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Article in *ACM Transactions on Multimedia Computing, Communications and Applications* · April 2020

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Machine learning techniques for the diagnosis of Alzheimer’s disease: A review

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Alzheimer’s disease is an incurable neurodegenerative disease primarily affecting the elderly population. Efficient automated techniques are needed for early diagnosis of Alzheimers. Many novel approaches are proposed by researchers for classification of Alzheimer’s disease. However, to develop more efficient learning techniques, better understanding of the work done on Alzheimers is needed. Here, we provide a review on 165 papers from 2005-2019 using various feature extraction and machine learning techniques. The machine learning techniques are surveyed under three main categories: support vector machine (SVM), artificial neural network (ANN), and deep learning (DL) and ensemble methods. We present a detailed review on these three approaches for Alzheimers with possible future directions.

CCS Concepts: • **Dementia** → Alzheimer’s disease; • **Machine learning** → Support vector machine; Artificial neural network; Deep learning; Ensemble methods.

Additional Key Words and Phrases: Magnetic resonance imaging (MRI), positron emission tomography (PET), diffusion tensor imaging (DTI), mild cognitive impairment (MCI).

ACM Reference Format:

M. Tanveer, B. Richhariya, R.U. Khan, A.H. Rashid, P. Khanna, M. Prasad, and C.T. Lin. 2020. Machine learning techniques for the diagnosis of Alzheimer’s disease: A review. *ACM Trans. Multimedia Comput. Commun. Appl.* 16, 1s, Article 30 (April 2020), 28 pages. <https://doi.org/https://doi.org/10.1145/3344998>

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1 INTRODUCTION

Alzheimer's disease (AD) is one of the most common cause of dementia in today's world. According to World Alzheimer Report (2018) [126], around 50 million people were affected by this disease in 2018, which is expected to triple by 2050. Usually, the symptoms of Alzheimers are visible after 60 years of age [43]. However, some forms of AD develop very early (30-50 years) for individuals having gene mutation [10]. Alzheimer's disease gives rise to structural and functional changes in the brain. In AD patients, the time between healthy state to Alzheimers spans over many years [180]. First, patients develop mild cognitive impairment (MCI), and gradually progress to Alzheimers. However, all MCI patients do not convert to Alzheimers [37]. So, the main focus of current research is to predict the conversion of MCI to AD. These changes can be measured using medical imaging [138] and other techniques like blood plasma spectroscopy [39, 125].

Many open source databases for Alzheimers have accelerated research in this field [67, 181]. The most widely used databases are ADNI [174] (adni.loni.usc.edu), AIBL (aibl.csiro.au), OASIS (www.oasis-brains.org). A new publicly available database for clinical Alzheimer data is J-ADNI database [44, 66] containing data from longitudinal studies in Japan. Further, processing of MRI images requires a lot of effort. To facilitate analysis of MRI images open source softwares like Statistical Parametric Mapping (SPM) have been developed by Wellcome Centre for Human Neuroimaging for public use. SPM is used for voxel based morphometry (VBM) [77] of MRI data. Another very popular open source software i.e., Freesurfer [36] is developed for volume based morphometry and is used by many researchers [4, 167].

Machine learning techniques are found to be very useful for the diagnosis of Alzheimers [118, 128, 170] in the last decade. The most widely used classification techniques are support vector machine (SVM), artificial neural network (ANN), and deep learning. The primary difference between SVM and ANN is the nature of the optimization problem. SVM gives a globally optimal solution [15], while ANN gives locally optimal solution. In both SVM and ANN, feature extraction is an important step. Shi et al. [154] suggested that combination of neural networks and intelligent agents can be useful for medical image analysis. However, deep learning incorporates the feature extraction step in the learning model itself [151, 159]. For large datasets, deep learning is found to be useful especially for image data [151]. Some researchers also used ensemble methods to improve the classification accuracy for Alzheimers [28, 100, 131].

For classification of Alzheimer's data, the accuracy is dependent on the type of problem. For example, the accuracy is highest for Control normal (CN) vs AD, lesser for CN vs MCI, and least for MCI vs AD [11]. Moreover, the classification of MCI converters (MCIC) vs non-converters (MCINC), and amnesic MCI (aMCI) vs non-amnesic MCI (naMCI) is also a challenging task [32, 119]. Moreover, the data generated from MRI scanners is 3-D in nature and thus amounts to large sized datasets. So, efficient feature extraction and classification techniques are needed to analyze this data [46, 200].

In recent years, researchers provided analysis on the works done using machine learning for Alzheimers. In 2017, Litjens et al. [96] presented a review on deep learning methods for medical image analysis. It is mentioned that although deep learning models are considered as 'black boxes', some statistical techniques can be used to estimate uncertainty of the network. Shen et al. [151] performed a survey on deep learning for Alzheimers. It also supported this fact of uncertainty in prediction by deep learning models. In 2018, Jose et al. provided a review on neuroimaging techniques for brain disorders. It is stated that machine learning techniques can be useful for finding the underlying neurological causes of brain disorders [112]. Pellegrini et al. [128] discussed the machine learning techniques used for dementia and cognitive impairment from 2006-2016 in 111 papers. It stressed on the development of novel machine learning models from interdisciplinary approach. Rathore et al. [138] also provided a review on feature extraction and classification of Alzheimers and its prodromal stages.

Among the different machine learning techniques, we selected three main approaches namely, support vector machine (SVM), artificial neural network (ANN), and deep learning (DL) methods and ensemble methods. In this review, we present a separate analysis for each of these techniques on diagnosis of Alzheimers. Section 3, 4 and 5 provide a survey on application of the three techniques on classification of Alzheimer's disease. Section 6 dwells on the possible future directions, while section 7 presents the conclusions of the review.

2 SEARCH STRATEGY

We searched prominent papers in the field from Google Scholar (<https://scholar.google.co.in/>) and Sciencedirect (<https://www.sciencedirect.com/>). We excluded the studies which did not use accuracy measures for classification performance. This resulted in a total of 165 papers. Out of 165, 60 papers used SVM, 45 used a combination of ANN, multi-task learning, transfer learning, multi-kernel learning and certain feature selection techniques. We also included 60 papers based on deep learning and ensemble methods for Alzheimers. Papers using SVM are from the period 2005-2019, ANN are from 2008-2019, and deep learning and ensemble methods are from 2007-2019.

3 SUPPORT VECTOR MACHINE

Support vector machine (SVM) [29] is a very stable [194] and widely used technique for classification and regression problems [47, 140, 141, 189]. By including the structural risk minimization principle (SRM), SVM gives good generalization performance. SVM uses the maximum margin principle to classify the data points as shown in fig. 1(a). After solving a convex optimization problem, the decision function of SVM is written as,

$$f(x) = \text{sign}(w^T x + b), \quad (1)$$

where w is the weight vector and b is bias.

To classify non-linearly separable data, kernel functions [30] have been used to transform the data to higher dimensions. Moreover, various variants of SVM have been proposed to increase its performance w.r.t. generalization ability and training time [171]. Some computationally efficient variants of SVM are twin support vector machine (TWSVM) [69] shown in fig. 1(b), and least squares based twin support vector machine (LSTSVM) algorithms [86, 168].

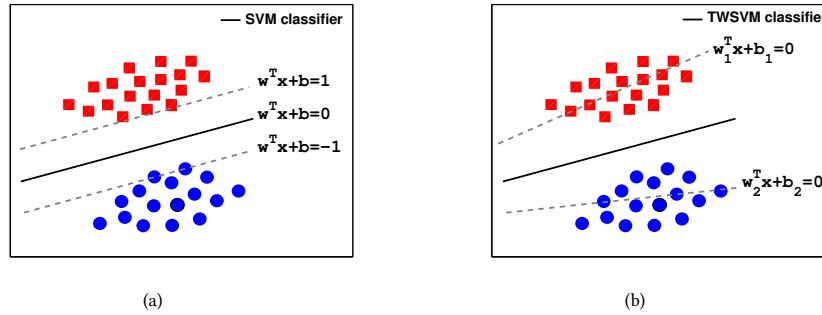


Fig. 1. Plot showing (a) SVM, and (b) TWSVM classifiers.

The details of all papers on SVM surveyed in this work are presented in Table 1. We present a detailed analysis of application of SVM for Alzheimers on various parameters in the following subsections.

3.1 Image modality

Image modality is a prominent factor for classification of MRI images. In case of structural MRI (sMRI) images, most of the researchers used T1-weighted images while only few researchers used T2 images [18, 75, 87]. This is because the delineation of ventricular surface of brain due to atrophy is clearly visible in T1-weighted images [176]. Fig. 2 shows the use of different modalities of data in classification of Alzheimers using SVM.

Fan et al. [41] suggested that positron emission tomography (PET) scans provide complementary information to sMRI scans, thus improving the classification accuracy of CN vs MCI using SVM. Dukart et al. [40] supported this fact that fluorodeoxyglucose-PET (FDG-PET) features are more discriminative as compared to sMRI. Further, better accuracy is found for CN vs AD [7] with PET images (100 %) as compared to single photon emission computed tomography (SPECT) images (97.5 %). Similar finding is observed for CN vs AD [150] with better accuracy for PET images (96.67 %) as compared to SPECT images (94.5 %). Kamathe et al. [75] used combination of T1, T2 and proton density (PD) scans for classification of CN vs AD. Hojjati et al. [58] used resting state functional MRI (rs-fMRI) to find the connectivity changes in brain for classification of MCIC vs MCInc, while Sheng et al. [152] used connectivity information from fMRI data. Fig. 2 shows the usage of image modality for SVM in our survey.

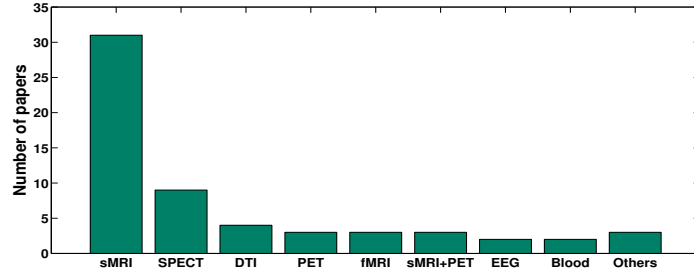


Fig. 2. Plot showing different image modalities and other data used with SVM for Alzheimers.

Diffusion tensor imaging (DTI) is also explored by various researchers for Alzheimer's disease [91, 119, 194]. Haller et al. [53] found that SVM based analysis of white matter DTI parameters is helpful in classification of different types of MCI patients.

3.2 Feature selection and extraction with SVM

Feature selection plays an important part in the classification of data. Different features are combined to form the feature vector in many works [58, 109, 120, 124, 193]. Vemuri et al. [175] found that including demographic and genetic information with sMRI scans improved the classification accuracy of CN vs AD. A refined parcellation method is proposed [115] for detecting subtle changes in gray matter (GM). Magnin et al. [109] presented a feature selection method based on histogram of regions of interests (ROIs) for CN vs AD. Gerardin et al. [48] used shape features of hippocampus to discriminate CN, MCI and AD, and found that shape deformation features are better than volumetric features. Normalized mean square error (NMSE) features are used [19] to discriminate CN with early AD. A clustering based approach is proposed [131] to group adjacent voxels for classification of CN, MCI and AD. Fisher discriminate ratio (FDR) is used [136] to extract useful voxels as features (VAF) from SPECT images.

Gaussian mixture model (GMM) is used in [150] for CN vs AD. It is stated that the proposed GMM based feature extraction makes the data linearly separable. Ortiz et al. [122] used PET and sMRI data to find the most discriminative features using sparse inverse covariance estimation (SICE) method with SVM. Non-negative matrix factorization (NMF) based features with SVM are found to give better performance than PCA with SVM to classify CN vs AD [124]. Moreover, Abdulkadir et al. [1] illustrated the affects of hardware heterogeneity on classification accuracy of SVM. They also found high confidence level of classification performance for large samples. Cuingnet et al. [32] stated that DARTEL based features are better than SPM features for CN, MCIc, MCInc, and AD. Moreover, it is concluded that feature selection techniques for sMRI images may lead to less classification accuracy due to addition of hyperparameters. Further, Schmitter et al. [147] found volume based features to be more useful than voxel based morphometry (VBM). Morphological features of brain regions are used by Plocharsky et al. [132] to classify CN vs AD, while Long et al. used shape differences in the subjects' brains for classification of CN, AD, sMCI, and pMCI. Fuzzy based classes for hippocampus volume are used by Tangaro et al. [167] for classification of CN vs AD, and MCIc vs MCInc.

Wavelet based features are used in various works. Chaplot et al. [18] used discrete wavelet transform (DWT) features, while Zhang et al. [193] found that 3-D DWT and SVM are useful for classification of CN, MCI and AD subjects. Segovia et al. [149] discovered that partial least squares (PLS) components have a higher FDR score as compared to principal component analysis (PCA) for CN vs AD using SPECT images. Ortiz et al. used self organizing maps (SOMs) [120] for unsupervised segmentation of sMRI images in classification of CN vs AD. However, Chaplot et al. [18] found that SVM performs better than SOM for classification of Alzheimer's patients using T2-weighted images.

Other techniques like SVM-RFE [52, 139] are used as an optimized feature selection technique in [56] to select prominent brain features for CN vs AD. Independent component analysis (ICA) is used in many works [79, 80] for classification of CN vs AD using SVM. EEG data is also used [85] for classification of CN vs AD using SVM. Mazaheri et al. [113] used EEG recordings of word comprehension by subjects to classify MCIc from MCInc and CN. Some researchers also focused on blood based biomarkers for Alzheimers [39, 125]. Gostolya et al. [50] used speech patterns of subjects and classified using linear SVM.

3.3 Kernel function

Different kernels have been used with SVM for classification of Alzheimers. Various researchers have used linear kernel with SVM to classify Alzheimer data as shown in fig. 3(a). This is due to the fact that in linear kernel, there is no kernel parameter to tune. Some researchers also utilized multiple kernels for SVM [4]. Moreover, in most papers, the sample size is also very small as shown in Table 1, which may lead to overfitting of the data with radial basis function (RBF) kernel [139]. This leads to the use of linear kernel due to its simplicity. The usage of different kernels as per our survey is shown in fig. 3(a).

Kloppel et al. [82] used linear SVM to classify pathologically confirmed cases of AD with CN, and suggested that SVM can help in the diagnosis of AD. It has been stated in [79, 136] that linear kernel provides better classification performance for high dimensional data as compared to polynomial or RBF kernel. However, polynomial kernel is also used by researchers. Lahmiri et al. [87] used polynomial kernel for multiclass classification of CN, MCI, and AD. Zhang et al. [191] found that polynomial kernel is useful in classification of CN vs AD using PCA features. In 2018, Lahmiri et al. [88] used volumetric features with cognitive test scores for classification of CN vs AD with polynomial kernel.

Some researchers also used an ensemble of kernels. Multiple kernel SVM is used by Alam et al. [4] for classification of CN, MCI, and AD. Kamathe et al. [75] used linear, polynomial and RBF kernel for classification of CN vs AD.

Table 1. Comparison of research on classification of Alzheimer data using SVM.

Sr. No.	Year	Authors	Target	Modality	Feature extraction	Machine learning	Dataset	Validation	Performance		
									Acc (%)	Sens (%)	Spec (%)
1	2005	Stoeckel et al. [158]	CN vs AD	SPECT	VBM+Spatial normalization	CSVM (Linear)	130 (31 CN, 99 AD)	LOOCV	72.5	93	-
2	2006	Chaplot et al. [18]	CN vs AD	sMRI (T2)	DWT	SVM (RBF)	52 (6 CN, 46 AD)	-	98	-	-
3	2007	Fung et al. [45]	CN vs AD	SPECT	Subsampling	CSVM (Linear)	130 (31 CN, 99 AD)	LOOCV	-	84.4	90.9
4	2008	Alvarez et al. [7]	CN vs AD	SPECT	Component based feature extraction	Ensemble SVM	79 (41 CN, 38 AD)	LOOCV	97.5	-	-
				PET			60 (18 CN, 42 AD)		100	-	-
5	2008	Ramirez et al. [136]	CN vs AD	SPECT	FDR	SVM (RBF)	52 (23 CN, 29 AD)	-	90.38	-	-
6	2008	Gonzalez et al. [143]	CN vs AD	SPECT	Component based feature extraction	SVM (Linear)-Classification tree	79 (41 CN, 38 AD)	LOOCV	90	-	-
7	2008	Vemuri et al. [175]	CN vs AD	sMRI (T1)	VBM	SVM (Linear)	380 (190 CN, 190 AD)	4-fold	89.30	-	-
8	2008	Fan et al. [41]	CN vs MCI	sMRI+PET	RAVEN maps+ODC	SVM (Linear)	30 (15 CN, 15 MCI)	LOOCV	100	-	-
9	2008	Kloppel et al. [82]	CN vs AD	sMRI (T1)	VBM	SVM (Linear)	68 (34 CN, 34 AD)	LOOCV	95.6	97.1	94.1
			CN vs mAD				90 (57 CN, 33 AD)		85.6	75.8	91.2
10	2008	Mesrob et al. [115]	CN vs AD	sMRI (T1)	SVM-RFE	SVM (RBF)	61 (28 CN, 33 AD)	LOOCV	90.2	-	-
11	2009	Magnin et al. [109]	CN vs AD	sMRI (T1)	VBM+Histogram	SVM (RBF)	38 (22 CN, 16 AD)	LOOCV	94.5	91.5	96.6
12	2009	Gerardin et al. [48]	CN vs AD	sMRI (T1)	SPHARM	SVM (RBF)	46 (23 CN, 23 AD)	LOOCV	94	96	92
			CN vs MCI						83	83	84
13	2009	Chaves et al. [19]	CN vs AD	SPECT	VBM+NMSE	SVM (Linear)	79 (41 CN, 38 AD)	LOOCV	98.3	-	-
			CN vs AD						90	96.88	77.78
14	2010	Plant et al. [131]	CN vs AD	sMRI (T1)	VBM+Clustering	SVM (Linear)	74 (18 CN, 24 MCI, 32 AD)	LOOCV	97.62	95.83	100
			CN vs MCI						95.83	88.89	100
			MCI vs AD						94.5	-	-
15	2010	Segovia et al. [150]	CN vs AD	SPECT	GMM	SVM (Linear)	91 (41 CN, 50 AD)	LOOCV	96.67	-	-
				PET					94.9	96.4	92.8
16	2010	Padilla et al. [124]	CN vs AD	SPECT	FDR+NMF	SVM (RBF)	97 (41 CN, 56 AD)	LOOCV	87	-	-
17	2011	Abdulkadir et al. [1]	CN vs AD	sMRI (T1)	VBM	SVM (Linear)	417 (226 CN, 191 AD)	LOOCV	96.91	94.64	100
18	2011	Illan et al. [65]	CN vs AD	SPECT	Image factorization	Ensemble SVM (RBF)	79 (41 CN, 38 AD)	LOOCV	-	81	95
19	2011	Cuingnet et al. [32]	CN vs AD	sMRI (T1)	VBM/ VolBM/ STAND- score	SVM (RBF)	76 MCIc, 134 MCInc, 137 AD)	LOOCV	-	73	85
			CN vs MCIc						-	70	61
			MCIc vs MCInc						-	-	-
20	2012	Doecke et al. [39]	CN vs AD	Blood plasma	Statistical methods	SVM (Linear)	1131 (812 CN, 319 AD)	CV	-	80	85
21	2012	O'Dwyer et al. [119]	CN vs MCI	DTI	TBSS	SVM (RBF)	73 (40 CN, 19 naMCI, 14 aMCI)	10-fold	93	92.8	-
			CN vs aMCI vs naMCI						92.2	93.4	-
22	2013	Segovia et al. [149]	CN vs AD	SPECT	PLS	SVM (Linear)	97 (41 CN, 56 AD)	LOOCV	91.75	92.68	91.07
23	2013	Ramirez et al. [134]	CN vs AD	SPECT	FDR	SVM (RBF)	52 (23 CN, 29 AD)	LMOCV (M=5)	90.38	93.1	86.96
24	2013	Dukart et al. [40]	CN vs AD	FDG-PET+sMRI	VBM	SVM (Linear)	56 (28 CN, 28 AD)	LOOCV	100	100	100
25	2013	Ortiz et al. [120]	CN vs AD	sMRI (T1)	SOM clustering +FDR	SVM (RBF)	50 (25 CN, 25 AD)	LOOCV	92	96	98
26	2013	Haller et al. [53]	md-aMCI vs sd-aMCI	DTI	TBSS	SVM (RBF)	66 (18 sd-aMCI, 13 sd-fMCI, 35 md-aMCI)	10-fold	98.4	-	-
			md-aMCI vs sd-aMCI						97.7	-	-
			sd-fMCI vs sd-aMCI						99.67	-	-
27	2013	Lee et al. [91]	CN vs MCI	DTI	TBSS	SVM (RBF)	84 (39 CN, 45 MCI)	10-fold	100	100	100
28	2014	Hidalgo-Munoz et al. [56]	CN vs AD	sMRI (T1)	VBM +SVM-RFE	SVM (Linear)	370 (185 CN, 185 AD)	10-fold	100	-	-
29	2014	Lahmiri et al. [87]	CN vs MCI	sMRI (T2)	MSA	SVM (Polynomial)	33 (11 CN, 11 MCI, 11 AD)	10-fold	97.08	98.09	96.07
			MCI vs AD						97.5	100	94.93
30	2015	Khedher et al. [80]	CN vs AD	sMRI (T1)	VBM+Fast ICA	SVM (Linear)	818 (229 CN, 401 MCI, 188 AD)	2-fold	87.12	89.92	83.98
			MCI vs AD						77.62	80.27	74.49
31	2015	Schmitter et al. [147]	CN vs AD	sMRI (T1)	VBM+VolBM	SVM (Linear)	818 (229 CN, 401 MCI, 188 AD)	LOOCV	85.41	85.59	85.11
			CN vs MCI						86	91	-
			MCI vs AD						78	68	-
			ADc vs ADnc						69	67	-
32	2015	Zhang et al. [193]	CN vs MCI vs AD	sMRI (T1)	VolBM+3D-DWT+PCA	SVM (RBF)	178 (97 CN, 57 MCI, 24 AD)	5-fold	81.5	-	-
33	2015	Zhang et al. [192]	CN vs AD	sMRI (T1)	DF+PCA	TWSVM	126 (98 CN, 28 AD)	10-fold	92.75	90.56	93.37
34	2015	Xu et al. [183]	CN vs AD	sMRI	Lasso features	S-LSTSVM (RBF)	329 (191 CN, 138 AD)	5-fold	92.1	92.52	92.07
35	2015	Ortiz et al. [122]	CN vs AD	FDG-PET+sMRI	VBM+SICE	SVM (Linear)	249 (68 CN, 111 MCI, 70 AD)	10-fold	92	96	86
			CN vs MCI						86	90	82
			MCI vs AD						84	87	81
36	2015	Retico et al. [139]	CN vs AD	sMRI (T1)	VBM+SVM-RFE	SVM (Linear)	635 (189 CN, 136 MCIc, 166 MCInc, 144 AD)	20-fold	88.9	-	-
			MCIc vs MCInc						70.7	-	-
37	2015	Zhang et al. [191]	CN vs AD	sMRI (T1)	PCA	SVM (Polynomial)	126 (98 CN, 28 AD)	10-fold	92.36	-	-
38	2016	Zhu et al. [200]	MCIc vs MCInc	sMRI	PIS	TS-SVM	151 (70 MCIc, 81 MCInc)	10-fold	82.5	-	-

Table 1 (Contd.)

Sr. No.	Year	Authors	Target	Modality	Feature extraction	Machine learning	Dataset	Validation	Performance		
									Acc (%)	Sens (%)	Spec (%)
39	2016	Moller et al. [117]	CN vs AD	sMRI (T1)	VBM	SVM (Linear)	178 (94 CN, 84 AD)	LOOCV	85	83	87
40	2016	Plocharsky et al. [132]	CN vs AD	sMRI (T1)	Morphological features (length, area, depth)	SVM (Linear)	210 (100 CN, 110 AD)	10-fold	87.9	90	86.7
41	2017	Alam et al. [4]	CN vs AD	sMRI (T1)	VolBM+KPCA	SVM (Multiple kernel)	293 (102 CN, 102 MCI, 89 AD)	10-fold	93.85	92.1	94.45
			CN vs MCI						86.54	84.85	87.74
			MCI vs AD						75.12	73.92	77.24
42	2017	Khedher et al. [79]	CN vs AD	sMRI (T1)	ICA	SVM (RBF)	818 (229 CN, 401 MCI, 188 AD)	k-fold	89	92	86
			CN vs MCI						79	82	76
			MCI vs AD						85	85	86
43	2017	Beheshti et al. [11]	CN vs AD	sMRI (T1)	VBM+GA	SVM (Linear)	458 (162 CN, 65 sMCI, 71 pMCI, 160 AD)	10-fold	93.01	89.13	96.8
			pMCI vs sMCI						75	76.92	73.23
			CN vs AD						96.5	93.85	97.78
44	2017	Long et al. [104]	CN vs AD	sMRI (T1)	MDS+PCA	SVM (Linear)	427 (135 CN, 132 sMCI, 95 pMCI, 65 AD)	10-fold	97.1	87.37	94.82
			CN vs pMCI						88.99	86.32	90.91
			sMCI vs pMCI						100	-	-
45	2017	Tangaro et al. [167]	CN vs AD	sMRI (T1)	VolBM	SVM (Linear)	372 (117 CN, 86 MCIc, 71 MCInc, 98 AD)	10-fold	83.4	-	-
			CN vs AD						-	-	-
			MCIc vs MCInc						-	-	-
46	2017	Lu et al. [108]	CN vs MCI	FDG-PET	VBM	RF-RSVM	272 (152 CN, 120 MCI)	3-fold	90.53	90.63	93.33
47	2017	Alam et al. [5]	CN vs MCI	sMRI	DTCWT/LDA	TWSVM	237 (130 CN, 137 AD)	10-fold	96.88	97.72	95.61
48	2017	Hojjati et al. [58]	MCIc-MCInc	rs-fMRI	PCC+F-score	SVM (Linear)	80 (18 MCIc, 62 MCInc)	9-fold	91.4	83.24	90.1
49	2017	Kulkarni et al. [85]	CN vs AD	EEG	ICA/ Wavelet/ Spectral	SVM	100 (50 CN, 50 AD)	LOOCV	96	-	-
50	2018	Sun et al. [166]	CN vs AD	sMRI (T1)	VBM+PCC	Group lasso SVM	509 (162 CN, 134 sMCI, 76 pMCI, 137 AD)	5-fold	95.1	93.8	83.8
			CN vs MCI						70.8	72.1	69.1
			sMCI vs pMCI						65.4	67.6	64.2
			MCI vs AD						65.7	63.2	67.3
51	2018	Zeng et al. [187]	CN vs AD	sMRI (T1)	PCA+PSO and SDPSO	SVM (RBF)	361 (92 CN, 82 sMCI, 95 pMCI, 92 AD)	10-fold	82.5	-	-
			sMCI vs pMCI						69.23		
			CN vs sMCI						76.92		
			CN vs pMCI						85.71		
			sMCI vs AD						72.94		
52	2018	Lahmire et al. [88]	CN vs AD	sMRI (T1)	VolBM	SVM (Polynomial)	70 (35 CN, 35 AD)	10-fold	100	100	100
			CN vs AD						100	-	-
53	2018	Kamathe et al. [75]	CN vs AD	sMRI (T1, T2)+PD	ICA	SVM (Polynomial)	20 (15 CN, 5 AD)	-	100	-	-
54	2018	Bi et al. [14]	CN vs AD	rs-fMRI	PCC	RSVM (RBF)	61 (36 CN, 25 AD)	-	94.44	-	-
55	2018	Mazaheri et al. [113]	MCIc vs (CN + MCInc)	EEG	TFRs	SVM (RBF)	36 (11 CN, 10 MCInc, 15 MCIc)	LOOCV	-	80	95
56	2018	Paraskevaiddi et al. [125]	CN vs AD	Blood plasma	PCA-LDA	SVM	41 (15 CN, 11 eAD, 15 IAD)	LOOCV	-	84	86
			CN vs IAD						-	84	77
			eAD vs IAD						-	66	83
57	2018	Zhang et al. [194]	CN vs AD	DTI	LDH +SVM-RFE	SVM (Linear)	213 (51 CN, 75 eMCI, 39 IMCI, 48 AD)	LOOCV	89.9	-	-
			CN vs eMCI						88.1		
			CN vs IMCI						100		
			eMCI vs IMCI						92.98		
			eMCI vs AD						84.55		
			IMCI vs AD						97.7		
58	2019	Peng et al. [129]	CN vs AD	sMRI+PET+SNP	Volume + Mean intensity features	SVM (Multiple kernel)	189 (47 CN, 93 MCI, 49 AD)	10-fold	96.1	97.3	94.9
			CN vs MCI						80.3	85.6	69.8
			MCI vs AD						76.9	65.9	82.7
59	2019	Sheng et al. [152]	CN vs eMCI	fMRI	RF-score	SVM	96 (24 CN, 24 eMCI, 24 IMCI, 24 AD)	5-fold	93.8	-	-
			CN vs LMCI						95.8		
			CN vs AD						95.8		
			eMCI vs IMCI						87.5		
			IMCI vs AD						91.7		
60	2019	Gosztolya et al. [50]	CN vs MCI	Acoustic signal	MFCC	SVM (Linear)	75 (25 CN, 25 MCI, 25 mAD)	5-fold	80	-	75.9
			CN vs mAD						86	-	87.5
			MCI vs mAD						80	-	85.7

Abbreviations: **LMOCV**- Leave M out cross validation, **CV**- Cross validated, **CT**- Classification tree, **ODC**- Optimally differentiating clusters, **SPHARM**- Spherical harmonics coefficients, **VolBM**- Volume based morphometry, **eMCI**- Early MCI, **IMCI**- Late MCI, **mAD**- Mild AD, **ADc**- AD converter, **ADnc**- AD non-converter, **MDS**- Multi dimensional scaling, **PCC**- Pearson correlation coefficient, **SNP**- Single nucleotide polymorphisms, **MFCC**- Mel frequency cepstral coefficients, **DF**- Displacement field, **MSA**- Multiscale analysis, **S-LSTSVM**-Structural least squares twin support vector machine, **RSVM**- Random SVM, **rs-fMRI**- Resting state fMRI, **PIS**- Partial image sequence, **TS-SVM**- Temporally structured SVM, **RF-score**- Relief feature score, **STAND**- score- Structural abnormality index score, **sd-aMCI**- Single domain amnesic MCI, **md-aMCI**- Multiple domain amnesic MCI, **sd-fMCI**- Single domain frontal MCI, **TBSS**- Tract-based spatial statistics, **TFR**- Time frequency representation, **KPCA**- Kernel PCA, **LDH**- Local diffusion homogeneity.

Peng et al. [129] used MRI and genetic data for features, and used multiple kernel learning with SVM to classify the subjects. The selection of optimal hyperparameters is a major step in the classification of SVM. Among the various

methods, leave one out cross validation (LOOCV) has been widely used for classification of Alzheimer using SVM. The details of the cross-validation methods are shown in fig. 3(b).

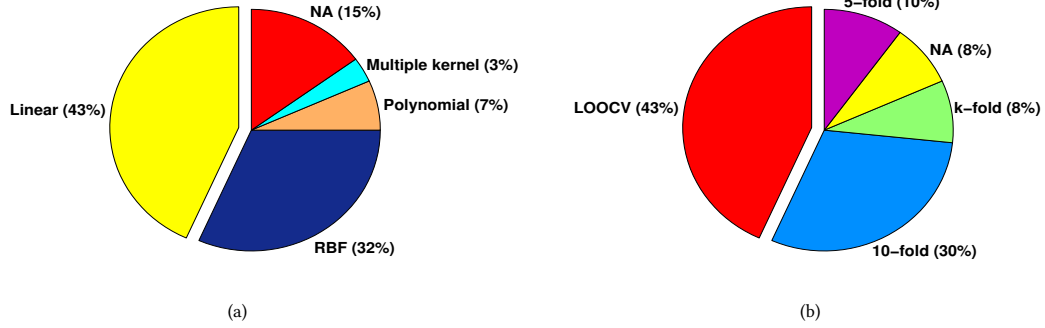


Fig. 3. (a) Plot showing usage of different types of kernels and (b) cross validation methods used with SVM for Alzheimers. NA means information about kernel is not available, and $k = 2, 3, 4, 9$ and 20 .

3.4 Variants of SVM used for Alzheimers

Many variants of SVM are developed for different types of classification problems. Standard SVM do not use spatial information of brain image in the optimization problem [33, 158]. To provide spatial information, contiguous SVM (CSVM) is used to classify SPECT images of Alzheimers and control subjects [45, 158]. CSVM uses the information about voxel connectivity to give a more robust classifier. For reducing the computation cost, Zhang et al. [192] used twin support vector machine (TWSVM) for classification of CN vs AD, while structural least squares twin support vector machine (S-LSTSVM) is used in [183]. For optimized feature selection, Beheshti et al. [11] used genetic algorithm (GA) with linear SVM for classification of CN vs AD and pMCI vs sMCI.

For early diagnosis of Alzheimers, Zhu et al. [200] used a temporally structured SVM (TS-SVM) for classification of longitudinal MR images of MCI converters and non-converters. Lu et al. [108] proposed a random forest robust SVM (RF-RSVM) for classification of CN vs MCI using FDG-PET images. TWSVM is used for classification of CN vs AD [5] using dual-tree complex wavelet transform (DTCWT), LDA and PCA features. Sun et al. [166] introduced spatial anatomical regularization with SVM for classification of CN, AD, sMCI, and pMCI. To optimize the SVM parameters, Zeng et al. [187] proposed a switching delayed particle swarm optimization SVM (SDPSO-SVM). In order to reduce the complexity of SVM, Bi et al. [14] used random support vector machine clusters for classification of CN vs AD using rs-fMRI. In RSVM clusters approach, samples and features randomly are chosen randomly from the dataset and trained accordingly. It helps to reduce the size of training data leading to less computational complexity. Some researcher also applied ensemble based SVM for better prediction accuracy in Alzheimer's disease (AD) classification [7, 65, 143].

The usage of different cross validation strategies is shown in fig. 3(b). LOOCV comes out to be the frequently used method. This may be attributed to small sample size in the works shown in Table 1.

4 ARTIFICIAL NEURAL NETWORKS, TRANSFER LEARNING & MULTI-KERNEL LEARNING

Artificial neural networks (ANN) shown in fig. 4, are widely used for machine learning models that can model highly nonlinear patterns of data. In this section, we review the approaches using ANNs and other approaches like

Table 2. Comparison of recent studies using artificial neural network, transfer learning, multi-task learning and connectivity features.

Sr. No.	Year	Authors	Target	Modality	Feature extraction	Machine learning	Dataset	Validation	Performance		
									Acc (%)	Sens (%)	Spec (%)
1	2008	Huang et al. [63]	CN vs AD	sMRI (T1)	VBM	ANN	22 (10 AD, 12 CN)	-	100	-	-
2	2009	Savio et al. [146]	CN vs AD	sMRI (T1)	VBM	LVQNN	98 (49 AD, 49 CN)	10-Fold	83	-	-
3	2010	Ahmadiou et al. [2]	CN vs AD	EEG	WT + VG	PCA-RBFNN	27 (7 CN, 20 AD)	-	97.7 ± 3.2	100	91.08
4	2010	Lopes et al. [34]	CN vs AD	EEG	-	PANN	67 (33 AD, 34 CN)	-	-	82	61
5	2010	Yang et al. [185]	CN vs AD	sMRI (T1)	VBM	PCA+BPNN	52 (24 probable AD, 28 CN)	LOOCV	92.17	79.91	88.61
6	2010	Long et al. [105]	CN vs AD	sMRI (T1)	Atlas	Quick shift clustering	75 (35 very mild-to-mild dementia, 40 CN)	-	94.67 – 97.33	-	-
7	2010	Joshi et al. [74]	AD vs PD	Health records	Feature ranking	Decision Tree	890 (578 AD, 312 PD)	-	97.3415	-	-
						Bagging			98.5685		
						BF Tree			99.182		
						RF Tree			99.591		
						RBF NN			97.137		
						MLP			98.9775		
						ANN			99.591		
8	2011	Sankari et al. [144]	CN vs AD	EEG	CC; WC	PNN	27 (7 CN, 20 probable AD)	-	100	-	-
9	2011	Zhang et al. [188]	CN vs AD	sMRI (T1)+PET+CSF	Atlas	MapRls	202 (52 CN, 99 MCI, 51 AD)	10-Fold	94	94	94
10	2011	Rodrigues et al. [142]	CN vs AD	EEG	WT; STFT	ANN	34 (14 CN, 20 probable AD)	LOOCV	91.5	92.1	90.8
11	2011	Quintana et al. [133]	CN vs AD	NPR	NPF, Age & Education	ANN	522 (346 CN, 79 MCI, 97 AD)	-	100	-	-
			CN vs MCI						98.33		
			CN vs MCI vs AD						66.67		
12	2012	Mahanand et al. [110]	CN vs AD	sMRI (T1)	VBM	ICGA+SRAN	60 (30 CN, 30 mild-to-mod AD)	10-Fold	92.13 ± 2.71	-	-
13	2013	Chyzyk et al. [27]	CN vs AD	sMRI (T1)	VBM	GA + ELM	98 (49 CN, 49 very mild-to-mild AD)	10-Fold	86	87	90
14	2013	Jie et al. [72]	CN vs AD	sMRI (T1) + PET	Atlas	M2TFS+MK-SVM	202 (52 CN, 43 MCI, 56 MCInc, 51 AD)	10-Fold	95.03	94.9	95
			CN vs MCI						79.27	85.86	66.54
			MCInc vs MCInc						68.94	64.65	71.79
15	2013	Liu et al. [97]	CN vs AD	sMRI (T1)	Atlas	SMSE	331 (77 CN, 169 MCI, 85 AD)	5-Fold	75.89	-	-
16	2013	Mahmood et al. [111]	CN vs AD	sMRI (T1)	Atlas	PCA+ANN	457 (357 CN, 100 AD)	-	89.22	-	-
17	2013	Naami et al. [3]	CN vs AD	sMRI (T2)	Atlas	ANN	37 (17 AD, 20 CN)	-	100	-	-
18	2014	Jie et al. [73]	CN vs aMCI	fMRI	Atlas (NBF)	SVM	37 (25 CN, 12 aMCI)	LOOCV	91.9	100	88
19	2014	Min et al. [116]	CN vs AD	sMRI (T1)	VBM	SVM	459 (128 CN, 117 pMCI, 117 sMCI, 97 AD)	10-Fold	91.64	88.56	93.85
			pMCI vs sMCI						72.41	72.12	72.58
			CN vs AD						90 ± 6	87 ± 7	92 ± 9
20	2014	Ortiz et al. [121]	CN vs AD	sMRI (T1)	VBM	SOM	818 (229 CN, 401 MCI, 188 AD)	10-Fold	83 ± 6	82 ± 7	87 ± 7
			MCI vs AD						95.27 ± 6.58	94	96.33
			MCI vs AD						74.60 ± 9.57	46.67	89
21	2014	Suk et al. [163]	CN vs AD	sMRI (T1) + PET + CSF	Atlas	SMTL+MK-SVM	202 (52 CN, 43MCI, 56 MCInc, 51 AD)	10-Fold	80.07 ± 8.42	86.78	67.33
			MCI vs AD						72.02 ± 13.80	58	82.67
			MCInc vs MCInc						100	100	100
22	2015	Wang et al. [179]	CN vs AD	sMRI (T2)	DWT	ANN	481 (73 CN, 408 AD)	5-Fold	100	100	100
23	2015	Cheng et al. [23]	MCInc vs MCInc	sMRI (T1) + PET + CSF	Atlas	M2TL	202 (52 CN, 43 MCI, 56 MCInc, 51 AD)	10-Fold	80.1	85.3	73.3
24	2015	Gorji et al. [49]	CN vs AD	sMRI (T1)	Pseudo Zernike Moment	PRNN; LVQNN	500 (148 CN, 172 MCI, 180 AD)	10-Fold	97.27	96.64	97.79
			MCI vs AD						94.88	94.18	95.55
			CN vs MCI						95.59	95.89	95.34
25	2016	Khazaei et al. [78]	CN vs MCI & AD	rs-fMRI	Atlas (NBF)	SVM	168 (45 CN, 89 MCI, 34 AD)	Hold-out	87.29	-	-
			MCI vs CN & AD						72.03	-	-
			AD vs CN & MCI						97.46	-	-
26	2016	Suk et al. [160]	CN vs AD	sMRI (T1) + PET + CSF	Atlas	DW-S ² MTL + SVM(Linear)	202 (52 CN, 43 pMCI, 56 sMCI, 51 AD)	10-Fold	95.09 ± 2.28	92	98
			CN vs MCI						80.11 ± 2.64	93.89	53.67
			pMCI vs sMCI						74.15 ± 3.35	50.5	92.67
			CN vs MCI vs AD						55	-	-
27	2016	Tong et al. [172]	CN vs AD	sMRI (T1) + FDG-PET+CSF +Genetics	Atlas	NGF+SVM	147 (35 CN, 37 AD, 75 MCI)	Leave-p-out	91.8	88.9	94.7
			CN vs MCI						79.5	85.1	67.1
			CN vs MCI vs AD						60.26	-	-
28	2016	Aljovic et al. [6]	CN vs AD	Biomarkers	-	ANN	-	-	-	95.5	91.43
29	2017	Liu et al. [99]	CN vs AD	sMRI (T1)	Atlas	MKBoost+SVM	710(230 CN, 120 MCI, 160 MCInc, 200 AD)	10-Fold	94.65	95.03	91.76
			MCI vs AD						89.63	91.55	86.25
			CN vs MCI						85.79	88.91	80.34
			MCInc vs MCInc						72.08	75.11	71.05
30	2017	Hon et al. [59]	CN vs AD	sMRI (T1)	-	CNN(TL)	200 (100 CN, 100 AD)	5-Fold	96.25	-	-
31	2017	Lama et al. [89]	CN vs AD	sMRI (T1)	Cortical	PCA+RELM	214 (70 CN, 74 MCI, 70 AD)	10-Fold	77.30	62.12	79.85
			CN vs MCI vs AD						61.58	54	62.25
32	2017	Jha et al. [70]	CN vs AD	sMRI (T1)	VBM	PCA + FNN	126 (98 CN, 28 AD)	10-Fold	90.06 ± 0.01	92.0 ± 0.04	87.78 ± 0.04
33	2017	Zheng et al. [197]	CN vs AD	sMRI (T1) + PET	Atlas	(SVM+) + (RBM+)	103 (52 CN, 51 AD)	10-Fold	88.52 ± 8.61	84.60 ± 15.24	92.20 ± 12.61
34	2017	Beheshti et al. [12]	CN vs AD	sMRI (T1)	VBM (NBF)	SVM	231 (61 CN, 42 sMCI, 45 pMCI, 83 AD)	10-Fold	84.17	88.83	79.00
			CN vs MCI						70.38	78.17	60.22
			pMCI vs sMCI						61.05	52.65	70.52
			AD vs sMCI						67.59	79.25	45.47
			AD vs pMCI						62.84	76.38	39.57
35	2017	Cheng et al. [22]	CN vs AD	sMRI (T1)	Atlas	MDTFS+MDTC	807 (226 CN, 167 pMCI, 228 sMCI, 186 AD)	10-Fold	94.7	94.1	94.8
			CN vs MCI						81.5	85.8	73.3
			pMCI vs sMCI						73.8	69	77.4
36	2018	Liu et al. [98]	CN vs AD	sMRI (T1)	Atlas	MKBoost+ SVM	680 (200 CN, 120 MCI, 160 MCInc, 200 AD)	10-Fold	95.37	92.49	96.08
			MCI vs AD						90.41	92.83	88.82
			CN vs MCI						86.56	90.74	84.83
			MCInc vs MCInc						73.95	76.13	72.24
37	2018	Kim et al. [81]	CN vs AD	sMRI (T1) +PET+CSF	Atlas + CSF	MSH-ELM	202 (52 CN, 99 MCI, 51 AD)	10-Fold	97.2	98.08	94.12
38	2018	Bi et al. [13]	CN vs AD	rs-fMRI	Atlas	Random NN cluster	60 (25 AD, 35 CN)	-	87.01	75	91.92
			CN vs MCI						92.3	-	-
39	2018	Li et al. [94]	CN vs AD	rs-fMRI	VBM	Subspace alignment	318 (129 AD, 189 CN)	LOOCV	84.6	92	79

Table 2 (Contd.)

Sr. No.	Year	Authors	Target	Modality	Feature extraction	Machine learning	Dataset	Validation	Performance		
									Acc (%)	Sens (%)	Spec (%)
40	2018	Cheng et al. [24]	CN vs AD	sMRI (T1)	VBM	rMLTFL	406 (112 CN, 86 pMCI, 106 sMCI, 102 AD)	10-Fold	95.2	95.2	95.3
			CN vs MCI						82.4	86.7	73.8
			pMCI vs sMCI						76.3	73.4	78.6
			MCI vs AD						76.7	61.4	81.8
41	2018	Zhou et al. [198]	CN vs AD	sMRI (T1)	Atlas	TrAdaBoost	543 (103 CN, 245 MCI, 195 AD)	-	93.75	87.5	100
42	2018	Veen et al. [173]	CN vs PD	FDG-PET	VBM	LGMLVQ	304 (82 CN, 146 PD, 76 AD)	-	-	79.23	68.15
			CN vs AD						-	91.47	91.45
			PD vs AD						-	84.7	86.63
43	2018	Cui et al. [31]	CN vs AD	sMRI (T1)	VBM	ANN+BGRU	427 (128 AD, 229 CN)	5-Fold	89.69	86.87	92.58
44	2019	Kar et al. [76]	CN vs AD	sMRI (T1), sMRI (T2), CT	ROI based	ANN	20 (9 AD, 11 CN)	-	100	100	100
45	2019	Fritsch et al. [42]	CN vs AD	Linguistic data	n-gram	LSTM	266 (168 AD, 98 CN)	LOOCV	85.6	-	-

Abbreviations: **SMSE**- Multi-view multimodal spectral embedding, **RNN**- Recurrent neural network, **PRNN**- Pattern recognition neural network, **LGMLVQ**- Generalized matrix learning vector quantization with local relevance matrix, **ERP**- Event related potential, **KNN**- K - nearest neighbours, **ICGA**- Integer coded genetic algorithm, **M2TL**- Multimodal manifold regularized transfer learning, **M2TFS**- Manifold regularized multi-task feature selection, **RELM**- Regularized extreme learning machine **MDTFS**- Multi-domain transfer feature selection, **MDTC**- Multi-domain transfer classification, **MKBoost**- Multi-kernel boosting, **MSH-ELM**- Multimodal sparse hierarchical extreme learning machine, **DBM**- Deformation based morphometry, **DW-S²MTL**- Deep weighted subclass based sparse multi-task learning, **CT**- Computed tomography, **NPR**- Neurophysiological records, **NPF**- Neurophysiological features, **CC**- Conventional coherence, **WC**- Wavelet coherence, **EEG**- Electroencephalogram, **NGF**- Nonlinear graph fusion, **ePANN**- Paraconsistent artificial neural network, **RF**- Random forest, **LC**- Lattice computing. **Atlas**- Atlas based parcellation of brain regions, **n-gram**- n-gram language model, **LSTM**- Long short term memory.

multi-task learning (MTL), transfer learning (TL) and multi-kernel learning (MKL) for AD classification. We also review certain feature selection (FS) techniques like network connectivity features, multi-view features and other machine learning approaches used for AD classification. The works using ANN for Alzheimers are presented in Table 2.

4.1 Transfer learning

Conventional machine learning models utilize samples from only a single domain which greatly affects their performance when the number of samples available is very low. Transfer learning is an approach that not only utilizes samples from the target domain but also from various auxiliary (related) domains. Cheng et al. [23] proposed a multimodal manifold regularized transfer learning (M2TL) to transfer knowledge learned from an auxiliary domain (CN vs AD) to aid in learning the target domain (MCIc vs MCInc).

In their subsequent work, Cheng et al. [22] went a stride ahead and proposed a novel multi-domain transfer learning model (MDTL). To deal with the small sample size problem in training deep neural networks, Hon et al. [59] used deep transfer learning by fine-tuning two popular pre-trained networks - visual geometry group 16 (VGG16) and Inception on the target task of classifying AD and CN subjects. Zhou et al. [198] used the TrAdaBoost algorithm to transfer knowledge learned from ADNI to AD samples from a local hospital. Transferring knowledge from all source domains without ignoring the unrelated domains degrades the performance of the model. Also, the class labels assigned to various samples might be erroneous. To deal with these problems, Cheng et al. [24] proposed a robust multi-label transfer learning (rMLTFL) approach that transformed original labels to multi-bit label coding vector, and simultaneously acquired common features to identify unrelated domains. Li et al. [94] also transferred knowledge gained from ADNI samples to the samples acquired locally through the subspace alignment algorithm.

4.2 ANN based machine learning models

Different variants of ANN were used on EEG signals of CN and AD subjects by [34, 144]. Savio et al. [146] compared different variants of ANN like radial basis function neural network (RBFNN), probabilistic neural network (PNN), learning

vector quantization neural network (LVQNN), and found that LVQNN performed the best. An unsupervised approach is employed by Long et al. [105] for classification of CN and AD. Joshi et al. [74] compared various classification algorithms like RBFNN, random forest (RF), best-first decision tree (BF tree), decision tree, bagging, multilayer perceptron (MLP) and ANN for classification of AD and Parkinson's disease (PD) subjects. In real world scenario, all the neuroimaging data required to train a model might not be available at hand. In these scenarios, the batch training scheme will prove ineffective. To this end, Mahanand et al. [110] used a self-adaptive resource allocation network (SRAN) classifier for AD classification. To deal with high dimensional data, Mahmood et al. [111] used PCA for dimension reduction and used ANN for classification. Naami et al. [3] also used ANN to classify CN from AD. To exploit the intrinsic correlation among features and obtain robust performance, Veen et al. [173] compared the performance of generalized matrix learning vector quantization (GMLVQ) with local and global relevance with SVM for classification of Parkinson's disease (PD) and AD subjects. To utilize longitudinal information from MRI scans, Cui et al. [31] cascaded an MLP and bidirectional gated recurrent unit (BGRU) together. Fritsch et al. [42] used the long short-term memory network to utilize information from sequential auditory data for classification of AD subjects. Kar et al. [76] used a fuzzy approach with ANN for discriminating CN and AD subjects using DTI images.

4.3 Feature selection techniques

Many techniques are proposed for better feature selection (FS) from neuroimaging data. Ahmadlou et al. [2] stated that non-linear features may reveal notable differences in certain EEG sub-bands but may not aid in separating the two groups (CN and AD) in band-limited EEG. To address this, visibility graphs (VG) were used for extracting features from EEG signals. Rodrigues et al. [142] used short time fourier transform (STFT) and WT features for classification using ANN. A characteristic of AD is the loss in GM and WM tissues which results in shrinkage of various regions and WM tracts thereby cause loss of GM and WM volume. This process is also accompanied by increase in size of ventricles and CSF volume. To utilize this information, Yang et al. [185] proposed a classification framework that combines GM, WM and CSF volumetric features with ventricular 2D and 3D shape features.

A different approach for extracting features from MR images is to extract cortical features using surface based morphometry. Cho et al. [26] proposed a robust incremental classification method using cortical thickness data, The data was transformed into the spatial frequency domain through a manifold harmonic transform. Along with MRI scans, various other types of data like neuro-psychological and physiological tests, genetic makeup and demographics can be analysed to get further information about the condition of a subject. Quintana et al. [133] leveraged data from neuropsychological tests, age and education for classifying MCI and AD using ANN. Chyzyk et al. [27] proposed a novel wrapper feature selection technique that combines GA with extreme learning machine (ELM). In their subsequent work, Yang et al. [184] used the combination of volumetric and shape features. To address the issues of prior knowledge in manual ROI selection and high dimensionality in whole brain multivariate analysis, Ortiz et al. [121] proposed a novel method for adaptively selecting important ROIs using SOM. Wang et al. [179] used a hybrid PSO with the artificial bee colony (ABC) optimization algorithm along with a feed forward neural network (FFNN). A popular approach to deal with the problem of high dimensionality in whole brain analysis is to extract features from specific ROIs of the brain. However, it comes with a disadvantage of requiring some prior knowledge. Gorji et al. [49] leveraged image moments to extract features from MR images. Jha et al. [70] proposed a dual-tree complex wavelet transform (DTCWT) for extracting features from MR images. It is stated that the property of translation invariance and directional selectivity is a better choice than DWT. Different classification tasks can also be jointly considered together for feature selection

as done by [72, 101, 163, 164]. The brain is an intrinsic complex network and to exploit this information many works have also focused on using network theory for AD classification [12, 73, 78, 98, 99].

4.4 Multiple kernel learning & multimodal data

Data from multiple modalities provides complementary information which can boost the performance of machine learning algorithms. To this end, Ye et al. [186] proposed a multiple kernel learning (MKL) framework that integrated ROI and tensor features into a common feature space. Zhang et al. [188] proposed a novel multimodal Laplacian regularized least squares (mLapRLS) model to utilize unlabelled samples in aiding the classification. Liu et al. [97] argued that selecting features separately from each modality ignores the strong inter-modal correlation within each subject which results in sub-optimal performance. To overcome this problem, a novel multi-task learning based feature selection approach was proposed that jointly selected sparse features from all the modalities. The MKL methods discussed till now combine multiple kernels from different modalities linearly, and is very sensitive to weights assigned to each modality. To address these problems, Tong et al. [172] proposed to combine data from multiple modalities non-linearly using non-linear graph fusion (NGF) technique. Zheng et al. [197] used the learning using privileged information (LUPI) approach during the training phase. A novel restricted Boltzmann machine (RBM+) was proposed for leveraging the privileged information. An ensemble of RBM+ and a LUPI variant of SVM (SVM+) were also used for the classification. In order to obtain high level features from different modalities and fuse them for classification, Kim et al. [81] proposed a multimodal sparse hierarchical extreme learning machine (MSH – ELM).

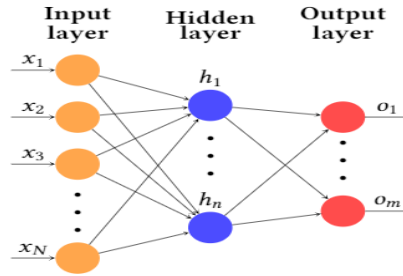


Fig. 4. Architecture of neural network.

5 DEEP LEARNING AND ENSEMBLE METHODS

Deep learning (DL) is a multi-layered neural network shown in fig. 4, capable of learning complex structures of data to achieve high degree of abstraction. In DL, there are two kinds of models. One is known as feed forward networks (FFNs) where information flows from input to output, and other is known as recurrent networks (RN) with information from past inputs affecting the present input through feedback connections. The ensemble methods includes techniques other than SVM, ANN, and DL for classification of dementia or AD. Fig. 5(a) shows the different types of modalities used by researchers in the classification or analysis of AD. Fig. 5(b) shows the types of cross-validation for DL and ensemble methods used by researchers.

In the upcoming subsections we discuss DL for classification of AD. We include the simple deep neural network (DNN) architecture, more complex networks such as stacked autoencoders (SAEs), and deep belief networks (DBN). We

also include the popular convolutional neural networks (CNN). Finally, we consider the ensemble algorithms used for classification of AD. Table 3 shows the review of papers using DL and ensemble methods for classification of AD.

5.1 Review of DL studies on Alzheimer's disease

Suk et al. [162] applied SAE and showed that non-linear correlations within the features can improve diagnosis accuracy of AD, MCI, and MCIC. Suk et al. [159] used patch based features from MRI, and PET for classification of AD and MCI from CN by deep Boltzmann machine (DBM). Payan et al. [127] combined SAE, and CNN, and found that 3D-CNN performs better in classification of AD, MCI from CN. Suk et al. [160] used DL-based latent feature representation with a SAE based classifier for classification of AD, MCI, from CN, and MCIC from MCInc. Best accuracies were obtained by multi-kernel SVM (MK-SVM) with low-level features (LLF) and SAE-learned features (SAEF). Liu et al. [102] used SAE based DL architecture for diagnosis of AD in four stages by obtaining high level features and soft-max logistic regressor (LR). Hosseini et al. [62] proposed a deeply supervised adaptive 3D-CNN (DSA-3DCNN) to classify AD and MCI from CN, which was pre-trained by 3D convolutional autoencoder (3D-CAE) using features from MRI. Ortiz et al. [123] extracted 3D patches defined by automated anatomical labeling (AAL) atlas and trained DBNs. The best classification accuracy is obtained by extracting features using DBN (FEDBN-SVM) architecture.

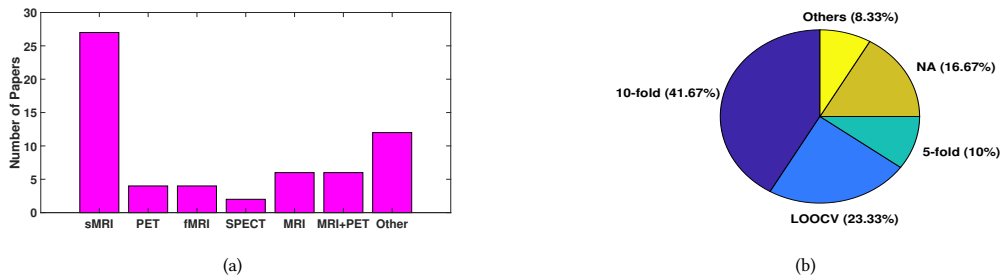


Fig. 5. (a) Plot showing usage of different types of image modalities, and (b) cross validation methods with DL and ensemble methods. NA means information not available.

Suk et al. [164] combined sparse regression models with a deep CNN known as deep ensemble sparse regression network (DeepESRNet), and were able to clinically diagnose AD. Suk et al. [165] combined DL and state-space modelling and functional dynamics with time of rs-fMRI to form a biomarker for the diagnosis of MCI. Sarraf et al. [145] are the first to use fMRI data with DL. Suk et al. [161] combined two conceptually different models of sparse regression multi-output linear regression (MOLR), joint linear and LR (JLLR) and deep CNN. Better performance in classification of AD is achieved with JLLR-Deep ensemble sparse regression network (JLLR-DeepESRNet).

Shi et al. [153] introduced a multimodal stacked deep polynomial networks (MM-SDPN) algorithm consisting of two-stage SDPNs which fuses and learns from multimodal neuroimaging data i.e MRI and PET. It is stated that MM-SDPN based algorithms are better than SAE based algorithms. Basaia et al. [9] used 3D sMRI (T1) and build a DL algorithm that predicts MCI who will convert to AD in 36 months. It is showed that the algorithm is not dependent on dataset, and their CNN based architecture is able to differentiate AD, MCI patients from CN. Leracitano et al. [64] used DL method based on power spectral density (PSD) of brain states using EEG. Patients affected by AD, MCI are differentiated from CN by using PSD spectrograms of EEG. Lu et al. [107] proposed DL multiscale DNN (MDNN) using measures from a single modality FDG-PET and showed that discriminative ability of DL architecture are better for diagnosis AD in case

of single modality. Ensemble of multiple classifiers are more robust, stable, and improve classification performance using different validation settings.

Li et al. [92] used multiple cluster dense CNNs (DenseNets) in which 3D patches were extracted from sMRI (T1) and clustered using K-Means clustering technique. This technique does not require segmentation and rigid registration of MRI for the classification and diagnosis of AD by DenseNets. Jain et al. [68] used transfer learning approach in which first sMRI (T1) slices are passed through a pretrained ImageNet VGG16 network for extraction of features. Spasov et al. [156] used deep CNN for extracting the descriptive features from sMRI (T1) based on 3D separable and grouped convolutions. The parameters are selected efficiently using CNN for classification of AD. Wang et al. [177] developed an ensemble of 3D densely connected CNNs (3D-DenseNets), which maximizes the information flow from one layer to next layer. It avoids over-fitting and enhances the performance for diagnosis of AD and MCI using sMRI images.

5.2 Review of ensemble and other methods for AD classification

Fan et al. [41] used features from MRI and PET and applied high-dimensional pattern classification (PC) to classify AD from MCI. Functional connectivity from rs-fMRI is used by Wang et al. [178] to discriminate AD from CN using LR. An increase in positive correlation is observed between parietal, prefrontal, and occipital lobe while decrease in parietal and prefrontal lobes. Davatzikos et al. [37] used voxel based analysis for the classification of AD and frontotemporal dementia (FTD) from CN using high-dimensional PC method. Better diagnostic accuracy is obtained by high dimensional multi-variate discriminant analysis than conventional measurement. Hinrichs et al. [57] used linear program (LP) for classification of AD using sMRI (T1) and FDG-PET with regularization using spatial smoothness. Lopez et al. [106] used PCA for dimension reduction, and used Bayesian classifiers for CN vs AD. Horn et al. [61] used ROI based features which were reduced by partial least squares (PLS) regression, and yield best accuracy using KNN for CN vs AD.

Chincarini et al. [25] used RF classifier to select informative features from intensity and textural based MRI features. In order to build more robust classifier, Termenon et al. [169] used relevance vector machine (RVM) to build the discriminant function, and applied two stage sequential ensemble of classifiers. Employing an RF classifier on all the available features can degrade the classifier performance due to overfitting. To address this, Li et al. [93] combined weak hierarchical lasso feature selection (wHLFS) with RF for MCIC vs MCInc classification. wHLFS selects only the most important subset of features improving the classification accuracy of RF. To exploit the complementary information provided by multiple modalities, Hor et al. [60] introduced tree-based feature transforms of MRI and PET scans and used RF for classification. Dominguez et al. [54] compared the performance of RF and SVM to classify AD and MCI from CN, on linguistic and phonetic metrics. RF also performed remarkably on features from combination of different modalities like MRI, PET, genetic data and CSF measures [28, 51, 90].

Techniques like LR, LDA, PLS and their variants are also used for diagnosis of AD. In [38, 114], LR was used on features from sMRI. Rao et al. [137] found better performance with sparse LR (SLR) and regularized sparse LR (SRSLR) on voxel wise GM volumes as compared to MLD, and penalized LR (PLR) models for CN vs AD. Liu et al. [100] found that sparse representation-based classifier (SRC) performed better than SVM with high dimensional features. Techniques based on sparse feature representations are also used in [71, 195]. Liu et al. [103] introduced locally linear embedding (LLE) in combination with RLR that leveraged information from patches of local brain regions. It resulted in significant improvement in classification accuracy. Casanova et al. [17] used RLR for CN vs AD, and found that AD pattern similarity (AD-PS) scores are powerful parameters to measure conversion of MCI to AD. Chen et al. [20] used Fisher LDA to classify AD and MCI from CN by large scale networks (LSN) analysis using brain pattern connectivity. Cho et al. [26] introduced incremental learning in neuroimaging and used a spatial

Table 3. Comparison of recent studies using deep learning and ensemble methods.

Sr. No.	Year	Authors	Target	Modality	Feature extraction	Machine learning	Dataset	Validation	Performance		
									Acc (%)	Sens (%)	Spec (%)
1	2007	Wang et al. [178]	CN vs AD	rs-fMRI	ROI	LR	44(18 AD, 26 CN)	-	81.1	-	-
2	2008	Fan et al. [41]	AD vs MCI	MRI, PET	VBM	PC	30(15 CN, 15 MCI)	LOOCV	93	-	-
3	2008	Davatzikos et al. [37]	AD-FTD CN vs FTD CN vs AD	sMRI (T1)	VBM	PC	98 (37 CN, 37 AD, 12 FTD, 12 CN)	LOOCV	84.3 100 100	- - -	- - -
4	2009	Hinrichs et al. [57]	CN vs AD	sMRI (T1), FDG-PET	GMPs WMPs	LP	183 (89 AD, 94 CN)	LMOCV	84	84	82
5	2009	Lopez et al. [106]	CN vs AD	SPECT	VAF	RF	147 (37 AD, 35 CN, 75 MCI 35 CN)	10-fold	89 74.6	87.5 77.5	90 67.9
6	2009	Horn et al. [61]	AD vs FTD	SPECT	ROI	KNN	173 (82 AD, 91 FTD)	LOOCV	88	93	85
7	2009	McEvoy et al. [114]	CN vs AD	sMRI (T1)	Morphometric measures	LR	398 (139 CN, 84 AD, 175 MCI)	LOOCV	89	83	93
8	2009	Desikan et al. [38]	CN vs AD CN vs MCI	sMRI (T1)	Anatomical Regions	LR	216 (94 CN, 65 AD 57 MCI)	-	95 95	- -	- -
9	2010	Plant et al. [131]	CN vs AD AD vs MCI CN vs MCI AD vs MCI vs CN	sMRI (T1)	GM WM CSF	SVM+Bayes+ VBI	74 (18 CN, 24 MCI, 32 AD)	LOOCV	92 95.83 97.62 75.0	93.75 100 95.83 55.56	88.89 93.33 100 86.67
10	2010	Ramirez et al. [135]	CN vs AD	SPECT	ROI	RF	97 (41 CN, 30 AD1, 22 AD2, 4 AD3)	LOOCV	89.69	100	92.7
11	2011	Chen et al. [20]	CN vs AD CN vs MCI	fMRI	116 ROI	Fisher LDA	55 (20 CN, 20 AD, 15 MCI)	LOOCV	87 91	85 95	80 93.90
12	2011	Dai et al. [35]	CN vs AD	sMRI, rs-fMRI	ALFF, GMD, RFCS	MLDA	38 (22 CN, 16 AD)	LOOCV	89.47	87.5	90.91
13	2011	Westman et al. [182]	CN vs AD MCIc vs MCIc	PET	ROI	OPLS	1067 (295 AD, 335 CN, 353 MCIc, 84 MCIc)	7-fold	-	83.4 71.4	87.8 60.1
14	2011	Chincarini et al. [25]	CN vs AD CN vs MCIc MCIc vs MCIc	sMRI (T1)	CSF, GM, WM	RF+SVM	635 (144 AD, 302 MCI, 136 MCIc 166 MCIc) 189 CN)	20-fold	97 92 74	89 89 72	94 80 65
15	2011	Rao et al. [137]	CN vs AD	sMRI (T1)	GM Density	LR	140(75 AD, 65 CN)	10-fold	85.25	90.77	80.26
16	2012	Liu et al. [100]	CN vs AD CN vs MCI	sMRI (T1)	GMPMs	SRC ensemble	652(198 AD, 225 MCI, 112 sMCI 113 sMCI) 229 CN)	10-fold	90.80 87.85	86.32 85.12	94.76 90.40
17	2012	Termonen et al. [169]	CN vs AD	sMRI	VBM	RVM+SVM	98 (49 AD, 49 CN)	10-fold	82	83	81
18	2012	Cho et al. [26]	CN vs AD MCIc vs MCIc	sMRI	Cortical Thickness	LDA	491 (128 AD, 160 CN, 72 MCIc, 131 MCIc)	-	-	82 63	93 73
19	2013	Spulber et al. [157]	CN vs AD CN vs MCI	sMRI (T1)	ROI	OPLS	1064 (295 AD, 335 CN, 261 sMCI, 173 MCIc)	7-fold	84.4 67.7	86.1 69.6	90.4 66.6
20	2013	Suk et al. [162]	CN vs AD CN vs MCI MCIc vs MCIc	MRI PET CSF	ROI	SAE	202 (51 AD, 99 MCI, 43 MCIc, 56 MCIc, 52 CN)	10-fold	89.9 73.7 60.2	- - -	- - -
21	2013	Gray et al. [51]	CN vs AD CN vs MCI pMCI vs sMCI	MRI, PET, CSF	83 ROI	RF	147 (37 AD, 75 MCI, 34 pMCI, 41 sMCI, 35 CN)	10-fold	89 75 58	87.9 77.5 57.1	90 67.9 58.7
22	2013	Chen et al. [21]	CN vs AD	MRI	GM maps	HMM	150 (75 AD, 75 CN)	LOOCV	80.7	81.3	80.0
23	2013	Liu et al. [103]	CN vs MCIc CN vs MCIc CN vs AD MCIc vs MCIc MCIc vs AD MCIc vs AD	sMRI (T1)	94 ROI	LR	413 (86 AD, 190 MCI, 97 MCIc, 93 MCIc, 137 CN)	LOOCV	-	65 81 86 80 77 56	63 82 93 56 73 61
24	2013	Casanova et al. [17]	CN vs AD CN vs MCIc CN vs MCIc MCIc vs MCIc	sMRI (T1), DNA, Cognitive data	Voxel intensities of GM, WM and CSF	RLR	689 (171 AD, 330 MCI, 153 MCIc, 182 MCIc, 188 CN)	10-fold	87.1 64.5 72.3 63.0	84.3 57.9 66.3 58.6	88.9 70.1 78.9 68.1
25	2014	Suk et al. [159]	CN vs AD CN vs MCI MCIc vs MCIc	MRI, FDG-PET	GM Intensity	CNN	780 (148 AD, 403 MCI, 167 MCIc, 236 MCIc, 229 CN)	RP	92.87 76.21 72.44	- - -	- - -
26	2014	Singh et al. [155]	MCIc vs MCIc	PET CSF	AS and NMA	QDA	127 (73 MCIc, 54 MCIc)	LOOCV	66.14	64.81	67.12
27	2014	Lebedev et al. [90]	CN vs AD MCIc vs MCIc	sMRI (T1)	41 ROI	RF	575 (185 AD, 225 CN, 35 MCIc, 130 MCIc)	5-fold	-	88.6 81.3	92 83.3
28	2014	Li et al. [93]	MCIc-MCIc	MRI	ROI	RF	293 (161 MCIc, 132 MCIc)	5-fold	74.7	66.7	81.4
29	2014	Jiang et al. [71]	CN vs AD	PET	83 ROI	KNN	103 (51 AD, 52 CN)	10-fold	91	92	-
30	2014	Lillemark et al. [95]	CN vs AD AD vs MCI	sMRI (T1)	ROI	LDA	524 (170 CN, 114 AD, 240 MCI)	-	87.70 76.60	- -	- -
31	2015	Korolev et al. [83]	MCIc vs pMCI	sMRI	ROI	pMKL	259 (120 MCIc, 139 pMCI)	10-fold	80.0	83.4	76.4
32	2015	Cabral et al. [16]	sMCI vs pMCI	FDG-PET	VI	SVM, GNB	100 (44 pMCI, 56 sMCI)	10-fold	85	-	-
33	2015	Payan et al. [127]	CN vs AD AD vs MCI CN vs MCI	MRI	3D patch	SAE	2265 (755 AD, 755 CN, 755 MCI)	-	95.38 86.84 92.11	- - -	- - -
34	2015	Suk et al. [160]	CN vs AD MCI vs CN AD vs MCI MCIc vs MCIc	sMRI (T1), PET CSF	GM, WM	SAE	202 (51 AD, 99 MCI, 43 MCIc, 56 MCIc, 52 CN)	10-fold	98.8 90.70 83.70 88.30	- - - -	- - - -
35	2015	Liu et al. [102]	CN vs AD CN vs MCI CN vs MCIc vs MCIc vs AD	sMRI (T1), PET	ROI	SAE	758 (204 CN, 180 AD, 214 MCIc, 160 MCIc)	10-fold	91.40 82.10 53.79	92.32 60.00 52.14	90.42 92.32 86.98
36	2016	Hosseini et al. [62]	CN vs AD AD vs MCI CN vs MCI	sMRI	VBM	CNN	210 (70 AD, 70 CN, 70 MCI)	10-fold	99.30 100 94.20	100 100 97.40	98.60 100 91.40
37	2016	Suk et al. [165]	CN vs MCI	rs-fMRI	ROI	CNN	37 (12 MCI, 25 CN)	LOOCV	81.08	77.78	82.14

Table 3 (Contd.)

Sr. No.	Year	Authors	Target	Modality	Feature extraction	Machine learning	Dataset	Validation	Performance		
									Acc (%)	Sens (%)	Spec (%)
38	2016	Ortiz et al. [123]	CN vs AD CN vs MCIc CN vs MCIs MCI vs AD MCInc vs MCIc	sMRI (T1)	VBM	DBN	241 (68 CN, 70 AD, 39 MCIc, 64 MCInc)	10-fold	90 83 80 84 78	86 67 60 79 61	94 95 90 89 88
39	2016	Suk et al. [164]	CN vs AD MCI vs CN MCIc vs MCIs	MRI	ROI	SAE	805 (186 AD, 393 MCI (167 MCIc, 226 MCIs), 226 CN)	10-fold	91.02 73.02 74.82	92.72 77.60 70.93	89.94 68.22 78.82
40	2016	Zhang et al. [190]	CN vs AD MCInc vs MCIc	MRI	TBM	Adaboost	810 (194 AD, 228 CN, 246 MCInc, 142 MCIc)	LOOCV	81 77	83 82	78 76
41	2016	Hor et al. [60]	AD vs MCIc AD vs MCInc MCIc vs MCIc	MRI, PET	ROI	RF	608 (108 AD, 322 MCI, (96 MCIc, 126 MCInc), 178 CN)	5-fold	78.8 79.5 81.5	74.7 73.7 83.1	80.5 89.7 80.3
42	2016	Zheng et al. [196]	CN vs AD	MRI, PET	93 ROI	MMSDPN	103 (51 AD, 52 CN)	10-fold	97.27	97.32	98.33
43	2016	Clark et al. [28]	CN vs MCI	sMRI	CT and volume	Ensembled classifier	158 (51 CN, 24 MCIc, 83 MCInc)	-	83.2	62.5	89.2
44	2016	Schouten et al. [148]	CN vs AD	rs-fMRI, MRI	GM density	RLR	250 (77 AD, 173 CN)	10-fold	89.6	82.6	92.7
45	2017	Sarraf et al. [145]	CN vs AD	rs-fMRI	Slice based	DL-CNN	144 (52 AD, 92 CN)	5-fold	100	-	-
46	2017	Suk et al. [161]	CN vs AD CN vs MCI pMCI vs sMCI	sMRI	93 ROI	JLLR DeepESRNet	805 (186 AD, 393 MCI, (167 pMCI, 226 sMCI), 226 CN)	10-fold	91.02 73.02 74.82	92.72 77.66 70.93	89.94 68.22 78.82
47	2016	Zhu et al. [199]	CN vs AD CN vs MCI MCIc vs MCInc CN vs MCI vs AD CN vs MCIc vs MCInc vs AD	sMRI (T1)+PET +CSF	Atlas	LDA+LPP	202 (52 CN, 43 MCIc vs 56 MCInc, 51 AD)	-	95.5 ± 1.05 79.7 ± 0.21 71.2 ± 1.22 73.35 ± 1.53 61.06 ± 1.40	-	-
48	2017	Leracitano et al. [64]	CN vs AD AD vs MCI CN vs MCI CN vs AD vs MCI	EEG	PSD, Epoch	CNN	189 (63 AD, 63 MCI, 63 CN)	-	92.95 84.62 91.99 83.33	- - - -	- - - -
49	2017	Asgari et al. [8]	AD vs MCI	Word count	LIWC	SVM+RF	41(27 CN, 14 MCI)	5-fold	74.7	6.51	72.3
50	2018	Liu et al. [101]	CN vs AD CN vs pMCI vs sMCI vs AD	sMRI (T1)	Patch based	Multi task multi channel deep neural network	1984 (881 CN, 459 sMCI, 202 pMCI , 442 AD)	-	93.7 51.8	94.6 -	93.2 -
51	2018	Basaia et al. [9]	CN vs AD CN vs MCIc CN vs MCIs AD vs MCIc MCIs vs AD MCIc vs MCIs	sMRI (T1)	GM, WM, CSF	CNN	1566 (418 AD, 741 MCI, (208 MCIc, 533 MCIs), 407 CN)	10-fold	98.2 87.7 76.4 75.8 86.3 74.9	98.1 87.3 75.1 74.8 84.0 75.8	98.3 88.1 77.1 77.1 88.7 74.1
52	2018	Lu et al. [107]	CN vs AD sMCI vs pMCI	FDG-PET	ROI	MDNN	1051 (226 AD, 304 CN, 409 sMCI, 112 pMCI)	10-fold	93.58 81.55	91.54 73.33	95.06 83.83
53	2018	Li et al. [92]	CN vs AD CN vs MCI	sMRI (T1)	Patch based	DenseNet	831 (199 AD, 229 CN, 403 MCI)	5-fold	89.5 73.8	87.9 86.6	90.8 51.5
54	2018	Zheng et al. [195]	CN vs AD CN vs MCI AD vs MCI sMCI vs pMCI	sMRI (T1)	ROI	MFN	528 (142 AD, 221 MCI, 126 pMCI, 75 sMCI, 165 CN)	10-fold	98.7 97.93 7383 67.92	98.59 98.64 64.08 72.22	98.79 96.97 80.09 61.05
55	2018	Dominguez et al. [54]	CN vs AD CN vs MCI	Audio transcription	Cov+lin	RF	517 (257 AD, 217 CN, 43 MCI)	10-fold	94 87	100 87	86 86
56	2018	Hett et al. [55]	CN vs AD CN vs pMCI AD vs sMCI pMCI vs sMCI	sMRI (T1)	Hippocampal segments	Fusion SVM	651(226 CN, 186 AD, 223 sMCI, 16 pMCI)	10-fold	- - - -	93.4 91.6 77.6 77.0	87.6 83.0 71.0 64.1
57	2018	Jain et al. [68]	CN vs AD AD vs MCI CN vs MCI	sMRI (T1)	Entropy based	CNN	150 (50 CN, 50 AD, 50 MCI)	-	99.14 99.30 99.22	- - -	- - -
58	2019	Krishnakumar et al. [84]	CN vs AD AD vs MCI CN vs MCI MCIc-MCInc	sMRI (T1)	GM, WM	SVM+RF+KNN	812 (227 CN, 396 MCI, (165 MCIc, 223 MCInc), 189 AD)	k-fold k=1 to 50	87.39 63.41 64.74 66.38	89.58 57.29 45.61 60.24	85.82 65.35 72.44 69.80
59	2019	Spasov et al. [156]	CN vs AD sMCI vs pMCI	sMRI (T1)	ROI, APOe4	CNN	785 (192 AD, 184 CN, 228 sMCI, 181 pMCI)	10-fold	100 92.5	100 86.5	100 85
60	2019	Wang et al. [177]	AD vs MCIs CN vs MCIs CN vs AD CN vs AD vs MCI	sMRI (T1)	Volume	3D-CNN	833 (221 AD, 297 MCI, 315 CN)	10-fold	93.61 98.42 98.83 97.52	- - - -	- - - -

Abbreviations: **RLR**- Regularized logistic regression, **BM**- Biological markers, **GMPs**- Grey matter probability maps, **WMPs**- White matter probability maps, **LMO**- Leave many out, **FDG**- Fluorodeoxyglucose, **MDNN**- Multi scale deep neural network, **ALLF**- Amplitude of low-frequency fluctuations, **ReHo**- Regional homogeneity, **RFCS**- Regional functional connectivity strength, **MLDA**- Maximum uncertainty linear discriminant analysis, **Cov+lin**- Coverage and linguistic measures, **RFCS**- Regional functional connectivity strength, **GMPMs**- Gray matter probability maps, **AS**- Anatomical shapes,

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NMA- Neuronal metabolic activity, **pMKL**- Probabilistic multiple kernel learning, **MFN**- Multifeature-based network, **MMSDPN**- Multimodal stacked deep polynomial network.

frequency representation of cortical thickness (CT) data using LDA. LDA was also used on multimodal data, surface connectivity data and MRI in [35, 84, 95]. Chen et al. [21] utilized hidden markov model (HMM) on features from MRI slices for early AD vs CN classification. Westman et al. [182] combined MRI data from two different cohorts and used orthogonal partial least square to latent structures (OPLS) models for combined and individual cohorts. Spulber et al. [157] also used OPLS to generate a severity index and found that there were significant differences in ROIs of MCIs (MCI stable) and MCInc. Bayesian classification methods were also used for AD classification in [16, 131]. Hett et al. [55] used texture-based grading framework which is capable of capturing structural alterations caused by AD using fusion SVM. Some other works like [8, 135, 148, 155, 190] have used different features which have shown significant results.

6 FUTURE DIRECTIONS

In the classification of dementia related data, there are various categories or targets. One classification target is MCI vs AD, which is one of the most important targets for early diagnosis of AD. It can be observed in fig. 6(b), 7(b), and 9(b) that most of the work has been done in classification of CN vs AD and CN vs MCI. Moreover, classifications like MCI vs AD are very less. This needs to be addressed in future research for early detection of AD. Other categories like MCInc vs MCInc, and MCInc vs MCIs are also addressed in very few papers. Therefore, researchers can focus on these particular problems for early detection of dementia caused by Alzheimer's disease.

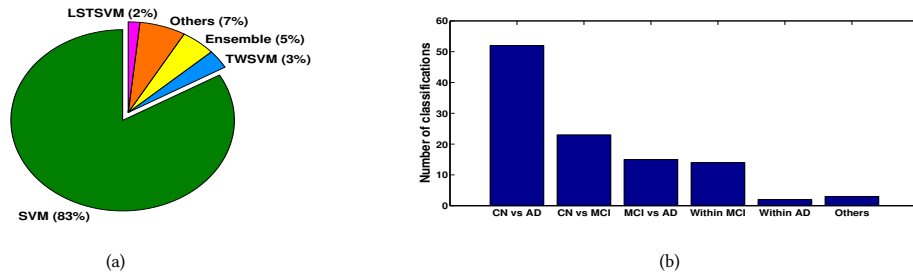


Fig. 6. Plot showing usage of (a) different variants of SVM and (b) different target groups for Alzheimers.

In AD diagnosis, an important focus point for research is the development of individual specific diagnosis models. For this, multimodal clinical data can be utilized as per the population. Moreover, novel learning techniques need to be developed for small datasets, since in real world scenarios the sample size from some population may not be large for training of model. Further, the data collection for Alzheimers includes noise from various sources. So, noise insensitive techniques must be applied for AD classification. In the next subsections, we suggest some future directions specific to the different machine learning approaches used for Alzheimers.

6.1 SVM

As discussed in previous sections, different variants of SVM have been employed for classification of Alzheimers. The usage of different types of SVM in our survey is shown in fig. 6(a). One can notice that among the different variants of SVM, 83% of the papers used standard SVM. This shows the popularity and robustness of SVM in the classification of

MRI data [112]. In 3% of the papers, TWSVM is used [5, 192], whereas LSTSVM [183] is used in only 1 paper. CSVM is used in [45, 158].

Some papers used ensemble of SVMs to classify Alzheimer's data [7, 65]. However, it can be observed that only 7% of the papers are in the others category. This category involves the algorithms based on SVM which are modified especially for Alzheimers. One can observe that very few variants of SVM have been applied for AD. This shows that research is needed in application of other variants of SVM for Alzheimers. Moreover, other than the existing models, some novel variants of SVM also need to be developed for Alzheimer's disease as was done in [33]. In this paper, the spatial regularization on MRI image is included with SVM using graph Laplacian approach. Also, one can develop and use novel kernel functions for diagnosis of AD using SVM. Such kind of novel models can increase the classification performance of SVM.

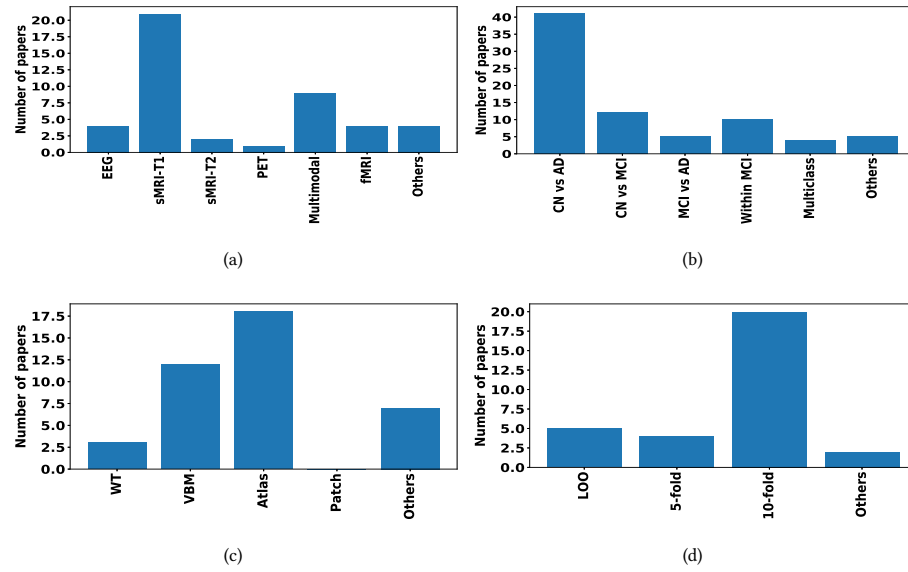


Fig. 7. Plots for application of ANN on different (a) modalities (b) classification tasks (c) feature extraction methods, and (d) cross validation methods

6.2 ANN, TL and MKL techniques

Techniques like transfer learning and multikernel learning can be used on multimodal data. We can see in fig. 7(a) that T1-weighted structural MRI is the most used modality. For feature extraction from MR images, atlas based methods have been mostly used by the researchers as shown in fig. 7(c). Atlas based methods employ some type of atlas to parcellate the brain regions from which different types of features are extracted. In future, other feature selection techniques can be utilized with ANN. For validating the model performance, 10-fold cross validation was the mostly used technique in fig. 7(d). However, one can also use methods like LOOCV, since it is the mostly used cross-validation method for SVM based algorithms in fig. 3(b).

The usage of different architecture of ANNs are shown in fig. 8(a). Mostly ANNs with backpropagation were used. Fig. 8(b) shows different learning paradigms used by researchers. Most of the effort has been given on selection of

better and more informative features. More informative features alone are insufficient for improving performance on classification of AD. Thus, more effort needs to be given on producing novel classifiers specifically designed for handling neuroimaging data. Also, more efforts need to be given on approaches like TL and MTL as they can aid in dealing with the problem of small sample size and high dimensionality.

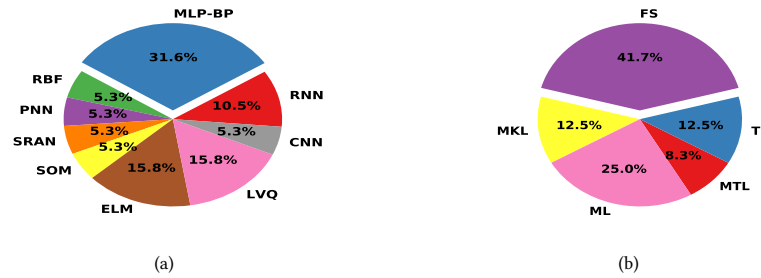


Fig. 8. Pie charts showing usage of (a) variants of ANN and (b) different learning paradigms.

It can be seen from fig. 7(a) that less efforts have been given on utilizing data from multiple modalities as compared to data from single modality. Hence, more efforts should be given on developing models that can leverage multimodal data.

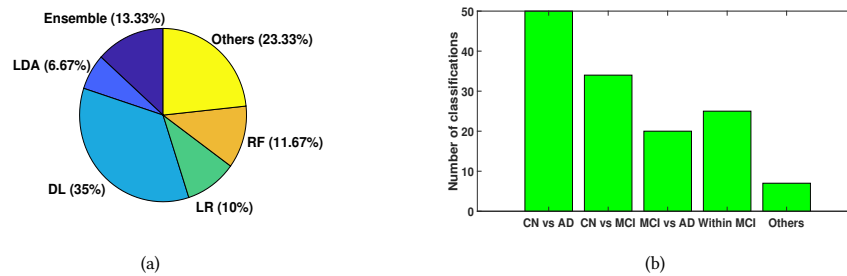


Fig. 9. (a) Plot showing usage of different types of machine learning algorithms, and (b) targets used for classification of AD data.

6.3 DL and ensemble methods

In most of the papers using DL and ensemble techniques, T1-weighted structural MRI is used for classification of AD as shown in Table 3. Most of the researchers used ROI based features to classify or diagnose AD. DL techniques based on CNN architectures perform better for classification of AD. Moreover, 10-fold cross-validation is mostly used for validation of learning algorithms as shown in fig. 5(b).

The usage of DL, ensemble, and other classification techniques in our survey is shown in fig. 9(a). Among the different techniques, 35% of the papers used DL, 10% of the papers used LR, 11.67% of the papers used RF, 6.67% of papers used LDA, and 13.33% of papers used ensemble methods, and about 23.33% of the papers used other methods. The DL, ensemble and other techniques reviewed in our paper have issues related to model interpretability for routine use by clinicians. It can be observed in fig. 5(a) that most of the machine learning algorithms use MRI scans. Hence, more focus

should be given on leveraging data from various other modalities. In future, DL models can be trained on large sized Alzheimers datasets for better classification performance.

7 CONCLUSION

In this work, papers using three major machine learning techniques - SVM, ANN and DL are analyzed for diagnosis of Alzheimers. Research on other learning techniques like transfer, ensemble, and multi-kernel learning is also discussed. This can be useful for researchers working on any of these techniques to work on Alzheimers. As per this survey, it can be stated that SVM based models have been widely used for Alzheimer's disease showing its robustness. This is because techniques like ANN suffers from the drawbacks of local minima, which is not the case with SVM. However, ANNs are more versatile and robust when it comes to incremental learning [110], modelling sequential data [130], and quantizing high dimensional spaces [121]. Therefore, novel variants of ANN can be used for Alzheimer's in future. Deep learning and ensemble learning techniques give promising results by modeling highly complex data with high accuracy. The abundant usage of SVM also stems from the fact that it is easier to interpret as compared to deep neural networks which act as black box models. This problem should be addressed in future by focusing on clinical interpretability of deep learning models. Also, more work is needed in proper integration of feature selection techniques and machine learning model for a particular modality of data.

It is also observed that researchers have given more importance to the feature extraction phase, and not much to the classification phase. This can be addressed in future research, since novel models can give some new insight in the diagnosis of Alzheimers. Moreover, more work is required in formulation of machine learning models which can integrate information from various modalities for early diagnosis of Alzheimer's disease.

ACKNOWLEDGMENTS

This work was supported by Department of Science and Technology, INDIA as Ramanujan fellowship grant no. SB/S2/RJN-001/2016. It is also supported by Council of Scientific & Industrial Research (CSIR), New Delhi, INDIA under Extra Mural Research (EMR) Scheme grant no. 22(0751)/17/EMR-II. We gratefully acknowledge the Indian Institute of Technology Indore for providing facilities and support. We are thankful to the Indian Institute of Technology Indore for providing Institute fellowship to Mr. Bharat Richhariya. We are also thankful to CSIR, New Delhi, INDIA for providing research fellowship to Mr. Riyaj Uddin Khan.

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