Multimodal assessment of communicative-pragmatic features in schizophrenia: a machine learning approach

Alberto Parola1,2, Ilaria Gabbatore2,5, Laura Berardinelli3, Rogerio Salvini2 and Francesca M. Bosco2,5

An impairment in pragmatic communication is a core feature of schizophrenia, often associated with difficulties in social interactions. The pragmatic deficits regard various pragmatic phenomena, e.g., direct and indirect communicative acts, deceit, irony, and include not only the use of language but also other expressive means such as non-verbal/extralinguistic modalities, e.g., gestures and body movements, and paralinguistic cues, e.g., prosody and tone of voice. The present paper focuses on the identification of those pragmatic features, i.e., communicative phenomena and expressive modalities, that more reliably discriminate between individuals with schizophrenia and healthy controls. We performed a multimodal assessment of communicative-pragmatic ability, and applied a machine learning approach, specifically a Decision Tree model, with the aim of identifying the pragmatic features that best separate the data into the two groups, i.e., individuals with schizophrenia and healthy controls, and represent their configuration. The results indicated good overall performance of the Decision Tree model, with mean Accuracy of 82%, Sensitivity of 76%, and Precision of 91%. Linguistic irony emerged as the most relevant pragmatic phenomenon in distinguishing between the two groups, followed by violation of the Gricean maxims, and then extralinguistic deceitful and sincere communicative acts. The results are discussed in light of the pragmatic theoretical literature, and their clinical relevance in terms of content and design of both assessment and rehabilitative training.

INTRODUCTION

Pragmatics is classically defined as the ability to use language to convey a specific communicative meaning in a given context1–3. More recently, this definition has also included the use of other expressive means such as non-verbal/extralinguistic modalities, e.g., gestures and body movements, and paralinguistic cues, e.g., prosody and tone of voice4. Schizophrenia is associated with a specific language impairment5–7. Patients’ difficulties refer to different levels of language processing, ranging from phonological aspects to word and semantic production8–10. The term schizophrenia was coined to include some of these difficulties, including clanging, neologism, and unintelligible utterances11–13. However, several studies have also pointed out that communicative difficulties may persist even when the syntactic and semantic abilities of patients with schizophrenia are preserved14–16.

In the current literature, a well-established notion is that patients with schizophrenia show pervasive difficulties in terms of communicative-pragmatic ability17–22. Pragmatic ability relies on inferential processes in order to fill the gap that often exists between the literal meaning of an utterance and what the speaker actually intends to communicate as, for example, in the statement “What a nice person!” referring to an individual acting very impolitely. A large number of studies have pointed out that patients with schizophrenia specifically have more difficulty than healthy controls with the comprehension of non-literal language23–24. Non-literal language refers to those communicative acts that imply a gap between the literal and the intended meaning: this is the case of indirect speech acts24, as well as figurative expressions like irony25–28, metaphors, idioms, and proverbs29–33. Furthermore, patients with schizophrenia may also encounter communicative difficulties when having to deal with other pragmatic phenomena, such as recognizing and repairing communicative failures34, as well as understanding deceit35. Moreover, patients with schizophrenia may often display difficulties in detecting violations of the Gricean maxims of communication36,37. Gricean maxims, i.e., quantity (violated by providing extra and redundant details), quality (violated when a speaker says something that is obviously false), relation (violated when the information that is provided is not related to the context of the communicative interaction) and manner (violated when the speaker uses expressions that are rude and inappropriate), represent those communicative rules to which communicative partners adhere, in order to make their communicative contributions effective and ensure a meaningful exchange of information37. Other difficulties have been reported in tasks assessing narrative ability38 and conversational skills39,40.

Non-verbal/extralinguistic expressive behavior, though less investigated than linguistic ability, is also impaired in schizophrenia, and represents a characterizing element of the disease41. Such difficulties range from perception, comprehension, and production of communicative gestures42–44 to facial expression recognition (for a review see refs. 45–47). Moreover, patients with schizophrenia display atypical prosodic patterns, in terms of flat intonation, increased pauses, distinctive tone, and abnormal voice quality46,49. Previous studies indicated slower speech40, more pronounced pauses45,50, and reduced prosodic variability33,44. A recent meta-analysis51 confirmed that voice atypicalities, especially those related to duration and pitch variability measures, represent a characteristic feature of schizophrenia. Further, the ability to recognize linguistic and emotional prosodic cues has also been reported to be impaired in...
schizophrenia\textsuperscript{56–58} as shown, for example, by a difficulty in decoding sarcasm based upon voice tone\textsuperscript{59}.

Despite this evidence, few previous studies have attempted to provide a multimodal assessment of communicative-pragmatic ability in schizophrenia, evaluating different communicative phenomena expressed through different expressive modalities within the same experimental sample. Among these, Meilijson and colleagues\textsuperscript{60} tested verbal, non-verbal, and paralinguistic aspects of conversation to evaluate communicative performance across different clinical populations. The authors pointed out that participants with schizophrenia performed less well than controls in all the expressive modalities. In part, this reflects the complexity of communicative-pragmatic ability. Indeed, pragmatic deficits can vary as a function of the different tasks used to assess the ability and the specific pragmatic phenomena evaluated. Moreover, deficits can affect different expressive modalities, and it is thus important to provide a multimodal assessment of communicative-pragmatic ability.

Although previous literature clearly indicated that communicative disorder is a core deficit in schizophrenia, it remains unclear which communicative features, i.e., which pragmatic phenomena expressed via different expressive modalities, are the most informative for discriminating between patients with schizophrenia and healthy controls. The identification of the communicative-pragmatic phenomena and the communicative expressive modalities in which patients experience greater difficulty could be a valuable aid for clinicians throughout the diagnostic procedure, helping them to identify the disease during the early stages of evaluation and improving the effectiveness of rehabilitative treatment specifically focused on these features\textsuperscript{62,66}.

The aim of the present research is to identify the pragmatic features—communicative phenomena expressed through different communicative modalities, i.e., linguistic, extralinguistic, and paralinguistic—that are the most informative for discriminating between patients with schizophrenia and healthy controls. For this purpose, we assessed the abilities of patients with schizophrenia and healthy controls in a wide range of communicative-pragmatic phenomena, i.e., basic speech acts (statements, questions, commands, and orders\textsuperscript{60}), sincere (direct and indirect), ironic and deceitful communicative acts, violation of the Gricean maxims, prosodic mismatch, social appropriateness, conversational ability (turn-taking and adherence to the topic). Compared to our previous studies\textsuperscript{67,68}, this research analyzes a wider range of pragmatic phenomena, as well as additional expressive means, i.e., paralinguistic modalities. Furthermore, the present study focuses on a new research question, i.e., the identification of the communicative phenomena and expressive modalities that more reliably discriminate between patients with schizophrenia and healthy controls, and to this aim it applies a different methodology, i.e., a Machine Learning (ML) approach, and specifically Decision Tree (DT) analysis. DT analysis can be used to find the pragmatic features that best separate the data into the two groups, i.e., individuals with schizophrenia and healthy controls. This ML technique has several advantages compared to regression models as, unlike linear regression methods, it can handle nonlinear interactions between multiple predictors. Further, it provides an intuitive and intelligible representation (tree diagram) of which variables combined with which configuration can better predict the outcome, i.e., belonging to the schizophrenia vs. healthy controls groups. In this way, we aim to move a step further also with respect to our previous work\textsuperscript{161} by providing a more detailed picture of the communicative profile of patients with schizophrenia, and exploring which communicative phenomena, expressed using multiple communication modalities, best discriminate between patients with schizophrenia and healthy controls.

On the basis of the previous meta-analytic evidence, we hypothesize that the most informative communicative-pragmatic phenomena for distinguishing between patients with
schizophrenia and controls are irony, Gricean maxims, and recognition of prosodic cues. However, no meta-analytic evidence is available for the comprehension and production of communicative acts expressed using the gestural modality, and no predictions can be made for these phenomena. Further, no previous studies have directly compared a wide range of communicative-pragmatic phenomena expressed using different communicative modalities. Thus, this study also has an explorative aim and intends to provide an initial basis for the identification of the multimodal communicative-pragmatic features which best discriminate between patients with schizophrenia and healthy controls.

RESULTS
Assessment of pragmatic abilities in schizophrenia using a DT model
Figure 1 shows the DT model generated. The leaf nodes (gray squares) represent the classes (schizophrenia or healthy controls), and the number in parentheses indicates the expected likelihood of new cases being classified as patients with schizophrenia or healthy controls after going through the previous decision nodes, i.e., after performing a conditional test on a specific feature (for example, new cases are classified as schizophrenia if their score on Linguistic irony is below 0.5 as indicated by the value in the branch between the two nodes). The main factors able to discriminate between the two classes (schizophrenia and healthy controls) in the generated tree are linguistic irony, Gricean maxims of linguistic communication, extralinguistic deceit, and extralinguistic sincere (direct and indirect) communicative acts. The strongest predictor for classifying patients with schizophrenia vs. healthy controls is linguistic irony (node 1): if the score on linguistic irony is below 0.5, a new case is classified as schizophrenia (with probability = 94.1%). The next decision point is Gricean maxims of linguistic communication (node 2) which, depending on whether its value is below 0.5 or above 0.5, leads to the evaluation of extralinguistic deceit (node 3) or extralinguistic sincere (direct and indirect) communicative acts (node 4), respectively. If extralinguistic deceit is below 0.8, the individual is classified as a patient with schizophrenia (probability = 92.1%), otherwise as a healthy control (probability = 75.1%). Similarly, if the score for extralinguistic sincere (direct and indirect) communicative acts is below 0.6, the individual is classified as a patient with schizophrenia (probability = 100%), otherwise as a healthy control (probability = 85.1%). Overall model Accuracy was 0.821 (SD = 0.118), Sensitivity was 0.758 (SD = 0.285), Precision was 0.910 (SD = 0.151), Specificity was 0.900 (SD = 0.175), and the area under the ROC curve (AUC) was 0.894 (SD = 0.143).

DISCUSSION
In the present paper, we provided a comprehensive multimodal assessment of communicative-pragmatic ability in patients with schizophrenia in order to investigate the communicative phenomena and expressive modalities most informative for discriminating between patients with schizophrenia and healthy controls. To this aim, we applied a DT analysis to identify the pragmatic features that best distinguish between the two groups.

First, we found that the overall performance of the DT model was good. Accuracy was 82%, indicating that the model was able to reliably distinguish between the two populations. Sensitivity was 76%, with 24 patients with schizophrenia classified correctly, and Precision was 91%, showing a low number (4) of false-positive errors.

The results showed that linguistic irony emerged as the most important pragmatic phenomenon for determining the class of a new case, i.e., the classification of an individual as a patient with schizophrenia or healthy control. Irony is one of the most investigated phenomena in the pragmatic literature, and a wide body of research has reported that irony comprehension is severely impaired in patients with schizophrenia. A recent meta-analysis showed a large and robust difference in irony recognition between patients with schizophrenia and healthy controls, thus suggesting a high level of impairment in irony comprehension in schizophrenia.

Understanding irony is a high-level linguistic task and requires the interplay of different cognitive functions. Previously, several studies found an association between irony comprehension and different cognitive functions, such as the theory of mind (ToM), i.e., the ability to infer the speaker’s mental states, executive functions (EF), and level of intelligence. More recently, some authors proposed that the additional cognitive effort required for irony comprehension, compared to other communicative expressions, may be due to the complexity of the
inferential ability necessary to identify the ironic communicative intention (see refs. 18,75–77). Recent neuroimaging studies confirmed that comprehension of irony, with respect to literal statements, engages an extended bilateral brain network including several fronto-temporal and fronto-parietal areas, which underlies the cognitive effort related to the use of different cognitive functions such as ToM, executive controls, and inferential processes (e.g., 78–81). Irrespective of the specific cognitive substrates at the origin of patients’ deficits in irony recognition, previous studies clearly showed how irony comprehension is a high-level task that recruits an extended cerebral network corresponding to the interplay of different cognitive functions 29,81. In line with this literature, the results of the present study confirm that, of the pragmatic features evaluated, the linguistic irony was the most complex for patients with schizophrenia to understand, and the most informative for distinguishing between patients and controls.

The second most important factor in classifying patients with schizophrenia or healthy controls in the DT model was the recognition of violation of the Gricean maxims of linguistic communication. Gricean maxims refer to the norms which regulate the discourse between two or more individuals, and serve as rules for rational and effective communication, by ensuring that the information provided by the interlocutors is as informative as necessary (maxim of quantity), the contribution is true (maxim of quality), relevant (maxim of relation), and clear (maxim of manner). More in detail, in the present investigation the items composing our experimental task assessed participants’ ability to recognize the interlocutor’s non-intentional violation of one of the Gricean maxims by providing a confused, or not precise, or not relevant or prolix contribution to the communicative interaction.

The difficulties encountered by patients with schizophrenia in appreciating Gricean maxims of communication are well known, with several studies reporting a pronounced impairment in the ability to attune to and recognize the maxims 10,20,23,35,69,82 and a recent meta-analysis 23 showing a large difference between patients with schizophrenia and healthy controls in tasks assessing the detection of violation of Gricean maxims (d = −1.33, p < 0.001). Frith and Corcoran 35 evaluated the comprehension of Gricean maxims in individuals with schizophrenia, and found that patients exhibiting negative symptoms, such as anhedonia, reduced social drive, and loss of motivation, committed more patients exhibiting negative symptoms, such as anhedonia, reduced social drive, and loss of motivation, committed more

with a wide body of literature showing specific language impairment in patients with schizophrenia (e.g., 11,25,49). The remaining relevant tasks identified by the DT model in classifying patients with schizophrenia or healthy controls were the comprehension and production of sincere communicative acts (direct and indirect speech acts) and deceit expressed through the extralinguistic, i.e., gestural, modality. As regards the role played by sincere communicative acts in our results, the tasks used in the present investigation are composed of items investigating direct and indirect sincere communicative acts. Indirect acts are those by which the speaker communicates more than what s/he is actually literally saying to the listener 84, as in the example “This soup is insipid” (example of unconventional indirect act) proffered in order to obtain the salt from the interlocutor. Several studies in the literature reported that patients with schizophrenia have difficulty with the comprehension of indirect speech acts 85,86 and proposed that such difficulty is principally explained by a patient’s deficit in Theory of Mind 82, i.e., the ability to conceptualize another person’s mental states 70. A similar explanation holds for deceitful tasks, that are often used to investigate ToM difficulties in patients with schizophrenia 35,87–89.

Moreover, empirical research in schizophrenia has traditionally focused on assessing language impairments, considered a hallmark of the disease ever since the first definitions of the disorder. However, it is only more recently that some studies have begun to report the presence of deficits affecting the extralinguistic, i.e., non-verbal modality. These studies found patients with schizophrenia to be impaired in non-verbal communication, especially in the production of communicative and social gestures 45,44,50 and showed that these deficits cannot merely be accounted for by patients’ motor disorder 50. Moreover, deficits have also been reported in the perception and recognition of communicative gestures, as well as in the recognition of facial expressions (for a review see refs. 45,47,91). Finally, deficits affecting non-verbal modalities have been found to be associated with functional outcome 2. The present results are in line with the recent evidence and point to the importance of focusing the assessment of pragmatic ability in schizophrenia not only on the linguistic modality, but also on the extralinguistic communicative modality.

Finally, we should also acknowledge the limitations of the present work. First of all, this is an exploratory analysis. ML methods benefit from larger sample size and different samples to perform out-of-sample validation, while the sample included in the present study is relatively small (n = 67). Further, schizophrenia is a heterogeneous disorder, and clinical samples can vary widely with respect to patients’ clinical features. Thus, the present results need to be replicated in future studies with larger samples and across different clinical profiles. Second, the pragmatic ability can be measured in different ways, and previous studies in the literature have used different batteries and tasks (e.g., 17,39,40,84). These tasks can vary widely with respect to the cognitive and inferential load. For this reason, the communicative features we found to be the most informative for classifying patients and controls need to be confirmed in future studies across different pragmatic tasks and contexts.

To conclude, pragmatic ability includes a wide range of different skills, all of which contributing to successful communication. While previous studies reported a wide array of communicative impairments in schizophrenia, it is hard to identify which of the skills affected are the most informative for distinguishing between schizophrenia and healthy controls. However, the identification of these features may be relevant as a valuable aid for clinicians throughout the diagnostic process, improving the effectiveness of rehabilitative treatment, and targeting future research. Further, recent studies reported that pragmatic and language impairments represent a risk factor for developing psychosis 53–55, and thus the identification of the most distinctive pragmatic features is crucial for targeting early
effective intervention to enhance these skills and which may diminish the risk. Indeed, some authors recently proposed pragmatic impairment as a marker for schizophrenia\textsuperscript{1,6,31,96,97}. In this perspective, it will be fundamental to identify which pragmatic behaviors can most reliably be associated with schizophrenia. In this work, we moved a step in this direction, showing how, in our sample, some communicative features and expressive means, i.e., linguistic irony processing, adherence to and recognition of Gricean maxims of linguistic communication, and comprehension and production of extralinguistic sincere and deceitful communicative acts, were the most informative features for distinguishing between patients and controls. A deeper understanding of the relevance of these deficits in patients with schizophrenia will also be useful in order to promote the creation and implementation of rehabilitation programs specifically designed (see for example\textsuperscript{65,66}) to help patients overcome such difficulties.

**METHODS**

**Participants**

Thirty-two individuals with schizophrenia (seven females; age: $M = 40.17$ years; SD = 10.19; education: $M = 10.59$; SD = 2.45) and 35 healthy controls (six females; age: $M = 39.46$; SD = 10.95; education: $M = 10.57$; SD = 2.46) took part in the research. Patients and controls were matched for gender, education and age (see Table 1). All patients with schizophrenia met the Diagnostic and Statistical Manual of Mental Disorders\textsuperscript{98} criteria for schizophrenia diagnosis. Inclusion criteria for patients were: (1) not in an acute stage: all patients were in the chronic stage of the illness and clinically stable (2) Italian native speaker (3) achievement of a cut-off score (MMSE\textsuperscript{99}). Cut-off 24/30; (b) Token Test\textsuperscript{100}. Cut-off 5/6; (c) Denomination controls\textsuperscript{18,20,77}. The Battery includes tools that can be able to discriminate between patients with schizophrenia and controls\textsuperscript{18,20,77}. The Battery includes five different scales assessing the comprehension and production of a wide range of pragmatic phenomena. The **linguistic scale** evaluates the comprehension and production of different communicative phenomena, i.e., basic speech acts, sincere communicative acts, deceit, irony, expressed using the linguistic modality. The extralinguistic scale assesses the same communicative acts, but expressed using the extralinguistic modality, i.e., gestures. The **paralinguistic scale** assesses the comprehension and production of those communicative aspects that complement the interaction, such as facial expressions, prosody, eye-gaze, etc. This scale evaluates communicative phenomena, i.e., basic communicative acts, communicative acts expressing an emotion, and paralinguistic contradiction. The context scale evaluates the adequacy of a communicative act with respect to the norms of discourse (i.e., Gricean maxims) and social norms of communication. The **conversational scale** assesses the ability to take part in a conversation appropriately, adhering to the topic and respecting turn-taking rules.

| ID Patients with schizophrenia | Sex | Age (Yrs) | Education | Treatment | Typical neuroleptics | Atypical neuroleptics | PANSS Negative symptoms | Positive symptoms | General symptoms | Total score |
|------------------------------|-----|-----------|-----------|-----------|---------------------|---------------------|-----------------------|------------------|----------------|-------------|
| 1                            | M   | 12        | 3         | 4         | 3                   | 1                   | 1                      | 1                | 0              | 0           |
| 2                            | M   | 13        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 3                            | M   | 14        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 4                            | M   | 15        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 5                            | M   | 16        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 6                            | M   | 17        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 7                            | M   | 18        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 8                            | M   | 19        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 9                            | M   | 20        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 10                           | M   | 21        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 11                           | M   | 22        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 12                           | M   | 23        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 13                           | M   | 24        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 14                           | M   | 25        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 15                           | M   | 26        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 16                           | M   | 27        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 17                           | M   | 28        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 18                           | M   | 29        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 19                           | M   | 30        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 20                           | M   | 31        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 21                           | M   | 32        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 22                           | M   | 33        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 23                           | M   | 34        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 24                           | M   | 35        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 25                           | M   | 36        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 26                           | M   | 37        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 27                           | M   | 38        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 28                           | M   | 39        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |
| 29                           | M   | 40        | 8         | 13        | 13                  | 13                  | 13                    | 13               | 13             | 13          |

*Table 1. Clinical details of patients with schizophrenia (N = 32).*
Table 2. Description of the structure of the Assessment Battery for Communication.

| Assessment Battery for Communication | Pragmatic phenomena |
|--------------------------------------|---------------------|
| **Linguistic and extralinguistic scales** | evaluate the comprehension and production of communicative acts expressed by using linguistic or extralinguistic modality. |
| The communicative acts are expressed verbally on the linguistic scale and through gestures and facial expressions on the extralinguistic scale. |
| **The paralinguistic scale** | assesses the comprehension and production of paralinguistic features, such as prosodic or vocal cues used by a speaker to accompany a communicative act and express emotional contents. |
| **The context scale** | evaluates the ability to comply with the norms of social appropriateness and with the conversational rules (i.e., Gricean maxims). |
| **(a) Basic speech acts (assertions, questions, requests, order):** | The examiner asks the subject to evaluate the truthfulness of assertions, answer easy questions, perform actions on request and execute orders (linguistic scale) and to understand the communication acts produced by the actor in a clip through the use of gestures. (b) **standard (direct and indirect) communication acts:** i.e., respectively, acts expressing literally and exactly what the speaker intends to say and acts through which the speaker communicates more than is literally said to the listener and (c) **non-standard (deceits and ironies) communication acts:** |
| **Example** | The participants are asked to observe some clips and understand – in the comprehension tasks - the communicative act expressed by the two actors. In the **production** tasks, the actors in the clip are engaged in a communicative interaction and, when the clip stops, the participant is required to assume one of the actor’s perspective in replying to his partner. |
| **Comprehension - BSA (Question), Linguistic Scale:** | You want to know where I was born. What do you ask me? |
| **Comprehension - BSA (Order), Linguistic Scale:** | Order me to give you the pen. |
| **Production - Basic emotions:** | Ask me what time it is. Ask me as if you were bored. |
| **Comprehension - Deceit, Extralinguistic scale:** | Nadia and Sergio are arguing - having a pillow fight - in their bedroom. In such confusion, Nadia hits the lamp on the bedside table, and it falls onto the floor. Having heard the noise, their father comes to their room, puts his hands on his hips and, with a questioning air, at the same time assuming a cross expression as if to say “What’s going on?” he points with his finger to the lamp on the floor. Nadia immediately picks up a book and shows it to her father, as if to say “I was reading”. |
| **Production - Basic emotions:** | Ask me what time it is. Ask me as if you were bored. |
| **Comprehension - Gricean Maxims:** | Could you pass that book, please? Mr. Marica, absent-minded, replies: “Right, we should definitely go on holiday!” |
| **Production - Social Norms:** | Imagine being late for an appointment with your lawyer, and you have to apologize. How do you apologize? |
| **Example** | - What do you think about the answer? Do you think it is ok? Why?Why not? |
| **The conversational scale** | evaluates the ability to appropriately participate in a conversation with the examiner, lasting 4-5 minutes on a particular topic such as, for example, hobbies or vacation. |
| **(a) Maintaining the topic of the discourse and (b) Managing the turn taking.** | Where do you usually go for vacation? Below are possible questions to ask: |
| **Example** | - Where would you like to go? - Where do you usually go on holiday? I really like the sea / the mountains... - Do you send postcards? - Do you like taking pictures? - Where do you usually spend your holidays, in a hotel / camping? |
and then asks specific open questions for each item. The specific pragmatic phenomena and skills assessed in each scale are described, with examples, in Table 2.

All items are scored as correct (1 point) or incorrect (0 points), based on precise coding rules that are set out in the ABaCo administration manual119,74. See also refs. 77,102,106,107, for a more detailed description of the administration and scoring procedures.

Data analysis

We analyzed the data using a DT classifier in order to identify the pragmatic phenomena most relevant for discriminating between patients with schizophrenia and healthy controls. DT is a commonly used ML method for classifying and predicting a target variable based on multiple covariates. It is a classifier with a tree structure, where each node is either: (1) A leaf node which represents the final outcome of a series of decisions and indicates the value on the target attribute (class). For example, in our case, it indicates whether a new case is classified as a patient with schizophrenia or a control (target attribute: class); (2) A decision node that represents a conditional test on a specific feature. For example, in our case, if the feature considered is Linguistic irony, the decision node represents the threshold scores on Linguistic irony for which an individual is classified as a patient with schizophrenia or healthy control. For example, if the participant’s score on Linguistic irony (feature) is below or above 0.5, that individual is respectively classified as a patient with schizophrenia or healthy control. Each branch of the subtree represents a possible outcome of the test, with subtrees representing conjunctions of features (and the tests performed on these features, i.e., decision nodes) that lead, in the end, to the class attribute, i.e., whether a case is classified as a patient with schizophrenia or healthy control. For example, if we consider the decision node of Linguistic irony (see Fig. 1), this gives origin to two branches based on the test performed on this feature: first branch: if Linguistic irony is below 0.5 a new case is classified as a patient with schizophrenia; second branch: if Linguistic irony is above 0.5, a further test is performed on a different feature (Gricean maxims of linguistic communication), which in turn gives origin to two further branches, and so on until a leaf node is reached and a case is classified as a patient with schizophrenia or healthy control.

The estimation criterion in the DT algorithm is the selection of a feature to test at each decision node in the tree. The goal of the estimation criterion is to select the feature that is most useful for classifying the cases. A good quantitative measure of the worth of a feature is a statistical property called information gain that measures how well a given feature discriminates the cases based on the class to which they are attributed. This measure is used to select the best feature from among the possible candidates at each step of the growing tree. In the present study we used the J48 algorithm (an implementation of Quinlan’s algorithm C4.5) in the Weka workbench for ML, version 3.8.3 to generate the DT model. We estimated the generalization performance of the DT model using 10-fold cross-validation, which is a technique for evaluating predictive models by partitioning the original sample into a training set to create the model, and a test set to evaluate it. We reported the following performance metrics: Accuracy, Sensitivity, Precision, Specificity, and the area under the ROC curve (AUC). Accuracy refers to the proportion of the total number of classifications that were correct in both classes (SCZ and HC). Sensitivity gives the proportion of cases of schizophrenia classified correctly. Precision gives the proportion of cases classified as schizophrenia that was correct, and Specificity gives the proportion of control cases classified correctly. The ROC (Receiver Operating Characteristic) curve tells us how well the model can distinguish between the two classes (schizophrenia and healthy controls). ROC is a probability curve, and AUC represents a degree or confidence factor at 0.5 and the number of minimum instances per node (minNumObj) at 2. Details regarding the analysis are available upon request to rogeriosalvini@ufg.br.

Received: 29 July 2020; Accepted: 18 March 2021; Published online: 24 May 2021

REFERENCES

1. Cummings, L. Clinical pragmatics. (Cambridge University Press, 2009).
2. Levinson, S. C. Pragmatics. (Cambridge University Press, 1983).
3. Morris, C. Foundations of the Theory of Signs. pure.mp.d (Chicago University Press, 1938).
4. Bara, B. G. Cognitive Pragmatics. (Press, MIT, 2010).
5. Corcoran, C. M. et al. Prediction of psychosis across protocols and risk cohorts using automated language analysis. World Psychiatry 17, 67–75 (2018).
6. Pauselli, L. et al. Computational linguistic analysis applied to a semantic fluency task to measure derailment and tangentiality in schizophrenia. Psychiatry Res. 263, 74–79 (2018).
7. Le, T. P., Najjola, G. M., Minor, K. S. & Cohen, A. S. The effect of limited cognitive resources on communication disturbances in serious mental illness. Psychiatry Res. 248, 98–104 (2017).
8. Rieber, R. W. & Vetter, H. The problem of language and thought in schizophrenia: a review. J. Psycholinguist. Res. 33, 149–195 (1994).
9. Sassen, H. H., Albers, M., Tewesmeier, M. & Woggon, B. Pergamon. Speaking behavior and voice sound characteristics associated with negative schizophrenia. J. Psychiatri Res. 29, 4–6 (1995).
10. Delisi, L. E. Speech disorder in schizophrenia: review of the literature and exploration of its relation to the uniquely human capacity for language. Schizophr. Bull. 27, 481–496 (2001).
11. Covington, M. A. et al. Schizophrenia and the structure of language: the linguis’t view. Schizophr. Res. 77, 85–98 (2005).
12. Knaepelin E. Dementia Precocix and Paraph capsules. (Edinburgh, UK: University of Edinburgh, 1919).
13. Leccours, A. & Vanier-Clément, M. Schizophrenia and jargonaphasia: a comparative description with comments on Chaux’s and Fromkin’s respective looks at “schizophrenic” language. Brain Lang. 3, 516-555 (1976).
14. Andreasen, N. C. & Grove, W. M. Thought, language, and communication in schizophrenia: diagnosis and prognosis. Schizophr. Bull. 12, 348–359 (1986).
15. Firth, C. D., & Allen, H. A. Language disorders in schizophrenia and their implications for neuropsychology, in Schizophrenia: The major issues (eds. Bebbington P. & Malcolm F.) p. 172–186 (Heinemann Medical Books/Heinemann Professional Publishing, 1988).
16. Moro, A. et al. Detecting syntactic and semantic anomalies in schizophrenia. Neuropsychologia 79, 147–157 (2015).
17. Bambini, V. et al. The communicative impairment as a core feature of schizophre- nia: frequency of pragmatic deficit, cognitive substrates, and relation with quality of life. Compr. Psychiatry 71, 106–120 (2016).
18. Bosco, F. M., Berardine, L. & Parola, A. The ability of patients with schizophrenia to comprehend and produce sincere, deceitful, and ironic communicative intentions: the role of theory of mind and executive functions. Front. Psychol. 10, 827 (2019).
19. Bucus, A. “Pragmatics disorders and indirect reports in psychotic language,” in Indirect Reports and Pragmatics in the World Languages, (eds. Capone A., Garcia-Carpintero M. & Falzone A.) 439–453 (Cham: Springer, 2018).
20. Cale, L. et al. Understanding the communicative impa- riments in schizophrenia: a preliminary study. J. Commun. Disord. 46, 294–308 (2013).
21. Parola, A. et al. Pragmatics, theory of mind and executive functions in schizo- phrenia: disentangling the puzzle using machine learning. PloS ONE 15, e0229603 (2020).
22. Parola, A., Brasso, C., Morese, R., Rucca, P. & Bosco, F. M. Understanding commu- nictive intentions in schizophrenia using an error analysis approach. npj Schizophrenia 7, 45–50 (2021).
23. Varga, E. et al. Compensatory effect of general cognitive skills on non-literal language processing in schizophrenia: a preliminary study. J. Neurolinguist. 29, 1–16 (2014).
85. Corcoran, R., Mercer, G. & Frith, C. D. Schizophrenia, symptomatology and social inference: investigating ‘theory of mind’ in people with schizophrenia. Schizophr. Res. 17, 5–13 (1995).
86. Champagne-Lavau, M. & Stip, E. Pragmatic and executive dysfunction in schizophrenia. J. Neurolinguist. 23, 285–296 (2010).
87. Shryane, N. M. et al. Deception and false belief in paranoia: modelling theory of mind stories. Cogn. Neuropsychiatry 13, 8–32 (2008).
88. Moore, R. et al. Misunderstanding the intentions of others? An exploratory study of the cognitive etiology of persecutory delusions in very late-onset schizophrenia-like psychosis. Am. J. Geriatr. Psychiatry 14, 410–416 (2006).
89. Langdon, R., Siegert, R. J., McClure, J. & Harriott, L. Schizophrenia, theory of mind, and persecutory delusions. Cogn. Neuropsychiatry 10, 87–104 (2005).
90. Walther, S. et al. Social communication and gesture control in schizophrenia. Schizophr. Bull. 41, 338–345 (2015).
91. Edwards, J., Jackson, H. J. & Pattison, P. E. Emotion recognition via facial expression and affective prosody in schizophrenia: a methodological review. Clin. Psychol. Rev. 22, 789–832 (2002).
92. Stegmayer, K. et al. Gesture performance in first- and multiple-episode patients with schizophrenia spectrum disorders. Neuropsychobiology 73, 201–208 (2016).
93. Sullivan, K., Winner, E. & Hopfield, N. How children tell a lie from a joke: the role of second-order mental state attributions. Br. J. Dev. Psychol. 13, 191–204 (1995).
94. Bedi, G. et al. Automated analysis of free speech predicts psychosis onset in high-risk youths. npj Schizophr. 1, 15030 (2015).
95. Sullivan, S. A. et al. A longitudinal investigation of childhood communication ability and adolescent psychotic experiences in a community sample. Schizophr. Res. 173, 54–61 (2016).
96. Bambini, V. et al. Communication and pragmatic breakdowns in amyotrophic lateral sclerosis patients. Brain Lang. 153, 1–12 (2016).
97. Pawelczyk, A., Lojek, E., Zurne, N., Gawłowska-Sawosz, M. & Pawelczyk, T. Higher-order language dysfunctions as a possible neurolinguistic endophenotype for schizophrenia: evidence from patients and their unaffected first degree relatives. Psychiatry Res. 267, 63–72 (2018).
98. American Psychiatric Association, DSM-IV: Diagnostic and Statistical Manual of Mental Disorders | JAMA | JAMA Network. (American Psychiatric Press Inc, 1994).
99. Folstein, M. F., Folstein, S. E. & McHugh, P. R. Mini-mental state: a practical method for grading the cognitive state of patients for the clinician. J. Psychiatr. Res. 12, 189–198 (1975).
100. De Renzi, E. & Vignolo, L. A. The token test: a sensitive test to detect receptive disturbances in aphasics. Brain 85, 665–678 (1962).
101. Huber, W., Poeck, K. & Willmes, K. The Aachen Aphasia Test. Adv. Neurol. 42, 291–303 (1983).
102. Angeleri, R., Bosco, F. M., Gabbatore, I., Bara, B. G. & Sacco, K. Assessment battery for communication (ABaCo): normative data. Behav. Res. Methods 44, 845–861 (2012).
103. Sacco, K. et al. Assessment battery for communication—ABaCo: a new instrument for the evaluation of pragmatic abilities. J. Cogn. Sci. 9, 111–157 (2008).
104. Bosco, F. M., Angeleri, R., Zuffranieri, M., Bara, B. G. & Sacco, K. Assessment battery for communication: development of two equivalent forms. J. Commun. Disorder. 45, 290–303 (2012).
105. Angeleri, R., Bara, B. G., Bosco, F. M., Colle, L. & Sacco, K. Batteria Per L’Assessment Della Comunicazione (ABaCo). (Giunti OS Organizzazioni Speciali, 2015).
106. Angeleri, R., Gabbatore, I., Bosco, F. M., Sacco, K. & Colle, L. Pragmatic abilities in children and adolescents with autism spectrum disorder: a study with the ABaCo battery. Minerva Psychiatr. 57, 93–103 (2016).
107. Parola, A. et al. Assessment of pragmatic impairment in right hemisphere damage. J. Neurolinguist. 39, 10–25 (2016).
108. Ross Quinlan, B. J., Kaufmann Publishers, M.& Salzberg, S. L. Programs for Machine Learning. 16, (1994).
109. Frank, E., Hall, M. A. & Witten, I. H. The WEKA workbench. Online Appendix for ‘Data Mining: Practical Machine Learning Tools and Techniques’. Online Appendix for ‘Data Mining: Practical Machine Learning Tools and Techniques’ (2016).

ACKNOWLEDGEMENTS

This work was supported by the Compagnia di San Paolo under Grant Bando Ex-post Università di Torino, grant number D11G19000220007 and by FAPEG Mobility Confap-Italy (MCI-2018).

AUTHOR CONTRIBUTIONS

Study design: A.P., R.S., I.G., and F.M.B. Data curation: A.P., R.S., and I.G. Formal analysis: R.S. Investigation: I.G., A.P., and L.B. Supervision: F.M.B. Original draft and revised versions: A.P., R.S., and I.G., F.M.B. Final approval of the completed version: A. P., R.S., I.G., L.B., and F.M.B.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41537-021-00153-4.

Correspondence and requests for materials should be addressed to I.G.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.