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Neuropsychological Testing and Structural Magnetic Resonance Imaging as Diagnostic Biomarkers Early in the Course of Schizophrenia and Related Psychoses

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Abstract

Making an accurate diagnosis of schizophrenia and related psychoses early in the course of the disease is important for initiating treatment and counseling patients and families. In this study, we developed classification models for early disease diagnosis using structural MRI (sMRI) and neuropsychological (NP) testing. We used sMRI measurements and NP test results from 28 patients with recent-onset schizophrenia and 47 healthy subjects, drawn from the larger sample of the Mind Clinical Imaging Consortium. We developed diagnostic models based on Linear Discriminant Analysis (LDA) following two approaches; namely, (a) stepwise (STP) LDA on the original measurements, and (b) LDA on variables created through Principal Component Analysis (PCA) and selected using the Humphrey-Ilgen parallel analysis. Error estimation of the modeling algorithms was evaluated by leave-one-out external cross-validation. These analyses were performed on sMRI and NP variables separately and in combination. The following classification accuracy was obtained for different variables and modeling algorithms. *sMRI only*: (a) STP-LDA: 64.3% sensitivity and 76.6% specificity, (b) PCA-LDA: 67.9% sensitivity and 72.3% specificity. *NP only*: (a) STP-LDA: 71.4% sensitivity and 80.9% specificity, (b) PCA-LDA: 78.5% sensitivity and 91.5% specificity. *Combined sMRI-NP*: (a) STP-LDA: 64.3% sensitivity and 83.0% specificity, (b) PCA-LDA: 89.3% sensitivity and 93.6% specificity. (i) Maximal diagnostic accuracy was achieved by combining sMRI and NP variables. (ii) NP variables were more informative than sMRI, indicating that cognitive deficits can be detected earlier than volumetric structural abnormalities. (iii) PCA-LDA yielded more accurate classification than STP-LDA. As these sMRI and NP tests are widely available, they can increase accuracy of early intervention strategies and possibly be used in evaluating treatment response.

Keywords

Schizophrenia; Schizophreniform; Schizoaffective; PCA; LDA; Biomarkers; Neuropsychology; MRI; Cross-validation; Diagnosis; MCIC

Introduction

Making an accurate diagnosis after a first psychotic episode is important for initiating treatment and counseling patients and families (Harrigan et al. 2003). Classification systems for psychiatric disorders are distinguished from the classification of other diseases by their major reliance on behavioral signs and symptoms. Nearly 40 years ago Robins and Guze (1970) outlined a means for developing laboratory tests for mental disorders in order to improve the reliability and validity of classification and move diagnostic assessment beyond

clinical description. They suggested that, following clinical description, one should strive to identify reliable and precise laboratory measures to assist in diagnosis. Neuropsychological (NP) measures of cognitive dysfunction are reliable and in most cases are precise throughout disease progression. On the other hand, structural MRI (sMRI) of the brain can generate reliable and precise estimates of brain volumes. Several experimental studies have revealed abnormalities in schizophrenia using NP or sMRI measures (Andreasen et al. 1990; Ballmaier et al. 2008; Hawkins 1999; Hulshoff Pol and Kahn 2008; Leeson et al. 2008; Midorikawa et al. 2008; Segall et al. 2009; Wang et al. 2008; Watson et al. 1981). Thus, NP and sMRI are suitable candidate laboratory tests for the early identification of individuals with schizophrenia and related psychoses.

Our goal in this study was to develop and evaluate diagnostic models for recent-onset schizophrenia spectrum illnesses based on NP and sMRI variables, in combination and separately. The choice to evaluate recent-onset patients was based on our intent to develop diagnostic tools that can be of practical adjunct use in a real-life first visit to a mental health clinic. To this end, we drew participants from four geographic regions of the United States (Minnesota, New Mexico, Iowa, and Massachusetts).

Previous work by our group demonstrated the potential of applying Linear Discriminant Analysis (LDA) (Green 1978) on accurately diagnosing adult (Georgopoulos et al. 2007) and adolescent (Pardo et al. 2006) schizophrenic patients. To evaluate recent-onset patients in the current study we followed two approaches. In the first approach, based on stepwise (STP) LDA (Dixon 1992), we selected subsets of pertinent variables which would lead to faster models, risking however the rejection of useful information. In the second approach, based on Principal Component Analysis (PCA) (Green 1978) and LDA, we aimed at maximally exploiting data information from our sample, leading to potentially more accurate tests. Through these two approaches we sought to develop NP and sMRI models that could be used as biomarkers for the diagnosis of recent-onset psychotic disorders. In addition, we sought to obtain an unbiased error estimate of future performance of the modeling algorithms using external-cross-validation (Ambroise and McLachlan 2002).

Method

Subject Selection

Subjects were selected from the larger MIND Clinical Imaging Consortium (MCIC) sample (Segall et al. 2009). In the Consortium, prospective recent-onset patients and healthy subjects underwent structured CASH or SCID-I diagnostic interview evaluations by trained assessors (Andreasen et al. 1992; First et al. 2001), sMRI scanning and NP testing. The disease was labeled as of “recent-onset” when any one of the following criteria was present: (a) psychotic symptoms of any duration with a maximum lifetime exposure of 10 mg haloperidol equivalents, (b) psychotic symptoms of no more than 5 years duration, combined with no or minimal antipsychotic exposure (no more than a total lifetime exposure of the equivalent of 10 mg haloperidol), (c) psychotic symptoms of no more than 5 years duration, combined with no more than 12 weeks of antipsychotic exposure, and with no exposure during the previous 3 weeks, or (d) psychotic symptoms of no more than 2 years duration, combined with no more than 6 months of antipsychotic exposure.

Patients had one of the following diagnoses: schizophrenia, schizophreniform disorder, or schizoaffective disorder. We used data from 47 healthy controls and 28 patients ($N_{\text{total}}=75$) in this analysis. (From a total of 84 subjects available, 9 were excluded due to incomplete NP testing.) The demographic characteristics of the two groups are presented in Table 1 (Hollingshead and Redlich 1958). After complete description of the study to the subjects, written informed consent was obtained. Procedures were in accordance with the policies and

ethical standards of the institutional review boards at the four sites and the Declaration of Helsinki (World Medical Association General Assembly 2004).

Neuropsychological Assessment

Neuropsychological assessment was based on a battery of tests (Annett 1970; Brandt 1991; Delis et al. 2001; Miller 1990; Reitan 1958; Ruff and Parker 1993; Shallice 1982; Wechsler 1997a, b; Wilkinson 1993) yielding a total of 75 scores, the specifics of which are given in Table 2. None of the NP variables was a composite of others (i.e. sums, averages), which allowed maximum non-overlapping information to be incorporated in the models without adding redundant variables. It is also important to note that none of these 75 variables was used in diagnosing patients. The approximate duration to complete these tests was 3 hours.

sMRI Processing

Cross-site sMRI acquisition calibration and reliability were established in a preceding study using human phantoms following guidelines developed by the Biomedical Informatics Research Network (BIRN) testbed for morphometry (Jovicich et al. 2006, 2009). The MRI acquisition protocol for high-resolution coronal T1-weighted images were matched across the four different sites (University of Minnesota: Siemens 3 T Trio, University of Iowa: Siemens 1.5 T Sonata, Massachusetts General Hospital and University of New Mexico: Siemens 1.5 T Avanto): 3 T Trio: TR/ TE/flip angle=2.53 s/3.79 ms/7°, 1.5 T Sonata: TR/ TE/flip angle=20 ms/6 ms/20°, 1.5 T Avanto TR/TE/flip angle 12 ms/4.76 ms/20°, FOV=16×16 cm, 128 contiguous slices (imaging matrix=256×256, in plane resolution=0.625×0.625 mm, slice thickness=1.5 mm), NEX=3. Acquisition time for this Gradient Echo sequence was approximately 20 minutes.

Volumetric measurements of brain areas were obtained from sMRI scans in an automated manner using the Freesurfer software package (<http://surfer.nmr.mgh.harvard.edu>, Version 4.0.1) (Fischl et al. 2002). Minor manual intervention following the standard Freesurfer processing manuals was required for the MRI data of one subject. A total of 95 sMRI variables were used in this analysis (Table 3). The approximate total duration for an MRI acquisition was 40 minutes.

Model Development

Two types of models were developed for discriminating recent-onset patients from healthy controls. Both analyses were based on LDA (Green 1978). The first analysis was applied on the raw data. STP-LDA was performed using Wilk's Λ as a criterion, with an enter-criterion of $p=0.05$ and a remove-criterion of $p=0.10$. This analysis yielded classification functions from subsets of the original variables. The second analysis involved a dimensionality reduction and was applied on standardized data. For that purpose, raw values were transformed to z-scores (across subjects, within each variable) and then subjected to PCA (Green 1978). An LDA was performed using the first k principal components as predictors; k was determined using Humphrey-Ilgen's permutation procedure (O'Connor 2000). Finally, in both analyses, prior probabilities for the two groups were set to be equal in the LDA (chance level= 50%). This allowed easier, and more accurate, data interpretation since more controls were in the study (47 vs. 28). If priors were not set equal and a model were biased towards controls, the model would have higher overall accuracy and specificity on the specific sample simply by chance (up to 47/75=62.7%), though sensitivity would be lower.

Variable Sets Used

The two analyses mentioned in the preceding paragraph were applied under three variable settings: (a) using only NP variables, (b) using only sMRI variables, and (c) using both NP

and sMRI variables. This approach allowed us to evaluate how accurate the prediction is by each set of variables separately, and whether their combination might improve or worsen classification.

External Cross-Validation

In addition to developing models that discriminate the two groups, we were interested in evaluating the accuracy of our modeling algorithms on new subjects through cross-validation. For that purpose, we used an external leave-one-out loop. Specifically, before any analysis was performed, a single subject was left out and was used only to cross-validate our results, avoiding selection bias and, thus, overfitting (Ambroise and McLachlan 2002; Duda et al. 2001). This operation was iteratively applied until all subjects were left out (Fig. 1). With respect to PCA-LDA, the z-scores and principal components of each external subject were computed based on coefficients derived from the remaining subjects.

Ultimately, both STP-LDA and PCA-LDA yielded classification tables from which the performance of the two classification methods was evaluated by computing the following measures: overall accuracy of classification, sensitivity, specificity, positive likelihood-ratio, negative likelihood-ratio, χ^2 and the odds-ratio (i.e. strength and direction of the association).

STP-LDA Models for All Subjects

The external cross-validation analyses described in the preceding section were aimed to assess the success (or error) rates of the classification algorithms but cannot provide consistent information concerning the relative importance of the NP and/or sMRI predictors, since those varied depending on the particular subject left out. This information can be gained by performing the same analyses using all subjects. For that purpose, we developed specific models for the STP-LDA using all 75 available subjects under the three settings described above, and evaluated the relative contribution of each variable to the respective model. Each variable's contribution was assessed based on its standardized coefficient. We further investigated how the variables selected in the STP-LDA models relate to the disease using ANOVA with group as a fixed factor and an ANCOVA using sex, age, and intracranial volume as covariates. In the case of the PCA-LDA the analysis described above was not performed since all variables contribute to all principal components and by extension to the LDA.

Software Packages Used

PCA-LDA was performed using the MatLab software package and built-in functions, except for Humphrey-Ilgen analysis which was based on free access code by O'Connor (2000). Regarding STP-LDA this was performed using the SPSS version 15 software package. Special care was taken to remove a subject from the external leave-one-out loop prior to any analysis (Fig. 1), since the SPSS built-in stepwise function selects variables prior to removing a subject and only removes a subject prior to calculating variable coefficients. Settings for each analysis are described in the respective methods sections.

Results

The results of the external cross-validation are presented in Table 4. Ordered contributions of original variables for the proposed final STP-LDA models are presented in Table 5 and their individual relations to the disease group are presented in Table 6.

In general, models developed under PCA-LDA achieved better classification than those under STP-LDA, except for the sMRI-only setting where results were comparable. For the

PCA-LDA, NP-only was better than sMRI-only models, while the combination of NP and sMRI variables provided the best classification. In contrast, classification accuracy for STP-LDA was comparable across all combinations of data (NP-only, sMRI-only, NP-sMRI).

The NP variables that were selected through STP-LDA reflected visual memory, problem solving, executive function, and spatial motor abilities. In all those NP tests patients performed worse than controls. Regarding the selected sMRI variables, they were mostly from frontal, temporal and subcortical areas. Of the sMRI variables that had a significant group effect, patients had smaller left precentral brain volume, but larger volume for all the other structures. This remained consistent even when accounting for age, sex, and intracranial volume for variables with significant differences between groups.

Discussion

Overall Diagnostic Usefulness

We applied STP-LDA and PCA-LDA under three settings (NP-only, sMRI-only, Combined NP-sMRI) to discriminate recent-onset psychotic patients and controls. Rejection of the null hypothesis that classification was due to chance was achieved for all modeling approaches under all settings ($\chi^2 \geq 11.6$; $p \leq 7 \times 10^{-4}$). These results indicate that both methods under all three settings can contribute at a variable level to disease diagnosis (i.e. accurately identifying whether an individual does or does not suffer from a psychotic disorder).

PCA-LDA vs. STP-LDA

When comparing between the two modeling methods, there was generally better classification with the PCA-LDA than with the STP-LDA algorithm, with the exception of the sMRI-only setting where results were comparable (compare top vs. bottom of Table 4). This finding indicates that PCA-LDA is more robust as a classification model probably due to the greater amount of accounted total variance. In the case of the STP-LDA, only certain variables are selected each time and, in addition, these variables partially covary (i.e. carry common information). On the other hand, the variables selected through PCA are composites of all original variables, and are between them orthogonal (zero covariance).

NP-Only vs. sMRI-only vs. Combined NP-sMRI

Comparison of the three variable settings is slightly more complicated. When comparing individually the NP-only setting to the sMRI-only setting, better classification is achieved using only NP variables under both algorithms. This finding indicates that there is more pertinent information in the NP relative to sMRI variables and, by extension, that cognitive deficits are probably more sensitive to the occurrence of psychotic disorders than structural abnormalities. However, this finding does not necessitate that an sMRI-only model cannot be developed, but rather that the amount of information used and the approach followed did not lead to any strong sMRI diagnostic measure.

The improved classification of the NP-sMRI combination only for the PCA-LDA, but not for the STP-LDA can be explained as follows. Through PCA-LDA all variables contribute to each principal component, and thus more of the original variance is incorporated in a model. On the other hand, through STP-LDA, a selection always has to be performed and the amount of variance explained will probably not be as large. In our case, the extra variance incorporated in the PCA-LDA was relevant to discriminating healthy subjects from patients. However, if the combination of variables added information irrelevant to disease diagnosis, then classification could have been worse. It is the relevance of variables to disease diagnosis that makes the NP-sMRI PCA-LDA method the best approach.

Best Model

From the modeling methods applied, the best diagnostic outcome for all measures was provided under the Combined NP-sMRI setting of the PCA-LDA algorithm. The high values of sensitivity (89.3%), specificity (93.6%), positive likelihood-ratio (13.99), and diagnostic odds-ratio (122.22), and the low negative likelihood-ratio (0.11) suggest a diagnostic usefulness of the PCA-LDA under combined NP-sMRI. The fact that all variables need to be used in this model makes it a better candidate as an adjunct in disease diagnosis rather than a fast screening tool (i.e. approximately three and a half hours for a subject to undergo all NP and sMRI testing).

Utility of Other Models

On the other hand, when it comes to a faster model, it is more practical to use fewer variables. That can be achieved through the STP-LDA models. In these models, sensitivity and specificity are good, yet not as high as in the best model presented above. Overall, the findings on the STP-LDA models do not make them ideal screening tests, but there are indications of their usefulness as faster tools (duration of about 1 h for the NP-only) and with the introduction of more subjects in the MCIC database prediction could improve. NP-only models can be useful to a health provider since NP tests are straightforward in their administration and, even more, there are now objective computerized tests that can be widely available to the community, even in remote areas. Similarly, in those cases where patients visiting the doctor's office have already had an MRI, an sMRI-only model could be used as an adjunct during initial evaluation.

Variable Contribution in STP-LDA

The fact that differences in NP score means were more significant than sMRI variables indicates that cognitive deficits are more sensitive for early diagnosis than volumetric structural deficits and, thus, also supports the findings discussed above. The specific variables that were selected by the STP-LDA related to memory (verbal and visual), motor dexterity and speed, visuospatial abilities, and executive function. Patients consistently performed worse in these tests relative to controls (see Table 6). These findings are in agreement with a large body of evidence on the nature of cognitive deficits in chronic and first-episode schizophrenia (Hawkins 1999; Leeson et al. 2008; Midorikawa et al. 2008; Watson et al. 1981).

The sMRI structures that were selected by STP-LDA were frontal, temporal and subcortical. The involvement of basal ganglia in schizophrenia has been reported in MRI studies of minimally medicated patients, however volumetric differences between groups have not been consistently observed, with larger, smaller, or equal volumes in patients versus controls (Ballmaier et al. 2008; Glenthøj et al. 2007; Kawasaki et al. 2004; Velakoulis et al. 2002; Wang et al. 2008). Our findings indicate a tendency for increased putamen and pallidum volumes in patients. On the other hand, the relation observed between increased ventricle size and schizophrenia is better characterized in the literature and consistently observed (Andreasen et al. 1990; Hulshoff Pol and Kahn 2008). Regarding the volumetric differences in the frontal and temporal lobes, results from previous research indicate an association between decreased volume and schizophrenia (Borgwardt et al. 2007; Hazlett et al. 2008; Kawasaki et al. 2004; Velakoulis et al. 2002). However, there are several reports for regional variability within lobes (Selemon 2001). Szeszko et al. (1999) report volume variability within lobes, specifically, more frontal subregions in the frontal lobe having increased size and posterior subregions having decreased size in patients, which agrees with our findings (increased frontal pole volume and decreased precentral volume). The only finding in our results that has not been reported in previous studies is the increased size of the right parahippocampal cortex (Baaré et al. 2001). This could be due to the fact that the

patients in the study were recent-onset, and decreased volume of temporal structures is associated with increased disease duration (Velakoulis et al. 2002). On a cellular level, the volumetric differences above can be explained through synaptic pruning in the cortex (Harrison 1999; Keshavan et al. 1994; Selemon 2001) and an increase in the number of synapses in the basal ganglia (Roberts et al. 2008).

This research, which uses computerized assessment of MRI scans, a thorough neuropsychological test battery, and a sophisticated analysis procedure carries potential for clinical application. It is possible that the MRI and neuropsychological indices may be useful for cases that are difficult to diagnose; however, in the current study only research subjects who met diagnostic criteria on a standard structured interview were included in the analysis. Therefore, the potential for neuropsychological and MRI procedures to assist specifically in complex cases is not fully tested. The present findings represent a first step in identifying indices that are viable candidates for biomarkers to enhance diagnostic determinations in schizophrenia.

As this study addresses the utilization of sMRI and neuropsychological testing for classification, it is appropriate to note prior results in this sample from more traditional group-based analyses. Regarding neuropsychological testing, Sponheim et al. (2009) have reported that both the recent-onset and chronic schizophrenic subjects exhibit a wide range of cognitive deficits compared to controls, which is consistent with the body of findings documenting cognitive dysfunction in schizophrenia. Regarding sMRI, one published report describes gray matter in MCIC subjects combined with a sample of BIRN subjects in order to increase power in detecting differences between patients and controls (Segall et al. 2009). Statistically significant differences in gray matter concentration were evident between schizophrenic patients and controls for similar brain regions across the various study sites. Thus, traditional group-based analyses on sMRI and neuropsychological measures carry some diagnostic utility. Of note, however, the above studies included both recent-onset and chronic schizophrenic patients in their analyses.

Practical Considerations

It is important to keep in mind that we evaluated minimally medicated patients who resemble patients coming to the office for the first time. This makes the derived models useful adjuncts in verifying the diagnosis early in the course of the disease with high specificity and sensitivity. The use of sMRI and NP tests allows objective measures to be incorporated into disease diagnosis, thus negating the subjectivity of structured interviews while allowing, at the same time, non-specialists to contribute in screening for disease through computerized tests. This would be an asset in rural areas and primary care centers. Even more, such models can potentially be used as surrogate biomarkers for treatment response. Full description of the Mind Clinical Imaging Consortium data base and tools for data abstraction can be accessed as referenced below (see Information Sharing Statement). The databases are currently being expanded to include data on genetic variation in the sample. Analyses that examine a combination of single nucleotide polymorphisms (SNPs), structural MRI, functional MRI, and cognitive performance may further enhance the utility of biomarkers to assist with diagnostic determinations of schizophrenia.

The best model proposed is that of the PCA-LDA with all NP and sMRI variables included. However, useful information can be obtained from the NP variables only, if, for example, a faster test were desirable. In general, the accuracy of modeling algorithms is likely to be improved with increase in the number of subjects studied. Moreover, this approach holds promise for differential diagnosis, for example, between schizophrenia and bipolar disorder (Pardo et al. 2006), with and without psychotic features, as well as between schizophrenia and schizophreniform disorder. Finally, current criteria require 6 months for the specific

diagnosis of schizophrenia to be established. If our models successfully pass all phases of biomarker development (Pepe 2005), they could help make these criteria more efficient and lead to early discrimination between schizophreniform disorder and schizophrenia.

Information Sharing Statement

For more information on the methods, models, applications and tools used in this article, when they are publically available, please visit <https://portal.mind.unm.edu/mcic/public/>. Data will be accessible on Xnat (<http://www.xnat.org/>) in the near future.

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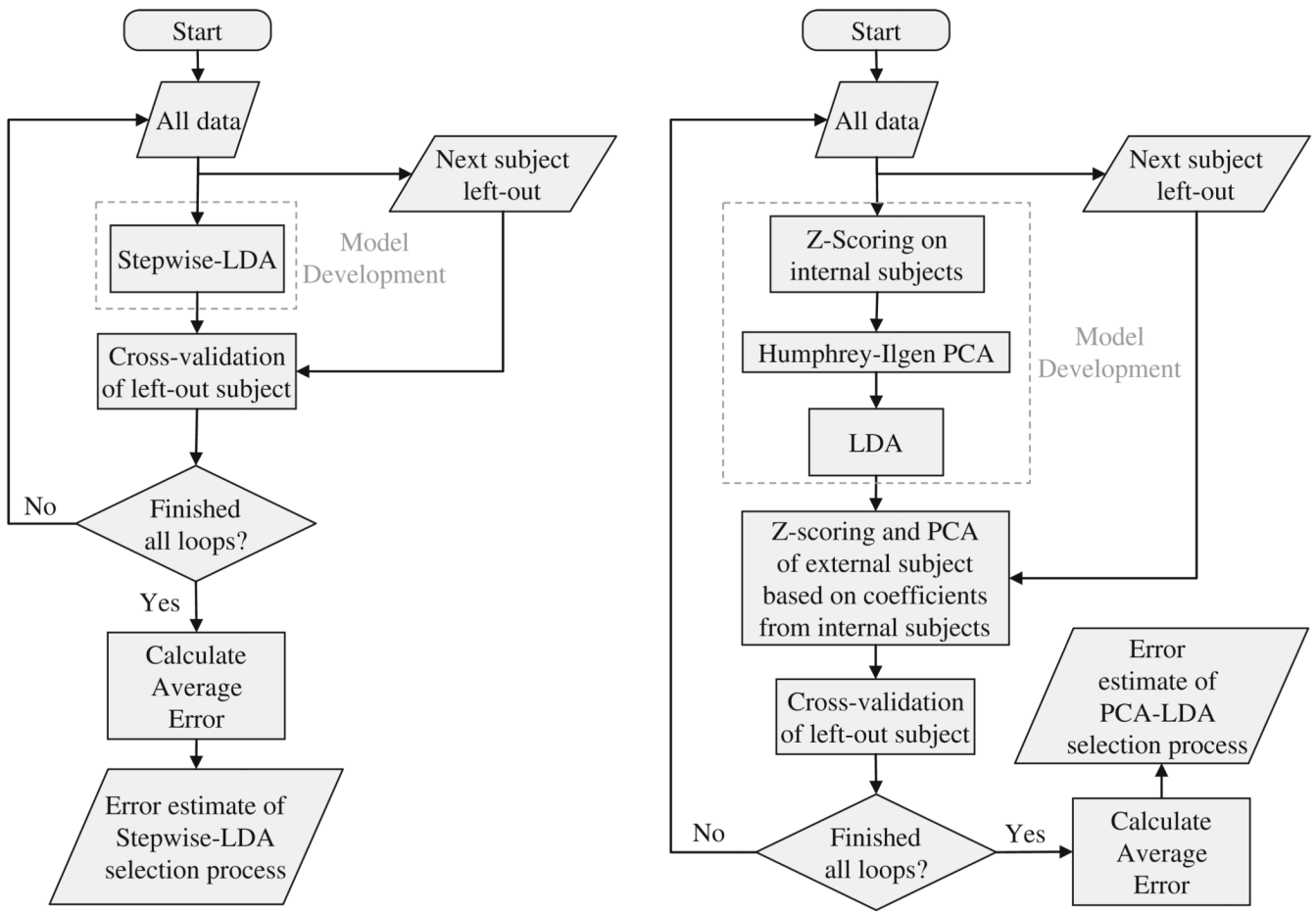


Fig. 1. Flowchart of model development and external cross-validation for the STP-LDA and the PCA-LDA

Table 1

Subject demographics

Group	Age (years)		Duration of Diagnosis (years)		Treatment Duration (years)		Sex		Ethnicity			Race					Parental SES ^a					Highest Education (years)			Handedness ^b				
	Mean	SD	Mean	range	Mean	range	Male	Female	Hispanic	Non-Hispanic	Native American	Asian	Black	White	1	2	3	4	5	0	1	2	3	4	5	Mean	SD	R	A
Patients	24.32	5.05	2.2	0.03–12.3	0.8	0.04–4.0	22	6	5	23	0	1	4	23	1	9	13	5	0	13.67	2.23	26	1	1					
Controls	26.38	6.6	NA	NA	NA	NA	27	20	6	41	2	1	0	44	1	10	34	2	0	14.98	1.81	43	2	2					

^aSES: socioeconomic status as measured by the modified Hollingshead scale. 1 = wealth, prestige; 2 = advanced degree; 3 = white collars, small businesses; 4 = semi-skilled workers, second level of education; 5 = semi-skilled workers, elementary education

^bR = right-handed; L = left-handed; A = ambidextrous

Table 2

Neuropsychological variables used

	NP Test^{a,b,c,d}	NP name	Function/Domain assessed
1	Annett Scale of Hand Preference	Continuous (SUM)	Handedness
2	WRAT-3 Reading	Total Reading	Reading/Potential or Premorbid IQ
3	Benton Visual Retention	Error Categories: Omissions	Visual memory
4	Benton Visual Retention	Error Categories: Distortions	Visual memory
5	Benton Visual Retention	Error Categories: Perseverations	Visual memory
6	Benton Visual Retention	Error Categories: Rotations	Visual memory
7	Benton Visual Retention	Error Categories: Misplacements	Visual memory
8	Benton Visual Retention	Error Categories: Size Errors	Visual memory
9	Benton Visual Retention	Error Categories: Left Errors	Visual memory
10	Benton Visual Retention	Error Categories: Right Errors	Visual memory
11	Benton Visual Retention	Number Correct Score	Visual memory
12	Category Fluency	Vegetables	Verbal/Linguistic
13	Letter Fluency	Starts With 'F'	Verbal/Linguistic
14	Letter Fluency	Starts With 'A'	Verbal/Linguistic
15	Letter Fluency	Starts With 'S'	Verbal/Linguistic
16	Category Fluency	Animals	Verbal/Linguistic
17	Category Fluency	Fruits	Verbal/Linguistic
18	WAIS-3	Block Design Total Raw Score	Spatial motor coordination
19	WAIS-3	Letter-Number Total Raw Score	Working memory
20	WAIS-3	Vocabulary Total Raw Score	Verbal/Linguistic
21	WAIS-3	Similarities Total Raw Score	Verbal abstraction
22	WMS-3 (Immediate)	Story A Recall Score	Verbal declarative memory
23	WMS-3 (Immediate)	Story A Thematic Score	Verbal declarative memory
24	WMS-3 (Immediate)	Story B 1st recall score	Verbal declarative memory
25	WMS-3 (Immediate)	Story B 1st recall Thematic score	Verbal declarative memory
26	WMS-3 (Immediate)	Story B 2nd recall score	Verbal declarative memory
27	WMS-3 (Immediate)	Story B 2nd recall Thematic score	Verbal declarative memory
28	Trail Making	Trials A: Time	Problem solving/Executive
29	Trail Making	Trials A: Errors	Problem solving/Executive
30	Trail Making	Trials B: Time	Problem solving/Executive
31	Trail Making	Trials B: Errors	Problem solving/Executive
32	CalCap	SRT Base: Reaction Time	Processing speed & attention
33	CalCap	CRT Base: Reaction Time	Processing speed & attention
34	CalCap	CRT Base: True Positive	Processing speed & attention
35	CalCap	CRT Base: False Positive	Processing speed & attention
36	CalCap	CRT SEQ1: Reaction Time	Processing speed & attention
37	CalCap	CRT SEQ1: True Positive	Processing speed & attention
38	CalCap	CRT SEQ1: False Positive	Processing speed & attention
39	CalCap	CRT SEQ2: Reaction Time	Processing speed & attention

NP Test ^{a,b,c,d}	NP name	Function/Domain assessed	
40	CalCap	CRT SEQ2: True Positive	Processing speed & attention
41	CalCap	CRT SEQ2: False Positive	Processing speed & attention
42	WMS-3 (Delay)	Story A recall score	Verbal declarative memory
43	WMS-3 (Delay)	Story A Thematic score	Verbal declarative memory
44	WMS-3 (Delay)	Story B recall score	Verbal declarative memory
45	WMS-3 (Delay)	Story B Thematic score	Verbal declarative memory
46	WMS-3 (Delay)	Recognition Total Score	Verbal declarative memory
47	WMS-3 (Delay)	Percent Retention	Verbal declarative memory
48	Tower of London	Moves Made: 3 Ring	Problem solving/Executive
49	Tower of London	Moves Made: 4 Ring	Problem solving/Executive
50	Tower of London	Moves Made: 5 Ring	Problem solving/Executive
51	Tower of London	Avg. Pickup Time: 3 Ring	Problem solving/Executive
52	Tower of London	Avg. Pickup Time: 4 Ring	Problem solving/Executive
53	Tower of London	Avg. Pickup Time: 5 Ring	Problem solving/Executive
54	Tower of London	Avg. Total Time: 3 Ring	Problem solving/Executive
55	Tower of London	Avg. Total Time: 4 Ring	Problem solving/Executive
56	Tower of London	Avg. Total Time: 5 Ring	Problem solving/Executive
57	Tower of London	Total Trials Time: 3 Ring	Problem solving/Executive
58	Tower of London	Total Trials Time: 4 Ring	Problem solving/Executive
59	Tower of London	Total Trials Time: 5 Ring	Problem solving/Executive
60	Tower of London	Avg. Trial Time: 3 Ring	Problem solving/Executive
61	Tower of London	Avg. Trial Time: 4 Ring	Problem solving/Executive
62	Tower of London	Avg. Trial Time: 5 Ring	Problem solving/Executive
63	WMS-3 Faces (Immediate)	Recognition total score	Visual memory
64	WMS-3 Faces (Delay)	Recognition Total Score	Visual memory
65	Hopkins verbal learning (Immediate)	Total Raw: Trial 1	Verbal declarative memory
66	Hopkins verbal learning (Immediate)	Total Raw: Trial 2	Verbal declarative memory
67	Hopkins verbal learning (Immediate)	Total Raw: Trial 3	Verbal declarative memory
68	Grooved pegboard	Dominant Hand: # Drops	Fine motor dexterity & speed
69	Grooved pegboard	Non-dominant Hand: Time	Fine motor dexterity & speed
70	Grooved pegboard	Non-dominant Hand: # Drops	Fine motor dexterity & speed
71	Grooved pegboard	Dominant Hand: Time	Fine motor dexterity & speed
72	Hopkins verbal learning (Delay)	Delay Total Raw	Verbal declarative memory
73	Hopkins verbal learning (Delay)	Recognition: Hits	Verbal declarative memory
74	Hopkins verbal learning (Delay)	Recognition: F/A Related	Verbal declarative memory
75	Hopkins verbal learning (Delay)	Recognition: F/A Unrelated	Verbal declarative memory

^aWRAT: Wide Range Achievement Test—Third Edition

^bWAIS-3: Wechsler Adult Intelligence Scale—Third Edition

^cWMS-3: Wechsler Memory Scale-III

^dCalCap: California Computerized Assessment Package

Table 3

sMRI variables used

	sMRI name	sMRI name	sMRI name
1	Right caudal anterior cingulate	33 Right transverse temporal	65 Left temporal pole
2	Right caudal middle frontal	34 Left caudal anterior cingulate	66 Left transverse temporal
3	Right corpus callosum	35 Left caudal middle frontal	67 Left Cerebral White Matter
4	Right cuneus	36 Left corpus callosum	68 Left Cerebral Cortex
5	Right entorhinal	37 Left cuneus	69 Left Lateral Ventricle
6	Right fusiform	38 Left entorhinal	70 Left Inferior Lateral Ventricle
7	Right inferior parietal	39 Left fusiform	71 Left Cerebellum White Matter
8	Right inferior temporal	40 Left inferior parietal	72 Left Cerebellum Cortex
9	Right isthmus cingulate	41 Left inferior temporal	73 Left Thalamus Proper
10	Right lateral occipital	42 Left isthmus cingulate	74 Left Caudate
11	Right lateral orbitofrontal	43 Left lateral occipital	75 Left Putamen
12	Right lingual	44 Left lateral orbitofrontal	76 Left Pallidum
13	Right medial orbitofrontal	45 Left lingual	77 Third Ventricle
14	Right middle temporal	46 Left medial orbitofrontal	78 Fourth Ventricle
15	Right parahippocampal	47 Left middle temporal	79 Left Hippocampus
16	Right paracentral	48 Left parahippocampal	80 Left Amygdala
17	Right pars opercularis	49 Left paracentral	81 Left Accumbens area
18	Right pars orbitalis	50 Left pars opercularis	82 Right Cerebral White Matter
19	Right pars triangularis	51 Left pars orbitalis	83 Right Cerebral Cortex
20	Right pericalcarine	52 Left pars triangularis	84 Right Lateral Ventricle
21	Right postcentral	53 Left pericalcarine	85 Right Inferior Lateral Ventricle
22	Right posterior cingulate	54 Left postcentral	86 Right Cerebellum White Matter
23	Right precentral	55 Left posterior cingulate	87 Right Cerebellum Cortex
24	Right precuneus	56 Left precentral	88 Right Thalamus Proper
25	Right rostral anterior cingulate	57 Left precuneus	89 Right Caudate
26	Right rostral middle frontal	58 Left rostral anterior cingulate	90 Right Putamen
27	Right superior frontal	59 Left rostral middle frontal	91 Right Pallidum
28	Right superior parietal	60 Left superior frontal	92 Right Hippocampus
29	Right superior temporal	61 Left superior parietal	93 Right Amygdala

sMRI name	sMRI name	sMRI name
30 Right supramarginal	62 Left superior temporal	94 Right Accumbens area
31 Right frontal pole	63 Left supramarginal	95 Intracranial Volume
32 Right temporal pole	64 Left frontal pole	

Table 4

Results of external cross-validation

	NP-only			sMRI-only			Combined NP-sMRI		
	SZ	HC		SZ	HC		SZ	HC	
STP-LDA									
Predicted SZ	20	9	18	11	8		18	8	
Predicted HC	8	38	10	36	10		10	39	
Sensitivity (CI)%	71.4 (51.3–86.8)		64.3 (44.1–81.4)		64.3 (44.1–81.4)		64.3 (44.1–81.4)		
Specificity (CI)%	80.9 (66.7–90.9)		76.6 (62.0–87.7)		83.0 (69.2–92.4)		83.0 (69.2–92.4)		
Accuracy (CI)%	77.3 (66.2–86.2)		72.0 (60.4–81.8)		76.0 (64.8–85.1)		76.0 (64.8–85.1)		
Positive likelihood ratio (CI)	3.73 (2.10–6.41)		2.75 (1.57–4.65)		3.78 (2.00–7.12)		3.78 (2.00–7.12)		
Negative likelihood ratio (CI)	0.35 (0.21–0.59)		0.47 (0.29–0.73)		0.43 (0.28–0.66)		0.43 (0.28–0.66)		
Odds ratio (CI)	10.56 (3.58–31.14)		5.89 (2.17–16.25)		8.77 (3.01–25.59)		8.77 (3.01–25.59)		
χ^2 (p)	20.22 (7×10^{-6})		12.36 (4×10^{-4})		17.31 (3×10^{-5})		17.31 (3×10^{-5})		
PCA-LDA									
Predicted SZ	22	4	19	13	3		25	3	
Predicted HC	6	43	9	34	44		3	44	
Sensitivity (CI)%	78.6 (59.1–91.7)		67.9 (47.7–84.1)		89.3 (71.8–97.8)		89.3 (71.8–97.8)		
Specificity (CI)%	91.5 (79.6–97.6)		72.3 (57.4–84.4)		93.6 (82.5–98.7)		93.6 (82.5–98.7)		
Accuracy (CI)%	86.7 (76.8–93.4)		70.7 (59.0–80.6)		92.0 (83.4–97.0)		92.0 (83.4–97.0)		
Positive likelihood ratio (CI)	9.23 (4.16–21.55)		2.45 (1.47–3.87)		13.99 (6.02–32.00)		13.99 (6.02–32.00)		
Negative likelihood ratio (CI)	0.23 (0.14–0.40)		0.44 (0.26–0.73)		0.11 (0.05–0.25)		0.11 (0.05–0.25)		
Odds ratio (CI)	39.42 (10.35–149.36)		5.52 (2.02–15.10)		122.22 (23.99–622.85)		122.22 (23.99–622.85)		
χ^2 (p)	38.03 (7×10^{-10})		11.6 (7×10^{-4})		51.5 (7×10^{-13})		51.5 (7×10^{-13})		

CI, 95% confidence intervals for sensitivity, specificity and accuracy calculated based on the binomial theorem p, p-values

Table 5

Variable selection and ordered contribution during STP-LDA. All-subject model

Rank	NP name	sMRI name	NP and sMRI name
1	Benton Visual Retention: Error Categories: Left Errors	Frontal: Left precentral	Frontal: Left precentral
2	Grooved pegboard: Dominant Hand: Time	Subcortical: Right Pallidum	Tower of London: Total Trials Time: 5 Ring
3	WMS-3 (Delay): Story B recall score	Subcortical: Third Ventricle	WMS-3 (Delay): Recognition Total Score
4	Tower of London: Total Trials Time: 3 Ring	Frontal: Right frontal pole	Frontal: Left superior frontal
5	WMS-3 (Delay): Recognition Total Score	Temporal: Right parahippocampal	Subcortical: Left Putamen
6	Benton Visual Retention: Error Categories: Rotations		Benton Visual Retention: Error Categories: Distortions
7	Tower of London: Total Trials Time: 5 Ring		WMS-3 (Immediate): Story B 1st recall Thematic score
8	WMS-3 (Delay): Story B Thematic score		WMS-3 (Delay): Story B recall score
9	Benton Visual Retention: Error Categories: Perseverations		Subcortical: Right Accumbens area
10	Benton Visual Retention: Error Categories: Misplacements		Frontal: Right superior frontal
11	Grooved pegboard: Dominant Hand: # Drops		Benton Visual Retention: Error Categories: Misplacements
12	WAIS-3: Block Design Total Raw Score		Grooved pegboard: Non-dominant Hand: Time
13			Temporal: Right temporal pole

Table 6

Relationship to disease of individual variables from the STP-LDA

Variable name	Patients vs. Controls	F _[1,73]	p
Story B recall score	Worse	79.63	3×10 ⁻¹³
Story B Thematic score	Worse	53.22	3×10 ⁻¹⁰
Error Categories: Left Errors	Worse	38.18	3×10 ⁻⁸
Story B 1st recall Thematic score	Worse	37.93	4×10 ⁻⁸
Non-dominant Hand: Time	Worse	31.54	3×10 ⁻⁷
Total Trials Time: 5 Ring	Worse	30.88	4×10 ⁻⁷
Recognition Total Score	Worse	24.39	5×10 ⁻⁶
Error Categories: Distortions	Worse	24.34	5×10 ⁻⁶
Dominant Hand: Time	Worse	22.24	10 ⁻⁵
Block Design Total Raw Score	Worse	16.36	10 ⁻⁴
Error Categories: Misplacements	Worse	15.99	2×10 ⁻⁴
Error Categories: Perseverations	Worse	15.84	2×10 ⁻⁴
Right frontal pole	Larger	11.5	0.001
Right parahippocampal	Larger	8.14	0.006
Left precentral	Smaller	7.56	0.008
Left Putamen	Larger	6.66	0.012
Total Trials Time: 3 Ring	Worse	6.03	0.016
Right Pallidum	Larger	4.34	0.041
Third Ventricle	Larger	4.07	0.047
Right temporal pole	Larger	3.45	0.067 (ns)
Right Accumbens area	Larger	3.36	0.071 (ns)
Dominant Hand: # Drops	Worse	2.03	0.158 (ns)
Left superior frontal	Larger	0.25	0.615 (ns)
Right superior frontal	Larger	0.21	0.651 (ns)
Error Categories: Rotations	Worse	0.03	0.858 (ns)