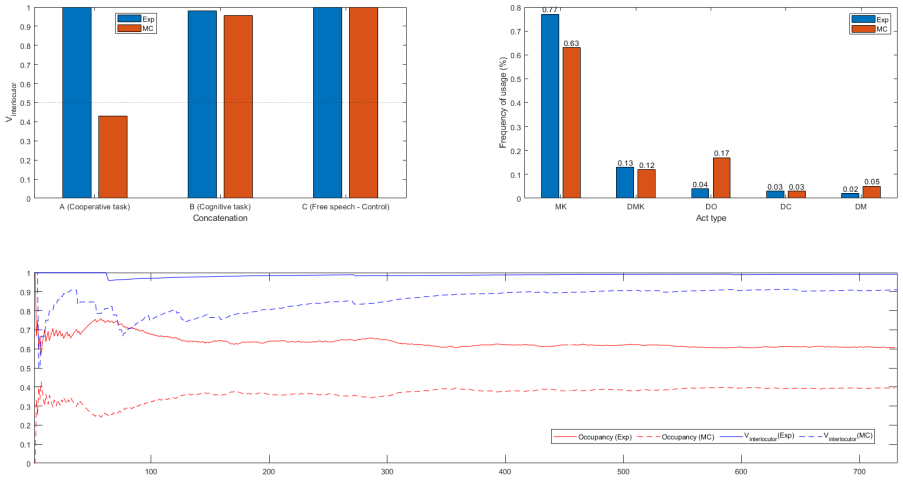

Figure 5.25: Pragmatic and kinetic analyses of the Experimenter-MC interaction in 2TK. The top left figure represents the vergence values towards the interlocutor in three situations: in a cooperative task situation (A: basket); in a cognitive task situation (B: WISC-V "Image Memory" subtest); in a free dialogue situation (C). The top right figure represents the frequency of speech act use for each interlocutor [MK: Make-Know; DMK: Do Make-Know; DO: Do; DC: Do Can; DM: Do Must]. The bottom figure represents the vergence towards the interlocutor (blue) and the rate of occupation of the dialogic space (red), for both interlocutors: hatched for the patient and solid line for the experimenter.

5.2.4.3.1 The economy of reactive action and the avoidance of cooperative engagement

The results concerning the frequency of use of the types of speech acts and for each of the interlocutors are available in Figure 5.25 (Top-Right). The results showed discriminable usage rates between the two interlocutors. In general, we can observe that both interlocutors ask the same number of questions (DMK% : Exp=.13 ; MC=.12) and produce the same rate of requests formulated as an invitation to cooperate (DC% : Exp=.03 ; MC=.03). Interestingly, we notice that the profiles start to dissociate at the level of the speech acts allowing the elaboration of the discursive situation: namely, the MKs and the DOs, which have the same properties but one of which is situated at the level of the motor action and the other at the level of the verbal production. It is interesting to note that the experimenter produces more information on the verbal level (MK%: Exp=.77) than on the motor level (DO%: Exp=.04); in contrast with the SDS patient who produces, from a ratiometric point of view, much more information on the motor level (DO%: MC=.17) than on the verbal level (MK%: MC=.63). Interestingly, if we add up the rates of these two types of acts, we observe similar frequencies of use between the two interlocutors (DO%+MK%: Exp=.81; MC=.8).

In general, we could ask ourselves about the reasons for this observed difference in the frequency of use of elaborative acts. An explanatory hypothesis could be found in the cognitive cost necessary to produce the response. It seems to be less costly to respond with an action or a gesture than to elaborate a response that is both relevant and adapted to the interactive setting. This hypothesis is reinforced by observing the occupancy rate of the interactive space and the vergence (Figure 5.25, Bottom), where we notice that the majority of the dialogic field is occupied by the experimenter (who is however only explaining the tasks on the majority of the corpus; red lines), and whose vergence at the scale of the interactive system seems to be maintained in full thanks to the experimenter (Figure 5.25, Bottom, blue lines). Looking back over the corpus, we can observe that the majority of the sequences produced by the patient were of a reactive nature, mostly through the production of laughter or sighs, as evidenced by the following sequence having taken place during a drawing activity requested by the subject in order to rest between the performance of the two batteries (Table 5.13).

In this section, the experimenter seeks to obtain an evaluation of his drawing from the patient. We can thus observe from the first formulation of the evaluation request that the interlocutors, although involved in the same task,

Locuteur	Epsilon	Enunciation
Exp	127	well I'm not bad ?
MC	128	huh ?
Exp	129	I'm not bad?
MC	130	[laughs]
Exp	131	no I'm not bad ?
MC	132	huh....
Exp	133	I don't know, do they normally have shoulder pads?
Exp	134	they are a little big there but...
MC	135	[laughs]

Table 5.13: Example of a corpus where MC uses reactive actions to reduce the cost of interaction, but cooperation remains minimal.

do not seem to converge between them. The subject thus does not seem to understand the formulated request, even though this subject has produced satisfactory performances in theory of mind tasks involving this level of inference. Two observations can then be made: firstly, the request is never satisfied (and no sequence can prove its success either, despite the inference that can be made about the laughter that followed); and secondly, no sequence allowed the interlocutor to make significant progress towards his goal, despite the fact that the interlocutor asked the subject several times. Thus, the difficulties of obtaining effective cooperative interaction with patients with Shwachman-Diamond syndrome can be observed once again; particularly in the need to repeat inductions to obtain information of a verbal rather than gestural nature.

5.2.4.3.2 Social disinhibition and directivity

During the analysis of the subtests of the SAT-ASAP, and in particular in the subtask "Syllogism", we began to outline the features of a certain social disinhibition, which can take the form of transgressions of commonly accepted social norms when benefits are expected (Table 5.14).

Concerning the MC patient in particular, we have already highlighted that the rate of occupation of the dialogic space was relatively low in this subject (Figure 5.25. Bottom, red line), and that the frequency of use of acts producing information seemed to be discriminable with respect to his interlocutor (Figure 5.25, Top-Right). On this same figure, we can make a second interesting observation: the subject produced more than twice as many speech acts of the "Do Must" type, representing the formulation of a direct order without a proposed

Locuteur	Epsilon	Enunciation
Exp	362	well, we're done for the morning
Exp	363	cool
Exp	364	we were quick
Exp	365	it's good
MC	366	you draw a footballer now
Exp	367	ah you want to make me suffer in fact
MC	368	yeah

Table 5.14: Example of a section where the subject makes inappropriate use of Do-Must speech act.

alternative (DM%: Exp=.02; MC=.05). This observation is all the more interesting as the measurement was carried out over the entire WISC-V run (where the experimenter produces a large quantity of DMs during the administration of the items), highlighting that the subject does not respect the social conventions normally observed in an interaction between a health practitioner and a young patient (where asymmetry is particularly important).

5.2.4.3.3 The effect of personal economic value in cooperative propensity

Results regarding the effects of personal economic value in cooperation are available in Figure 5.25 (Top-Left) and Tables 5.15, 5.16, and 5.17. Data showed a strong impact of the interactive context on convergence between interlocutors.

Locutor	ϵ	Enunciation
MC	6	Are you... do you work here?
Exp	7	not at all
Exp	8	I don't even live here
Exp	9	I drove 400km this morning to come
MC	10	oh
Exp	162	I don't even know...[we hear someone playing guitar and singing in the hallway] f*** is he still here?
MC	163	[laughs]
Exp	164	you won't tell your mother I said bad words
MC	165	[laughs]
MC	166	yes
MC	167	[laughs]
MC	168	you are too funny frankly
Exp	168	ah thank you it's cool

Table 5.15: Example of interaction obtained in a free dialogue situation. The concatenation concerned a guitar player present in the hospital corridor at the time of the evaluation. It is discontinuous since the concatenation was reopened each time the musician was heard. The portion involved 13 speech acts out of the 37 total in the concatenation.

In this example presenting an interaction obtained in a free dialogue situation (Table 5.15, not cognitively expensive), we can observe a strong convergence between the interlocutors (Figure 5.25, Condition "C"; V_{int}: Exp=1; MC=1). We can also observe that the dialogic terrain seems to be occupied in a relatively homogeneous way, despite the DO/MK production that contrasts between the interlocutors and that has already been described previously.

In this second example presenting a section of interaction having been ob-

Locutor	Epsilon	Enunciation
Exp	286	look it right, ok ?
MC	287	yeah
Exp	288	ok good
Exp	289	ok
MC	290	all the old stuff there
Exp	291	yeah
MC	292	ok nice
MC	293	planet shoe alarm clock star planet shoe alarm clock star ok
MC	294	planet shoe alarm clock star ok
MC	295	nice
MC	296	hourglass... heart cube
MC	297	hourglass kite cube heart
Exp	298	ok nice

Table 5.16: Example of interaction obtained in a cognitive task situation. The concatenation concerned the performance of the WISC-V "Picture Memory" subtest. It is contained since the concatenation was not reopened after its closure and the example concerns 13 speech acts out of the 101 total of the concatenation.

tained in a cognitive task situation (Table 5.16), we can also observe a strong convergence between the interlocutors (Figure 5.25, Condition "B"; V_{int}: Exp=.97; MC=.98). Here, the dialogic field is mostly occupied by the subject, and in particular by his subvocal repetitions of the test items.

The corpus of the last example concerning the interaction obtained in the cooperative task situation are shown in Table 5.17. Results are particularly interesting and contrasts with the measurements made in the other situations (Tables 5.15 ; 5.16).

The result is a clearly differentiable vergence towards the interlocutor between the two interlocutors (Figure 5.25, Condition "A"; V_{int}: Exp=.1; MC=.4). In this condition, the convergence between the interlocutors is so low that the values measured in the patient fall below the divergence threshold (V<.5), highlighting that less than one out of every two speech acts produced by the patient provide evidence of concatenation resolution.

We can therefore conclude from these three points of observation that the interactive engagement of this patient depended on two critical parameters: the estimated cost of producing the interactive sequence, relative to the expected benefits; and the interactive context of the exchange, especially in the direction of the expected benefits.

Locuteur	Epsilon	Enunciation
MC	65	do you have any colored pencils?
Exp	66	colored pencils?
Exp	67	yeah I do
MC	68	[MC sings]
Exp	69	but the lead isn't in a good state
Exp	70	so I'll give you a pencil sharpener
Exp	71	but you need the basket to put the cuttings
MC	72	it's okay
MC	73	[MC presses hard on the pencil to get the lead]
MC	76	[MC sings]
MC	77	it doesn't color the way I want
Exp	78	how do you want to color?
MC	79	the shield
Exp	80	[laughs]
MC	123	well I didn't color like I wanted because it wasn't cut
Exp	124	well prune it
MC	125	oh my knight he is too hot
MC	643	make the pants
MC	644	I want to see the pants
Exp	645	could you get me the basket then you by chance?
MC	646	huh ?
Exp	647	could you get the basket, by any chance?
MC	648	which basket?
Exp	649	to uh put the cuttings
Exp	650	so I can color it
MC	651	What's Nike looks like again?

Table 5.17: Example of interaction obtained in a cooperative task situation. This discontinuous concatenation concerned the break time when the interlocutors engaged in a drawing activity at the patient's request. All 26 speech acts of the concatenation are presented.

5.2.5 Conclusions and differential diagnosis

The overall findings to establish the differential diagnosis are presented in Table (5.18 ; 5.19) and Figure 5.26.

Regarding intellectual efficiency, the data showed that individuals with Shwachman-Diamond syndrome were particularly affected in integrative intellectual dimensions (i.e., subtests measuring the GAI), in contrast to preserved cognitive intellectual dimensions (i.e., subtests measuring the CPI). This measure is differentiable from those obtained in other populations with neurodevelopmental

disorders such as autism, attention deficit disorder with or without hyperactivity, where GAIs are higher than CPIs; and differentiable from control individuals and those with specific learning disorders where GAI and CPI measures are equivalent (Table 5.18).

Clinical condition	Composite measures
ADHD-I (Becker, 2021)	IAG > ICC
Learning Disorders (LeCerf, 2016)	IAG > ICC
SLD (Cornoldi, 2014)	IAG = ICC
Borderline Intellectual Functioning (Breuer, 2011)	IAG = ICC
ADHD-C (Breuer, 2011)	IAG > ICC
ADHD-I+SLD (Breuer, 2011)	IAG > ICC
ASD (Styck, 2019)	IAG > ICC
SDS (in the present work)	**IAG < ICC**
Controls (in the present work)	IAG = ICC
Controls (LeCerf, 2016 ; Becker, 2021)	IAG = ICC

Table 5.18: Differential diagnosis of Shwachman-Diamond syndrome on the intellectual level.

Regarding social cognition and cooperativeness, the data showed that individuals with Shwachman-Diamond syndrome had a discriminable profile compared to control subjects and subjects with autism spectrum disorders (Table X). Indeed, the literature agrees that subjects with autism show deficits in all these modalities, namely emotion recognition, and theory of mind, in all its dimensions (Lord et al., 2020). Concerning cooperation, it would seem to depend on the directionality, with an induction of cooperative behavior that would depend on the explicit nature of the formulation of the request (Collet, 1999). These results contrast with the observations that were obtained in the subjects with Shwachman-Diamond syndrome in the present study, who showed performances in emotion recognition comparable to control subjects, as well as performances in theory of mind in 1st order false-belief situations; in contrast with performances in theory of mind in 2nd order false-belief situations homogeneously impaired in all subjects with Shwachman-Diamond syndrome. Similarly, it would appear that cooperation does not depend on the directive nature of the request formulation, but critically on the direct benefits expected from engaging in the cooperative task (i.e., the economics of the interaction and the cost/benefit balance).

Finally, and based on the data to discriminate individuals with Shwachman-

Clinical condition	Emotion recognition	Theory of Mind (FB)		Cooperativity
		1st-O	2nd-O	
ASD (Lord, 2020)	Altered	Altered	Altered	Directivity dependent (Collet, 1999)
SDS (in the present work)	Functional	Functional	Altered	Dependent on personal economic value
Controls (in the present work)	Functional	Functional	Functional	Dependent on context and interpersonal economic value

Table 5.19: Differential diagnosis of Shwachman-Diamond syndrome in terms of social cognition

Diamond syndrome from controls, a decision tree was produced in an automated manner in Python through the sci-kit learn libraries and based on the data obtained in the present study (Figure 5.26).

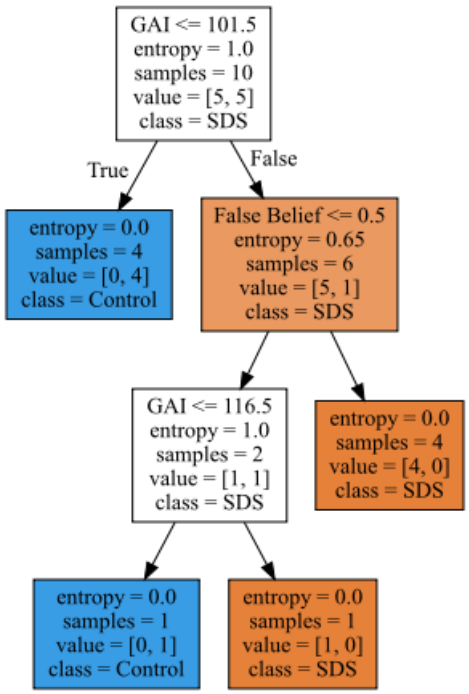

Figure 5.26: Diagnostic decision tree for discriminating control individuals from individuals with Shwachman-Diamond syndrome based on psychometric data collected in the present study.

The decision tree reads as follows: If the GAI score is below 101.5: the subject is probably SDS. If the GAI score is higher than 101.5, we look if the theory of mind item in false belief situation, 2nd order, is false. If it is false, we look again at the GAI scores: if the GAI is lower than 116.5: the subject is SDS; otherwise, it is a control subject.

We could add to this tree the decision step concerning the differential diagnosis of autism (not measured in the present study, therefore absent on Figure 5.26) by measuring the theory of mind performance in a 1st order false belief situation, and which would be deficient in autistic subjects; in contrast with subjects with Shwachman-Diamond syndrome who would pass the item.

5.3 Computational diagnosis of Shwachman-Diamond syndrome through cognitive and dialogic investigations

5.3.1 Material and method

5.3.1.1 Data

In this experiment, we used two quite distinct datasets: our own dataset, consisting of the results obtained in this study on the WISC-V and NEPSY-II (controls: n=5; SDS: n=5); and the datasets associated with the studies of (Batt et al., 2017; Canton et al., 2016), whose authors have transferred ownership of the data in its entirety by written agreement (SDS: n=7); and concerning results obtained on the WISC-IV and NEPSY-II.

5.3.1.2 Machine-Learning models

To test our diagnostic hypotheses regarding the identification of SDS symptomatology in children, we chose to base our analysis on machine-learning models and to control for our results using control experiments, given our small number of observations. Given the linear nature of the data and the likely presence of outliers, we chose a Naive Bayes Gaussian algorithm, which uses pooled variance to make its decisions probabilistic (H. Zhang, 2004). We then performed a k-fold cross-validation with k=4 and evaluated the models with our three usual metrics: accuracy, sensitivity and specificity.

In all conditions, we used our own dataset as training data, and used the dataset provided by (Batt et al., 2017; Canton et al., 2016) as test data. Indeed, although the measures were conducted using the WISC-IV, they still allow for the calculation of GAI and CPI scores (and whose ratio is the differential diagnostic criterion previously identified in the present work) using tables available in the Canadian francophone literature (Saklofske et al., 2005, 2010). It also shares two composite scores: the Working Memory Index and the Information Processing Speed Index, and whose joint measures performed on the WISC-IV and WISC-V are highly correlated; as are the GAI and CPI measures, as specified in the (Table 5.7) available in the interpretation manual provided by the publisher (Wechsler, 2016). NEPSY-II data were also collected.

5.3.1.3 Conditions

We conducted our experiment under three conditions in order to allow for proper control.

The first condition, the target condition (i.e., based on our differential diagnostic criteria), consisted of training our Bayesian algorithm using three variables: the general ability index, the cognitive efficiency index, and the response to the NEPSY-II question measuring second-order theory of mind in false belief situations.

The second condition was a noisy positive condition, it consisted of training our Bayesian algorithm with three other variables: the information processing index, the working memory index, and the response to the NEPSY-II question measuring first-order theory of mind in the false belief situation. The use of the two composite scores of information processing and working memory is all the more interesting as it is these two tests that allow the calculation of the index of cognitive competence (CPI), thus allowing to appreciate the degree of information brought by a diversification of the measures belonging to this very precise domain, and as we have previously described as not or little affected in the Shwachman-Diamond syndrome, except for some outlayers.

Finally, the last condition was a negative control condition (i.e. assumed to be non-functional). It consisted of training the Bayesian algorithm with two variables: the child's biological sex, and the response to the NEPSY-II question measuring first-order theory of mind in the false belief condition.

Next, a two-way ANOVA ($score \sim condition * metric$) was performed to control for differential condition performance in terms of accuracy, sensitivity, and specificity. The machine-learning algorithms were coded in Python using the Sci-Kit Learn libraries and the statistical analyses were coded in R and interpreted in RStudio v1.0.143.

5.3.2 Results and discussion

The cross-validation results for all conditions are shown in Figure 5.27. The classifiers exhibited highly differential performance.

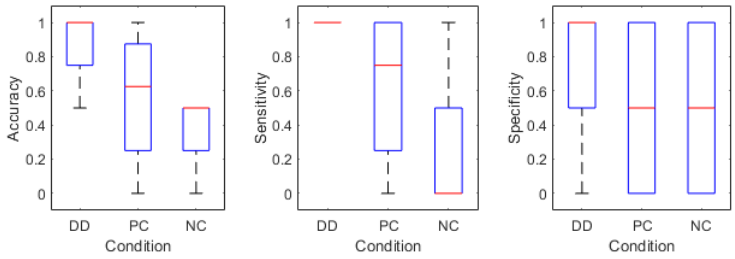

Figure 5.27: Results for detection metrics in 4-fold cross-validation. [DD: Differential diagnostic criteria; PC: Noisy condition; NC: Negative control. [Left: Precision; Middle: Sensitivity; Right: Specificity]

Naive Bayesian classifiers trained on the data from this doctoral work and based on the differential diagnostic criteria (GAI+CPI+Response to the NEPSY-II "Ferris Wheel" item) identified the true group of the studies participants of (Batt et al., 2017; Canton et al., 2016) with a mean accuracy of .875(±.25), coupled with a mean sensitivity of 1(±0) and a mean specificity of .75(±.5). In contrast, classifiers trained on noisy data (WMI+PSI+Response to the NEPSY-II "Cube" item) showed a mean accuracy of .56(±.42), associated with a mean sensitivity of .62(±.47) and a mean specificity of .5(±. 57); whereas classifiers trained on the negative control data (Gender+Response to the NEPSY-II "Cube" item) exhibited a mean accuracy of .375(±.25), with a mean sensitivity of .25(±.5) and a mean specificity of .5(±.57) (Figure 5.27).

Regarding the detection measures, the two-way ANOVA ($score \sim scale * metric$) revealed a significant effect of condition [$F_{(2,42)}$=5.11, p=.01], but showed no other significant effects, including in the interaction between variables.

These data suggest an effect of the type of data used to perform the classification task and conceptually validate our diagnostic criteria. Indeed, training with the GAI (WISC-V) and the 2nd-order theory item on our own dataset effectively performed the automated diagnosis of the Shwachman-Diamond syndrome subjects from the study by (Batt et al., 2017; Canton et al., 2016) with high accuracy, despite the facts that the respective subjects in the two datasets took different editions of the WISC; and that the experimenters who calculated

these results were different.

Chapter 6

Discussion

The main objectives of the present work were to produce evidence to explain the heterogeneous symptomatology encountered in Shwachman-Diamond syndrome and to produce a framework for differential diagnoses with control subjects and other neurodevelopmental pathologies.

We have thus situated this work in a global epistemological framework, that of the Global Network Workspace (Dehaene et al, 1998), whose conceptual framework makes it possible to explain the symptomatology of complex and heterogeneous pathologies such as schizophrenia or autism; in particular by the histological dissection that it allows to operate between elementary cognitive processes (such as perception) and complex inferential processes (such as the emergence of consciousness); and which predicts in particular the possibility of functional dissociations between these processes.

In order to model this histological dissociation, we have chosen to perform analyses on two levels: the psychometric level, allowing us to account for the functionality of elementary and integrative cognitive processes; and the dialogical level, allowing us to account for the integration of these elementary cognitive processes in a global interactive framework.

In a concern for an algebraic reading of the interactive properties of dialogue and in order to make use of all the available techniques of interactive analysis stemming from the three major traditions of linguistics : namely theoretical linguistics and Ludics (Girard, 2001), computational linguistics and SDRT (Lascarides & Asher, 1993), and interlocutionary analysis (Trognon, 2003) ; we have built a global mathematical framework, Trognon's Topological and Kinetic Model (2TK), allowing to unify these three approaches by describing first the

interactive system as a physical system, whose events take place in a defined spatio-temporal framework; and whose parametric decision rules are based on the logical laws that govern these respective models.

Subsequently, we postulated that the contributions of 2TK, in particular in the cross-reading that the model brings with psychometric data and theoretical data (such as the Global Network Workspace); allowed us to glimpse new analytical perspectives in the field of psychology, no longer limited to the field of cognition, but extending into the whole multidimensionality of human behavior, thus opening the field of computational psychology.

In order to conceptually verify this assertion, we have successfully carried out several machine-learning experiments in order to perform classical psychometric operations (i.e. construct validity and discriminative validity), thus allowing us to verify that the performance of validation operations by means of computational strategies allowed us to arrive at the same conclusions as those produced by classical techniques, while remaining within the validity framework commonly accepted in the discipline. We then performed automated diagnostic experiments using artificial neural networks, and were able to successfully discriminate clinical populations from neurotypical counterparts using the topological positions of dialogic interactions as the sole discriminative variables.

We then performed cognitive and dialogic measures in individuals with Shwachman-Diamond syndrome and compared the results with control counterparts.

In terms of intellectual efficiency, we found that individuals with Shwachman-Diamond syndrome were particularly impaired on the General Ability Index (i.e. GAI) subtests; this was in contrast to average performance on the Cognitive Proficiency Index (i.e. CPI) subtests. These results are in stark contrast to data available in the literature for the more typical neurodevelopmental disorders, where GAIs are notably observed above CPIs for attention deficit disorder with or without hyperactivity (Becker et al., 2021; Breuer et al., 2011), as well as for autism spectrum disorders (Styck et al., 2019). They are also discriminable from control and SLI individuals, in whom equivalent GAI and CPI scores are measured (Breuer et al., 2011; Cornoldi et al., 2014; Lecerf et al., 2016). These data are consistent with what has been observed previously in the literature (Batt et al., 2017; Canton et al., 2016; Perobelli et al., 2015).

In terms of social cognition, we observed that individuals with Shwachman-Diamond syndrome showed a dissociated profile, including preserved abilities in emotion recognition and first-order theory of mind; which contrasted with

selective deficits in second-order false belief situations. These features allow for differential diagnosis with pathologies associated with autism spectrum disorders, whose patients are deficient in all of these modalities (Lord et al., 2020). These results appear to contrast with data obtained previously in the literature (Batt et al., 2017; Canton et al., 2016), which measured overall emotion recognition deficits, but were not controlled for using a matched sample.

Finally, on the pragmatic level, we observed that individuals with Shwachman-Diamond syndrome had altered pragmatic abilities in their presentation compared to control subjects, despite a sensitivity to the implicit, and whose behaviors at the interaction level would be governed by an economic principle of interaction, where the actions of individuals with Shwachman-Diamond syndrome would be mainly conditioned by the direct benefits that the interaction can bring to them individually, producing on their part a selective and context-related ignorance of commonly accepted social norms.

Thus, we provided an additional level of evidence for our observations by building diagnostic models of Shwachman-Diamond syndrome through machine-learning techniques, using our own dataset as training data, and using the dataset provided by (Batt et al., 2017; Canton et al, 2016) as test data; and showed that our diagnostic criteria correctly identified the entirety of the subjects in this previous study, even though GAI scores were calculated from scores on tests of an earlier version of the WISC than the one used in the present work.

From a fundamental integrative point of view, the Global Network Workspace theory could explain the symptomatology observed in individuals with Shwachman-Diamond syndrome. Indeed, the Global Network Workspace theory predicts conditions where information processing can be efficient, but the global integration of all intermediate inferential products in the computational hubs of prefrontal cortex and anterior cingulate cortex could fail, as in pathologies such as schizophrenia (Berkovitch et al., 2017). In Shwachman-Diamond syndrome, carrier patients are anatomically and projectively affected in these two integrative centers and in a particularly homogeneous manner, as well as in striatal regions; in contrast to primary information processing regions that appear healthy in their anatomies and projections (Perobelli et al., 2015). This neuroanatomical dissociation between preserved sensory processors and impaired integrative centers would explain the observation made at the level of cognitive measurement, where scores measuring elementary abilities are in the middle thresholds; in contrast to scores measuring integrative abilities, which are in

the lower norms. Similarly, neuroanatomical alterations of the striatum as well as alterations of its projections to the anterior prefrontal and cingulate centers would explain this behavioral peculiarity observed in subjects with Shwachman-Diamond syndrome in interactive cooperative situations, given the well known functions of the striato-cingulate network in economic calculation based on social parameters (Behrens et al., 2008; Cui et al., 2021; Lockwood & Wittmann, 2018; Reutskaja et al., 2018; Wittmann et al., 2018), and whose computation would allow for the assessment of interlocutors' motivation and the economic value of social events (Apps et al., 2016). These hypotheses were fortified by conducting a human-computer interaction experiment exposing GPT-3 software (which has a virtually unlimited knowledge span, but lacks integrative centers to properly integrate contextual elements) to verbal comprehension and theory of mind tasks, and showing that the performance of subjects with Shwachman-Diamond syndrome on the integrative tasks (i. this theory would also allow for the development of a new approach to theory of mind). Finally, this theory would also explain why psychotic transitions are observed in some subjects with Shwachman-Diamond syndrome (Davies et al., 1997; Perobelli et al., 2012, 2015), and in particular by the progressive corruption of Bayesian models of the world that shape perception, potentially in the same way as in schizophrenic individuals and as described by (Berkovitch et al., 2017).

Clinically, and concerning the Shwachman-Diamond syndrome, the present work has provided the first elements of differential diagnosis, allowing to discriminate this population from control individuals, in children. However, this work will have to be elaborated by increasing the size of the observed population and by refining the weights of the prediction algorithms. The increase in the sample size will allow, in the same way, to add an additional dimension, that of the topology of the exchange, and thus will allow the creation of multi-layer algorithms integrating both cognitive and dialogical dimensions to make their decision. The computational analysis of the anamnestic data (for the moment in insufficient quantity) will also allow, in the long run, to create a psychometric scale for the diagnosis of the Shwachman-Diamond syndrome, in hetero-evaluation by the teachers or the parents, and whose decision could be entirely automated, thus facilitating the decision of the engagement in a genetic diagnosis process. However, these algorithms will need to be trained not only with data from patients with Shwachman-Diamond syndrome and control individuals, but also from patients with other neurodevelopmental disorders, such as attention

disorders; autism spectrum disorders; and specific learning disabilities, for effective decision making based on intellectual parameters. They will also need to be checked with other pathologies producing theory of mind disorders such as Down syndrome (Antonarakis et al., 2020). However, this work will have allowed us to verify and refine certain clinical observations, in strong relation with electrophysiological data. Indeed, the cases presented in detail and analyzed on the dialogue level had the common characteristic of presenting selective deficits on the second-order theory of mind and on the pragmatic level. These elements could thus represent a core feature of Shwachman-Diamond Syndrome. This postulate being strengthened by the fact than all studies shown neuroanatomical abnormalities in the anterior cingulate over Shwachman-Diamond Syndrome population (Perobelli et al., 2015) a core region of mentalizing compound of theory of mind and cooperation (Abu-Akel Shamay-Tsoory, 2011; Haas et al., 2013, 2013; Kanske et al., 2017; Rilling et al., 2007; Wittmann et al., 2018).

Finally, on the methodological and fundamental levels, we believe that the present work has made it possible to overcome certain methodological barriers that remained in the discipline of psychological sciences, and in particular in the possibility of carrying out algebraic calculations on interactive parameters; thus opening the way to statistical and algorithmic operations on the scale of group analysis, as well as the cross-reading of dialogical or behavioral parameters with psychometric data; but above all opening the way to the computational exploration of the subjectivity of each patient, as shown by the analysis carried out on the case of the young AG, whose measurements carried out on the scale of a single interaction, but with a large number of observation points, allowed the algebraic confirmation of an intuition that had manifested itself on the clinical level. The present work would allow to glimpse a use of computational techniques described as reading the intersubjective processes taking place at the level of the interactive system and producing objective information on the underlying cognitive processes. One could thus imagine an anamnestic metric, which could be used clinically, and which would provide complementary information to psychometric evaluation, thus allowing less reliance on artificial tests, focusing more precisely on the relevant ecological elements in the human ecosystematic framework of life (i.e. interaction, which implies the simultaneous use of a wide variety of cognitive processes). Moreover, we believe that the methodological advances produced by the present work will allow us to link more efficiently the data obtained on the interactive planes with those obtained on planes of

different dimensions, such as neurophysiological data, and in particular thanks to the use of computational methods allowing to link the patterns of neuronal activity with ad hoc models (Combrisson et al., 2021). We also believe that these methodological advances will open up the field of investigation of theoretical psychology, as currently exploited by theoretical neurosciences, and in particular in the realization of in silico experiments using artificial neural networks, which would allow both the confirmation of experimental results by their implementation in a computerized way ; and to guide future experiments, by observing the activity pattern of artificial neural networks exposed to interactive tasks using techniques from theoretical neuroscience (Beiran et al. , 2021; Dubreuil & Leblois, 2021; Francl & McDermott, 2022; Mastrogiuseppe & Ostojic, 2018) and whose measurement would allow to orientate in vivo research by focusing investigations on neural networks possessing properties similar to those observed in artificial settings, as it has been shown very recently, few days ago, in the prestigious journal Science, that brain-like functional specialization emerges spontaneously in deep neural networks (Dobs et al., 2022), thus suggesting very broad perspectives for theoretical and computational psychology.

Chapter 7

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Chapter 8

Résumé étendu en français

Le Syndrome de Shwachman-Diamond (SDS), est une maladie autosomique récessive rare ayant une incidence annuelle de 1 cas sur 200.000 naissances (5 nouveaux cas par an en France), et induite par une mutation sur le locus q11 du chromosome 7, dans la région du gène SBDS. Le gène SBDS est un gène quasi-ubiquitaire et est exprimé dans presque tous les tissus adultes, incluant le myocarde et le système nerveux central. Chez la souris, la perte de fonction de ce gène induit une mortalité embryonnaire. Chez les humains, les mutations du gène SBDS produisent la plupart du temps une insuffisance du pancréas exocrine, une insuffisance médullaire, ainsi qu'une dysplasie squelettique, mais d'autres caractéristiques ont déjà été rapportées dans la littérature telles des insuffisances cardiaques, qui peuvent devenir létales dans certains cas.
Une étude plus récente a décrit l'impact des mutations du gène SBDS sur le développement du système nerveux. Ces données ont suggéré que les patients SDS présentent un rétrécissement global des volumes corticaux dans les deux hémisphères, en particulier dans le cortex cingulaire antérieur et les régions hippocampiques. Ils ont également observé des anomalies cérébrales diffuses dans la matière grise ainsi que des disruptions de la connectivité myélinique.
Bien que ces données cérébrales pourraient permettre d'expliquer en partie la symptomatologie clinique observée chez les patients SDS, les données de la littérature disponibles concernant le retentissement linguistique, psychologique et psycholinguistique de ces altérations sont rares. Actuellement, il a été montré que les sujets porteurs du SDS présentent des altérations cognitives diffuses, avec notamment un affaiblissement de l'efficience intellectuelle et un syndrome dysexécutif, en dépit d'une importante variabilité intragroupe. Cependant, aucune

donnée n'existe concernant le retentissement de ces anomalies cognitives sur les interactions sociales et en particulier dans le cas de l'interaction sociale humaine la plus naturelle : l'interaction dialogique.
Certains travaux ont déjà examiné les conduites conversationnelles associées à certaines pathologies mentales comme la schizophrénie, ou l'autisme ; ainsi qu'à certaines pathologies dégénératives ou traumatiques comme la maladie d'Alzheimer ou le polyhandicap, et les traumatismes crâniens. Le Syndrome de Shwachman-Diamond, n'a, quant-à-lui, jamais donné lieu à aucune étude systématique, bien qu'une étude exploratoire ait été réalisée ayant conclu que ces patients présentent des capacités pragmatiques conservées.
Cependant, alors que dans cette étude exploratoire, la partie dialogique et l'évaluation neuropsychologique ont été conçus séparément, ils ont été intégrés dans une lecture conjointe dans le présent travail, de façon à ce que l'évaluation des conduites dialogiques ne soit pas une tâche parmi d'autres, mais se positionnant comme une tâche super-ordonnée et dont les mesures comportementales sont explicables et objectivables dans leur observation croisée avec les données psychométriques (fonctions intellectuelles ; attention et fonctions exécutives ; cognition sociale), à l'aide d'un dispositif dialogique écologique créé pour l'expérience, le Trognon Ecological Side Task for the Assessment of Speech-Act Processing (TEST-ASAP). Cette tâche est subdivisée en trois sous tâches afin de mesurer les aspects inférentiels d'une part ; l'induction comportementale sous instruction sans bénéfice et l'induction comportementale nécessitant une inférence préalable mais porteuse de bénéfices, permettant ainsi de mettre en évidence des dissociations, cette tâche étant intégrée dans le processus même d'évaluation neuropsychologique, permettant de garantir son aspect écologique.
Ces données dialogiques ont été enregistrées, transcrites verbatim, puis analysées à l'aide du modèle Topologique et Cinétique de Trognon (2TK), un cadre analytique mathématique permettant d'unifier les trois approches dominantes de l'analyse interactive : la linguistique computationnelle et la linguistique théorique et la Ludics, la linguistique computationnelle et la SDRT, ainsi que l'analyse interlocutoire. L'utilisation conjointe de techniques d'analyse d'interaction homme-machine et d'interaction homme-homme pour étudier le dialogue naturel se justifie ici par la construction de la tâche, dont l'issue et son déroulement sont prédictibles chez le sujet neurotypique (i.e. dialogue idéal ayant les caractéristiques d'un dialogue coopératif où les interactants s'entraident vers un but commun), et dont toutes les autres configurations seraient considérées comme artéfactuelles (i.e. non optimales et détectées par ces méthodes).

L'originalité de ce travail se situe ainsi dans l'exploration multidimensionnelle des paramètres psychologiques et cognitifs permettant de décrire la symptomatologie clinique des patients atteints du syndrome de Shwachman-Diamond, et dans la production d'éléments permettant de poser les jalons qui permettront à terme de développer des algorithmes de diagnostic automatisé multidimensionnel et en fournissant leurs preuves de concept, et dont l'usage pourrait dépasser le cadre du présent travail.

Nous avons tout d'abord situé ce travail dans le cadre global de la théorie du Global Network Workspace, une théorie de la conscience basée sur l'hypothèse que des bases neurales spécifiques permettent l'exécution d'un effort mental conscient. Selon ce modèle, le système nerveux central est composé de deux espaces computationnels distincts. Le premier, appelé le "processing network", est composé de neurones spécialisés dans le traitement de l'information spécifique. Le deuxième, appelé le Global Network Workspace, est composé de neurones distribués dans l'ensemble du système nerveux central. Ces neurones sont capables d'échanger des informations avec d'autres neurones dans différentes régions corticales. Le Global Network Workspace pourrait ainsi interconnecter et coordonner les traitements computationnels dans tout le système nerveux central, permettant ainsi leur émergence dans la conscience. Grâce à ses projections vers les "processing networks", le Global Network Workspace pourrait mobiliser et reconfigurer dynamiquement cinq réseaux neuronaux distincts : les réseaux perceptuels, les réseaux moteurs, les réseaux de mémoire à long terme, les circuits évaluateurs, et les circuits attentionnels. En effet, les individus atteints de la maladie de Shwachman-Diamond présentent souvent des anomalies structurelles dans certaines régions du système nerveux, notamment le cortex préfrontal, le cortex cingulaire antérieur et le striatum, des régions qui jouent un rôle clé dans le fonctionnement du Global Workspace : le cortex préfrontal est notamment impliqué dans les processus cognitifs de haut niveau tels que la planification, la résolution de problèmes, la prise de décision et le contrôle de l'attention ; alors que le cortex cingulaire antérieur joue un rôle dans l'attention, la régulation des émotions et la prise de décision ; et enfin, le striatum est impliqué dans la régulation des mouvements, le contrôle de l'attention et les processus de récompense et de motivation. Dans le cadre de la théorie du Global Workspace, ces régions du cerveau seraient impliquées dans le "routage" de l'information vers le "théâtre" mental global, permettant ainsi une intégration de l'information de différentes sources pour créer une perception consciente. Les déficits observés chez les patients atteints de la maladie de Shwachman-

Diamond pourraient donc être le résultat d'une altération du fonctionnement de ce Global Workspace, conduisant à une incapacité à intégrer efficacement l'information de différentes sources et à une atteinte des processus cognitifs de haut niveau. Ce modèle, compatible avec la théorie de l'information, semble être à la fois le plus pertinent pour étudier la pathologie, étant donné ses similarités neuroanatomiques avec d'autres pathologies déjà étudiées sous l'angle du Global Workspace, mais également en raison de la possibilité de lecture croisée entre des données interactives obtenues dynamiques et des potentielles données électrophysiologiques qui pourraient être obtenues, dans le cadre global que le travail a dénommé l'approche pragmatique en psychologie computationnelle.

Nous avons ainsi développé un modèle d'analyse des interactions, le modèle Topologique et Cinétique de Trognon (2TK) inspiré des sciences physiques et ancrée dans la théorie de l'information, synthétisé à partir des trois courants dominants de la linguistique : la Ludique, encodant les phénomènes topologiques ; la SDRT, encodant les phénomènes cinétiques ; et la Logique Interlocutoire, encodant avec précision les actes de langages qui constituent notre unité analytique et représentant l'information que des entités échangent. Le modèle a été testé sur un ensemble de corpus clés des différents courants synthétisés, notamment des corpus sains, d'enfants présentant des troubles du spectre autistique, ainsi que d'individus schizophrènes ; et dans des conversations synthétiques ; dans des paradigmes directement issus du modèle 2TK ou dans des paradigmes dérivés (e.g. déviation topologique) permettant de mesurer des composantes interactives telle que la cohérence dialogique.

Ce travail a tout d'abord commencé par examiner l'impact du syndrome de Schwachman-Diamond (SDS) sur l'efficience intellectuelle, les habiletés intellectuelles, les performances aux tests individuels, l'attention et les fonctions exécutives, la reconnaissance des émotions, et la théorie de l'esprit chez les patients atteints par voie neuropsychologique classique.

Concernant l'efficience intellectuelle, les patients SDS ont montré des performances significativement inférieures aux contrôles, indépendamment du sexe, mesuré par le quotient intellectuel à la WISC-V. Cependant, les atteintes ne sont pas distribuées de manière homogène au sein d'un même patient, même si une tendance semble se dégager au niveau du groupe : les habiletés générales (IAG), mais pas les compétences cognitives (ICC), semblent particulièrement affectées.

Concernant l'attention et les fonctions exécutives, une atteinte hétérogène a été observée. Cette atteinte était significativement plus importante chez les femmes que chez les hommes, dont les performances au test de Catégorisation de la

NEPSY-II ont été significativement plus basses que chez les individus témoins. En ce qui concerne la perception sociale, aucun déficit observable dans la reconnaissance des émotions faciales chez les patients SDS n'a été mis en évidence. Cependant, les performances en théorie de l'esprit étaient significativement impactées, sans distinction entre les dimensions verbales et contextuelles. Fait intéressant, malgré un déficit global dans la théorie de l'esprit, les patients SDS n'ont pas montré de déficit dans la mentalisation de premier ordre. Néanmoins, ils ont tous échoué à la tâche de fausse-croyance de second-ordre, démontrant une dysfonction homogène dans la théorie de l'esprit du second-ordre en situation de fausse croyance.

Ces résultats neuropsychologiques ont ainsi pu permettre d'entraîner un algorithme de machine-learning explicable de type Decision Tree a discriminer automatiquement les individus SDS des individus témoins, qui a pu avec succès identifier les patients SDS qui avaient été rencontrés dans le cadre d'une étude exploratoire antérieure.

Ils ont ainsi été replacés dans le cadre du Global Network Workspace, qui postule un rôle crucial des deux hubs computationnels, à savoir le cortex préfrontal dorsolatéral et le cortex cingulaire antérieur dans l'établissement et le maintien des fonctions intégratives impliquées dans l'intelligence et la théorie de l'esprit. Nous avons ainsi utilisé des modèles de réseaux de neurones artificiels (GPT-3, modèle Da Vinci, 2021) pour simuler des discours d'agent ne possédant pas de hubs computationnels tels que les deux sus-décrits, derrière le postulat qu'une exposition à des tâches verbales nécessitant l'intégration du contexte produirait des réponses similaires à celles observées dans des conditions pathologiques où ces deux centres intégrateurs seraient touchés.

Les performances des patients SDS ont été comparées à celles de GPT-3 et d'individus neurotypiques dans les tests verbaux qui ont été administrés dans le cadre du travail tels que les subtests "Similitudes" et "Information" de la WISC-V, et les subtests de la sous-échelle "Théorie de l'Esprit - Modalité verbale" de la NEPSY-II. Aucune différence significative n'a été observée dans l'indice de compréhension verbale. En revanche, des différences significatives ont été observées dans les tests de théorie de l'esprit, avec des performances inférieures pour les patients SDS et GPT-3 par rapport aux sujets neurotypiques. De plus, l'expérience a mis en évidence que la performance dans la mentalisation de second-ordre, était significativement différente entre les groupes : les patients SDS et GPT-3 ont montré des performances similaires et inférieures aux sujets neurotypiques, suggérant une déficience ou une absence de certains processus

intégratifs liés à cette capacité.
Ces résultats soutiennent ainsi l'application de la théorie du Global Network Workspace pour expliquer les déficits observés chez les patients SDS et mettent en évidence l'importance des hubs computationnels pour les fonctions cognitives complexes, telle que la théorie de l'esprit. Ils suggèrent également de manière indirecte que les modèles de langage de type GPT-3, bien qu'ils puissent réussir des tests basés sur des connaissances sémantiques, manquent de capacités inférentielles contextuelles nécessaires pour réussir des tâches plus complexes. Ainsi, ces résultats ouvrent des perspectives prometteuses pour une meilleure compréhension des pathologies cognitives humaines par la modélisation computationnelle de processus dialogiques.
Enfin, l'analyse dialogique réalisée à l'aide du modèle 2TK dans le paradigme du TEST-ASAP a révélé des informations intéressantes sur les chevauchements entre la théorie de l'esprit et les compétences pragmatiques, fournissant une compréhension des différences dans les modalités de coopération inter-agents dans le cadre du Syndrome de Shwachman-Diamond, souvent créatrices de conflits d'après les éléments rapportés par les aidants de patients. L'analyse a ainsi révélé que les patients SDS ne coopèrent pas systématiquement lors de l'émission d'une demande de coopération par le biais d'un acte de langage indirect. En effet, l'analyse du sous-test « Corbeille » a révélé que les patients SDS avaient tendance à ne pas coopérer avec leur interlocuteur lorsque le bénéfice économique de coopération semble négligeable mais que le coût semble élevé, y compris lorsqu'ils en sont le bénéficiaire et en condition asymétrique. En contraste, le sous-test « Porte » a révélé que les individus SDS avaient tendance à coopérer immédiatement lorsque les bénéfices étaient partagés et que le coût de coopération était relativement faible. Enfin, le sous-test « Syllogisme » a montré que les individus SDS avaient tendance à rompre les normes sociales pour coopérer lorsque les bénéfices attendus sont élevés de manière personnelle. Ainsi, sur les plans cliniques, le présent travail a permis de fournir les premiers éléments de diagnostic différentiel permettant de discriminer les individus enfants présentant un Syndrome de Shwachman-Diamond des individus témoins et atteints des pathologies neuro-développementales les plus fréquentes. Ces travaux devront cependant être élaborés en augmentant la taille de la population observée et en affinant les poids des algorithmes de prédiction. L'augmentation de la taille de l'échantillon permettra, de la même manière, d'ajouter une dimension supplémentaire, celle de la topologie de l'échange, et ainsi permettra la création d'algorithme multicouches intégrant à la fois des dimensions cog-

nitives et des dimensions dialogiques pour prendre leur décision. L'analyse computationnelle des données anamnéstique (pour le moment en quantité insuffisante) permettra également, à terme, de créer une échelle psychométrique diagnostic du syndrome de Shwachman-Diamond, en hétéro-évaluation par les enseignants ou les parents, et dont la décision pourra être entièrement automatisée, facilitant ainsi la décision de l'engagement dans un processus de diagnostic génétique. Ces algorithmes devront cependant être entraînés non seulement avec des données issues de patients atteints du syndrome de Shwachman-Diamond et d'individus témoins, mais également des patients atteints d'autres troubles neurodéveloppementaux, tels que les troubles de l'attention ; les troubles du spectre autistique ; et les troubles spécifiques des apprentissages, pour une décision efficace basée sur les paramètres intellectuels. Ils devront également être contrôlés avec d'autres pathologies produisant des troubles de la théorie de l'esprit tel que le syndrome de Down.

Enfin, sur les plans méthodologiques et fondamentaux, nous pensons que le présent travail a permis de franchir certaines barrières méthodologiques qui demeuraient dans la discipline des sciences psychologiques, et notamment dans la possibilité de réaliser des calculs algébriques sur des paramètres interactifs ; ouvrant ainsi la voie aux opérations statistiques et algorithmiques à l'échelle de l'analyse de groupes, ainsi que la lecture croisée de paramètres dialogiques ou comportementaux avec des données psychométriques ; mais surtout ouvrant la voie à l'exploration computationnelle de la subjectivité propre à chaque patient, comme en témoigne l'analyse réalisée sur le cas de la jeune AG, dont les mesures réalisées à l'échelle d'une seule interaction, mais avec un grand nombre de points d'observations, a permis de confirmer de manière algébrique une intuition s'étant manifestée sur le plan clinique. Nous pensons ainsi que les avancées méthodologiques produites par le présent travail permettront de relier de manière plus efficace les données obtenues sur les plans interactifs avec celles obtenues sur des plans relevant de dimensions de nature différentes, telles que des données neurophysiologiques, et notamment grâce à l'usage de méthode computationnelles permettant de lier les patterns d'activité neuronale avec des modèles ad hoc. Nous pensons également ces avancées méthodologiques permettront d'ouvrir la voie du champ d'investigation de la psychologie théorique, telle qu'exploitée actuellement par les neurosciences théoriques, et notamment dans la réalisation d'expériences in silico à l'aide de réseaux de neurones artificiels, qui permettrait à la fois la confirmation de résultats expérimentaux par leur implémentation de manière informatisée ; et qui permettrait à la fois de guider

les expérimentations futures, en observant le pattern d'activité de réseaux de neurones artificiels exposés à des tâches interactives et dont la mesure permettrait d'orienter les recherches in vivo en focalisant les investigations sur des réseaux neuronaux possédant des propriétés similaires à celles ayant émergées spontanément dans le réseau artificiel, étant donné qu'il a été montré que ces réseaux artificiels semblent se distribuer fonctionnellement de la même manière que les réseaux neuronaux physiologiques.