Multimodal Classification: Current Landscape, Taxonomy and Future Directions

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Multimodal classification research has been gaining popularity with new datasets in domains such as satellite imagery, biometrics, and medicine. Prior research has shown the benefits of combining data from multiple sources compared to traditional unimodal data that has led to the development of many novel multimodal architectures. However, the lack of consistent terminologies and architectural descriptions makes it difficult to compare different solutions. We address these challenges by proposing a new taxonomy for describing multimodal classification models based on trends found in recent publications. Examples of how this taxonomy could be applied to existing models are presented as well as a checklist to aid in the clear and complete presentation of future models. Many of the most difficult aspects of unimodal classification have not yet been fully addressed for multimodal datasets, including big data, class imbalance, and instance-level difficulty. We also provide a discussion of these challenges and future directions of research.

CCS Concepts: • **Computing methodologies → Classification and regression trees**; **Neural networks;**

Additional Key Words and Phrases: Multimodal learning, neural networks, machine learning, classification

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1 INTRODUCTION

In the past decade, there has been an increased focus on combining data from multiple modalities to further improve machine learning–based classification models. Data is becoming more important to every sector of business and research, which has led to the creation of larger and more diverse datasets. The ever-increasing rate of data collection and the reported benefits of multimodal data for machine learning modals has fueled interest in this field. By using information from several representations of the same subject, a more complete picture of the problem at hand can be constructed. Multiple data modalities are naturally present in many problem domains such as medicine [27, 35, 40, 49], hyperspatial imagery [7, 30], sentiment analysis [14, 83, 89], and many others.

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The majority of existing classification algorithms were designed for unimodal datasets that represent a single data source for each specific problem. These datasets typically use only one data type such as tabular, images, or text but many real-world scenarios include data of mixed types. Price prediction datasets may include both text from news articles and tabular data from financial reports, or medical records may have both signal-based heart monitoring data and diagnostic imaging. Combining data modalities can be challenging when each individual representation is significantly different with combinations like image-text, audio-video, or multiple sensors that are not time-synchronized. These challenges have led to solutions that utilize unimodal algorithms to solve multimodal problems.

The increasing interest in multimodal learning has led to a number of recent survey papers covering entire domains [9, 59, 122, 124], with many of these surveys focusing on deep learning [32, 77, 115], domain-specific solutions [7, 27, 29], or non-classification methods [35, 49, 78]. While these works cover the breadth of multimodal learning, there are no surveys that specifically investigate classification problems and their unique properties. This article has been guided by the following motivations:

(1) **The lack of a specific multimodal classification taxonomy**
Although several taxonomies have been previously presented, they are directed at multimodal learning in whole instead of classification. For example, the work by Baltrušaitis et al. [9] addresses many types of learning such as image captioning, video descriptions, text-to-image conversions, co-training, transfer learning, and zero-shot learning. While that taxonomy can be applied to almost any multimodal problem, it is not specific enough to fully describe the recent multimodal classification architectures.

(2) **Identifying recent trends in model architectures**
Since the prior surveys have focused on the high-level aspects of multimodal learning or domain-specific problems, there has not been a review of recent classification models and their architectures. A comparison of the architectures is needed to identify current trends and how they could be described with a common taxonomy.

(3) **Providing a way to describe multimodal classification architectures**
While reviewing multimodal classification papers, we observed that a significant amount of work was required to decompose many of the model architectures. Each model used its own set of terms and method of presentation, so reviewing each paper was a new experience that made the process more difficult. Paired with the taxonomy, a common descriptive framework is needed to make model architecture depictions and comparisons easier.

(4) **Discussion of future challenges**
Issues related to big data, distributed computing, and difficult datasets have been well studied with unimodal problems, but limited work has been done for multimodal learning. A discussion on how these challenges could affect multimodal classification is needed.

The rest of this article is organized as follows: Section 2 provides a brief overview of multimodal learning and examples of existing domain-specific solutions. Section 3 gives descriptions of multimodal classification architectures and our proposed taxonomy, and Section 4 reviews recent multimodal classification research using these common terms, which addresses the motivations 1 and 2 above. Section 5 gives examples of how to apply the taxonomy on both existing and future models for motivation 3. Section 6 discusses the challenges with classification that have not been addressed for multimodal problems as mentioned in motivation 4. Finally, Section 7 provides our concluding remarks. In Table 1, we introduce the list of abbreviations that will be frequently used in the rest of this article.

Table 1. A List of Terms Used to Describe Algorithms or Methods Used in Multimodal Classification Architectures

List of Terms	
Term	**Description**
AE	Autoencoder
AN	Attention Network
CCA	Canonical Correlation Analysis
CNN	Convolutional Neural Network
DBN	Deep Belief Network
DL	Deep Learning
DNN	Deep Neural Network
DT	Decision Tree
ELM	Extreme Learning Machine
FCNN	Fully Connected Neural Network
GAN	Generative Adversarial Networks
GBT	Gradient Boosted Trees
GRU	Gated Recurrent Unit
*k*NN	*k*-Nearest Neighbors
LR	Linear Regression
LSTM	Long Short-Term Memory
Manual	Feature extraction performed by hand or with a manually chosen method
MKL	Multiple Kernel Learning
ML	Machine Learning
MLP	Multilayer Perceptron
Multi-SVNN	Multi Support Vector Neural Network
RF	Random Forest
SVD	Singular Value Decomposition
SVM	Support Vector Machine
RNN	Recurrent Neural Network
WE	Word Embedding
XGBoost	Extreme Gradient Boosting

2 PREVIOUS MULTIMODAL RESEARCH

The potential benefit of utilizing information from multiple data sources has led to many recent papers focusing on multimodal learning. In this section, we review core concepts of multimodal learning, taxonomies, and domain-specific research.

However, we must first discuss the terms *multimodal* and *multi-view,* as both are commonly used throughout the literature. These terms are often used interchangeably as learning systems that incorporate information from multiple sources, usually to differentiate from traditional problems using a single (unimodal) data source. Although these terms are used to describe learning models that explicitly combine multiple data sources, *multi-view* appears to be more commonly associated with different kinds of algorithms, such as co-training [92, 124], **Canonical Correlation Analysis (CCA)**-based cross-modality retrieval [59, 124], semi-supervised [124], clustering [15, 50], unsupervised feature selection [99, 100], and subspace learning [110].

For the sake of consistency, we have chosen to use the term *multimodal* to describe learning algorithms that include information from multiple data sources for the purpose of improving predictive performance. Other use cases, such as transfer learning or co-training, could then be described as *multi-view* to provide some distinction between these learning approaches. While we believe these definitions would be useful to the research community, further discussion will be required to form a consensus.

2.1 Multimodal Concepts

Several surveys have identified co-training [92, 110, 124] and co-regularization [92, 124] as major categories of multimodal learning. Co-training is used in semi-supervised problems where a mix of labeled and unlabeled data is present where knowledge from one modality can be used to support a model trained on another modality. Potential applications of co-training include zero-shot learning, transfer learning, and the annotation of unlabeled examples. Co-regularization transforms each modality to ensure that they are compatible. This can be achieved with techniques such as CCA or regularizing modality-specific classifiers.

A more comprehensive work was later presented by Baltrušaitis et al. [9] that identified five challenges with multimodal learning: representation [9, 122], translation [9], alignment [9, 59, 92], fusion [9, 59, 92, 122], and co-learning [9, 124]. A number of other multimodal learning tasks have also been investigated including semi-supervised learning [92, 110, 124], encoding [25], clustering [92, 124], and multi-task learning [55, 124]. Although many of these surveys address aspects of classification problems, such as alignment and fusion, they tend to cover a much wider range of topics.

2.2 Taxonomies

Several review papers have presented taxonomies, often targeting specific problem domains. Di Mitri et al. [19] investigated the use of multimodal data for learning human behavior with sensors. A feedback system called **Multimodal Learning Analysis Model (MLeAM)** used multimodal sensor data, manual annotation, and machine learning to guide behavioral change. The authors also provided a tree structure taxonomy that described different data sources that could be acquired with sensors. Garcia-Ceja et al. [27] also reviewed sensor-based systems addressing mental health issues. Their taxonomy addressed the study type, study duration, and the sensing types.

Yan et al. [115] reviewed multimodal methods in the context of deep learning. Their taxonomy separated algorithms depending on if they were native to deep learning (i.e., CNN, GAN) or traditional machine learning techniques adapted to deep learning (i.e., CCA, spectral clustering). This review also discussed different network fusion strategies, bimodal auto-encoders, and GAN-based methods.

Jiang et al. [49] provided a comprehensive review of multimodal image matching and registration techniques that correlated the same concept across multiple images. They also identified two major classes of solutions: area-based and feature-based image registration. Using intensity information of the entire image to find matching regions, area-based methods produce a transformation that can be used for the image registration. Feature-based registration methods include feature detection (corner, blob, and learnable features), feature description (float, binary, and learnable descriptors), and feature matching (graph matching, point set registration, indirect methods).

Ramachandram and Taylor [77] provided a taxonomy with a review of deep learning multimodal research. In their taxonomy, models were described by their input modalities, problem space, fusion method, model type, and architecture. Input modalities included audio, video, images, text, and others specific to the field of medicine. The problem space covered domains such as action recognition, medical diagnosis, and robot grasping. The fusion method described how data from each modality was combined and used the terms *early*, *intermediate*, and *late*. The model type was either *generative* or *discriminate*, with the architecture defined as the actual model used, such as CNN, RNN, or LSTM.

We next provide a brief overview of the multimodal taxonomy proposed by Baltrušaitis et al. [9] that included the learning concep ts of representation, translation, alignment, fusion, and co-learning.

Representation is described as how data from each modality is presented as feature vectors. Since data can be text, image, or video, the potential heterogeneity may introduce additional complexity to learning models. The representation challenges were grouped as *Joint* or *Coordinated*.

Joint representations combine data from multiple modalities to create a single representation. This can be achieved with neural networks by concatenating modality-specific layers to create a new hidden layer. Probabilistic graphical models like deep Boltzmann machines can be used to create representations from latent space, also allowing for the generation of missing data from one of the modalities. Sequential representations are used for handling variable length data, such as sentences or audio clips, often with RNNs.

Coordinated representations are learned using similarities between modalities and enforced constraints. Similarity models can force representations of each modality to be close to each other, such as the word "car" should be closer to a picture of car than that of a boat. Structured coordinate spaces use hashing-based compression, which constrains the placement of embedded modality data.

Translation is used to map one modality to another, such as generating text captions from image or video data. These tasks were categorized as *Example-based* or *Generative*.

Example-based translations use dictionary look-ups to find a matching value in another modality. In addition to dictionaries, *k*-nearest neighbor searches have been used to perform consensus-based retrievals. Both approaches are restricted by the specific modality data they have at training.

Generative translations can create new translated values from the source modality instead of simple retrieval. Grammar-based solutions can create text for the target modality using high-level concepts in the source modality but only within the predefined grammatical rules. Encoder-decoder networks encode source modality data that can then be decoded into examples in the target modality. Tasks like speech-to-text can utilize continuous generation modals by sampling a latent space common to both modalities.

Alignment finds corresponding sub-components between each modality. This is often done for multimedia retrieval such as syncing audio with video frames or marking images that include a specific individual. The alignment techniques were identified as *Explicit* or *Implicit*.

Explicit alignment is used when the goal is to align multiple modalities bases on related components. Unsupervised alignments do not use labels but rely on similarity metrics, such as matching gene sequences. Supervised learning methods can also be used if the modality alignments are labeled.

Implicit alignment is used when the specific alignment is not known and has been used with tasks such as speech recognition and translation. One approach has been to use graphical models where the structure of language relationships is mapped to audio data. Neural networks using encoder-decoder and attention-based models have been used to align audio-video data using a latent space.

Fusion is the method for combining data from multiple modalities before applying a learning algorithm. Data fusion is a core concept of all multimodal approaches and was grouped into *Model-agnostic* and *Model-based* solutions.

Model-agnostic approaches use unimodal classifiers with early, late, and hybrid fusion techniques, which has also been discussed by Di Mitri et al. [19] and Simonetta et al. [86]. Early fusion combines modality data before classification, late fusion performs modality-specific learning before the results are combined, and hybrid fusion uses a combination of both.

Model-based approaches are designed to address modality fusion more directly than the Model-agnostic methods, which do not take in account inter-modality relationships. Multiple kernel learning, deep belief networks, and neural network models have all been used for multimodal fusion while considering all of the modalities.

Co-learning uses knowledge from one modality to support the learning of a different modality. This approach can address missing or low-quality data in one modality by using high-quality data from another. Co-learning methods were identified as *Parallel*, *Non-parallel*, and *Hybrid*.

Parallel methods use data from examples shared across multiple modalities at the same time. Co-training uses information from a well-labeled modality to generate missing labels for another modality. Transfer learning can use data from one parallel model to perform new but similar tasks.

Non-parallel methods do not need shared modality examples but only shared concepts. Like with Parallel models, transfer learning can be utilized as well as zero-shot learning that can identify unseen classes. Conceptual grounding is another technique that learns semantic meaning from multiple modalities within a common latent space.

Hybrid methods use two non-parallel modalities that are bridged using a common modality or dataset. This has been used for multilingual image captioning where image data is shared between different language-based models.

2.3 Domain-specific Solutions

One of the common applications for multimodal learning is remote sensing with hyperspectral satellite imagery. This method collects image data from the target area using multiple light wavelengths such as standard RGB, infrared, or imaging technologies like LiDAR. In one review paper [30], multiple kernel learning approaches were investigated for image classification. These kernel methods map input data to a new feature space that then can be used by SVM-based classifiers, resulting in something similar to late fusion architectures, as later discussed in Section 3.3. Focusing on deep learning methods, Audebert et al. [7] covered different networks designed for hyperspectral classification. The authors observed that 2-D approaches work well on data with spatial relationships and 3-D approaches for hyperspectral data where the third dimension represents image modalities. It was also suggested that Gaussian mixture models and GANs can be used to augment training data by approximating the embedded space. Results of the 2017 IEEE Geoscience and Remote Sensing Society Data Fusion Contest showed that the top teams all utilized data from multiple sources and used ensemble methods [118].

In a similar fashion, multimodal learning has also been applied to medical imaging. Today, it is common for multiple image modalities such as **computed tomography (CT)**, **magnetic resonance imaging (MRI)**, or **positron emission tomography (PET)** to be fused together to provide additional information for determining a diagnosis or the best treatment procedure. A number of image fusion architectures were reviewed by Huang et al. [40], and they observed a current limitation that few existing fusion methods utilized more than two image modalities at the same time. A survey by Haskins et al. [35] also covered medical image fusion while comparing both rigid and deformable registration techniques. To address unrealistic image deformations used for non-linear image registrations, GANs were proposed, as they often can learn to generate plausible synthetic images. In both papers, it was mentioned that the lack of standard evaluation metrics makes accurate assessment of image fusion methods difficult. The field of neuroimaging has also utilized multimodal imagery to improve scientific understanding and diagnostic performance [18], including two surveys [68, 80] that focused on Alzheimer's disease.

Another problem space well adapted for multimodal learning is human activity tracking. With the reduced cost and size, wearable sensors including microphones, accelerometers, and GPS are now practical to use. In one work [76], deep learning techniques for activity and context recognition were investigated. Several neural network architectures with the traditional early and late fusion methods were evaluated as well as different feature extraction and data modality combination methods. The authors also mentioned a challenge with feature extraction, as it was not clear if signal data should be treated as time domain points or be further processed with methods like a **Fast Fourier Transform (FFT)**. In another survey [27], wearable sensors were used to monitor mental health conditions with traditional machine learning algorithms. Based on modalities used in prior driver stress detection systems, Rastgoo et al. [79] proposed a multimodal framework using various types of sensors.

Other domain-specific surveys have also covered biometrics, 3-D image classification, and music information processing. The field of biometrics uses human features, such as images of the face, ear, or fingerprints, to identify individuals. Oloyede and Hancke [70] reviewed different multimodal architectures and fusion methods for that domain. Griffiths and Boehm [29] also reviewed works on 3-D object classification using multimodal inputs. By using different representations of objects, such as with 2-D images taken from multiple angles or **RGB plus depth (RGB-D)** images, multimodal models were used for identification. In addition to the presentation of many different network architectures, it was observed that multimodal 2-D models can perform well on a 3-D task, especially since pre-trained 2-D networks were more mature than 3-D networks. Zhang et al. [123] also performed a review of research using multimodal image data such as RGB-D for image segmentation. In the context of music processing, Simonetta et al. [86] explored preprocessing steps such as modality synchronization, feature extraction methods, and the conversion of multiple modalities to a common feature space.

3 MULTIMODAL CLASSIFICATION TAXONOMY

A current challenge with multimodal learning research is the wide mix of terms describing different aspects of the learning process. Many of the previously discussed papers used terms such as *early*, *late*, *intermediate*, or *hybrid* to describe such architectures, but their definitions are not always the same. Today, practitioners of deep learning methods are immediately familiar with networks described in terms of CNNs, GANs, or fully connected neural networks, but those kinds of portrayals are not present for multimodal classification architectures. Prior taxonomies tend to be either domain-specific or general for all multimodal learning systems, so their applicability for arbitrary multimodal classification problems is limited.

The taxonomy presented by Ramachandram and Taylor [77] was most closely aligned to classification, however, it only focused on deep learning, earlier research (2011–2016), and may not be specific enough to fully describe current multimodal pipelines. To address some of these challenges, we propose a new multimodal classification taxonomy that provides a descriptive, high-level set of terms that can be used to more completely describe existing or future model architectures. Table 2 provides a list of the five main stages used by this taxonomy and Table 3 includes other topics that are important to consider when describing multimodal architectures.

From the reviewed works in Tables 4 and 5 and the surveys dating since 2017, we propose a taxonomy with five major stages used for building multimodal classification models: *Preprocessing*, *Feature Extraction*, *Data Fusion*, *Primary Learner*, and *Final Classifier*. In Section 4, we present recent research using these terms, discuss some of the scenarios where multiple architectural concepts are employed in a single multimodal architecture, and where the exact architectural description is more subjective.

3.1 Preprocessing

Although not always used, many classification models require some preprocessing, whether it will be addressing missing data values, cropping images, filtering noise, or class balancing. Here, we describe preprocessing as a data-cleaning step, done with some level of domain expertise that may

Table 2. A List of the Five Stages Used by This Taxonomy to Describe Multimodal Classification Architectures

		A Taxonomy for Describing Multimodal Classification Models
	Stage	**Description**
1	Preprocessing	This is the initial step of data modification, which may include tasks such as removing noise, class balancing, or augmentation.
2	Feature Extraction	Higher-level features are extracted from the raw input data before being used for the direct model training. This stage can include methods such as manual feature engineering, text encoding, or CNN-generated filters.
3	Data Fusion	This stage combines raw features, extracted features, or class prediction vectors from multiple modalities to create a single data vector. Multimodal models can be further defined by their architecture and data fusion techniques.
	– Fusion Architecture	A descriptor of how and when modality-specific portions of the multimodal architecture is being combined. These styles can include: *early fusion*, *late fusion*, and *cross-modality fusion*.
	– Data Fusion Technique	A descriptor of how data from each modality is fused, including *concatenation* and *merge*. These fusion methods could be applied to traditional features or neural network node activations.
4	Primary Learner	The bulk of the overall learning process is performed in this stage and may be done independently for each modality or shared with the *Feature Extraction* or *Final Classifier* stages.
5	Final Classifier	This stage produces the final results, such as predicted labels or class likelihood scores. The classification stage could include anything from a shallow neural network or decision tree to a complicated ensemble model.

Table 3. Other Topics beyond the Taxonomy Stages that Should Be Discussed when Describing Multimodal Architectures

	Other Considerations when Describing Multimodal Modals
	Description
Shared Stages	In some cases, the same instance of a model or algorithm is shared between multiple stages such as *Feature Extraction - Primary Learner* or *Primary Learner - Final Classifier*. These shared resources are denoted with a * marker in Tables 4 and 5.
Cross-modality Architectures	These types of multimodal models can be quite complicated and may not fit well in any specific pattern. The tasks described in Table 2 are still applicable, but the specifics of such architectures must be described in detail.

be difficult to generalize in this proposed taxonomy. While there are many ways to clean unimodal data, even more options are possible with multimodal datasets if each modality is processed independently. For example, if CT and MRI data is used, then different strategies for cropping, scaling, and noise reduction may be required. These images may also need to be registered, or aligned, using a rigid or deformable transformation. However, all preprocessing could be skipped for one or both modalities to use the raw data instead. Because this work is very user- and domain-dependent, the preprocessing step is not further discussed in detail but should be considered in practice on a case-by-case basis.

3.2 Feature Selection

Each multimodal classification model uses feature selection in some capacity, which may include manual feature engineering, deep learning methods, or be an inherent part of a classifier algorithm. The feature selection process can be performed independently for each modality or be part of multiple steps in the overall model architecture. Deep learning methods like CNNs are often used for feature extraction but the same network may also perform the primary learning step, thus doing two tasks at once. Although classifiers like Random Forests can perform the feature selection process by identifying the most useful cut points during the creation of decision trees, this operation could be performed at one explicit step, such as with a CNN for image feature extraction followed by an FCNN classifier. Dimensionality reduction using **Principal Component Analysis (PCA)** or **Linear Discriminant Analysis (LDA)** can be used as part of the feature selection process, most commonly used in traditional machine learning models that can struggle with very high dimensional data.

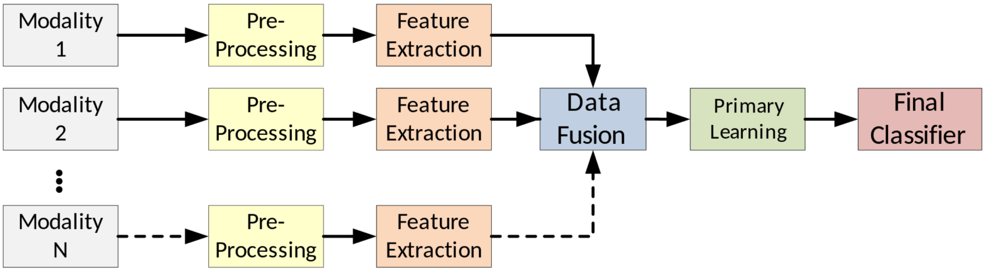


Fig. 1. An example architecture for multimodal classification with early fusion.

3.3 Data Fusion

Data fusion is a unique aspect of multimodal learning where information from different data sources need to be combined when building a joint model. This process may happen right after the input data is presented, right before the final classification, or multiple times in the middle. Commonly used terms for these architectures include early or late fusion, but these terms may not be enough to fully describe a multimodal model. Since previous works presented these fusion approaches differently, we propose a series of definitions that will be used throughout this article.

3.3.1 Fusion Architecture. **Early Fusion** occurs when all of the multimodal data is merged before the primary learning model has been performed. As shown in Figure 1, data from two or more modalities are joined and then passed to a learning algorithm. One of the most common ways to achieve this kind of fusion is to simply concatenate the incoming modality data, which can include traditional feature vectors or output nodes from pre-trained neural networks. Each modality could also represent a different channel in a CNN model, and this early fusion method may be most appropriate when there is a strong association between each data source. For example, radiotherapy datasets with imaging (CT) and planning dose volumes can be stacked as CNN channels, since each modality usually has a one-to-one voxel (3-D pixel) relationship. Satellite imagery using different light wavelengths could also be fused in a similar manner if each modality is representing the same ground area.

Late Fusion performs the feature extraction independently for each modality before the final classification, as shown in Figure 2. Output from the fusion stage can include low-level learned features with deep networks or class probabilities from full classifier algorithms. In both cases, the learned results are combined for the final classification. This architecture benefits from the ability to train each modality with a specific algorithm and may make it easier to add or exchange different modalities in the future. One downside is the lack of cross-modality data sharing, which could hinder learning the relationships between modalities.

Cross-modality Fusion allows for the sharing of modality-specific data before or during the primary learning stage. Unlike early or late fusion, this approach provides a way that each modality can use the context of each other to improve the predictive power of the overall model. This data sharing can be represented in many ways including at different parts of the learning process, the type or amount of data shared, or which modalities participate in the sharing. Figure 3 shows an architecture sharing data between each modality once before fusion, and Figure 4 shows data sharing occurring multiple times during training. A number of the presented papers showed that this kind of data sharing can outperform the traditional early or late fusion approaches, suggesting

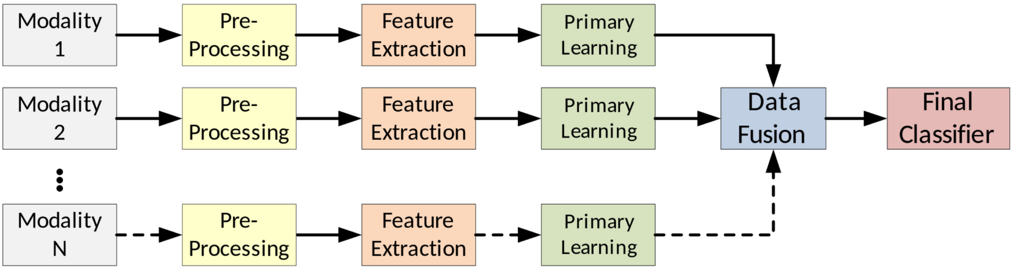


Fig. 2. An example architecture for multimodal classification with late fusion.

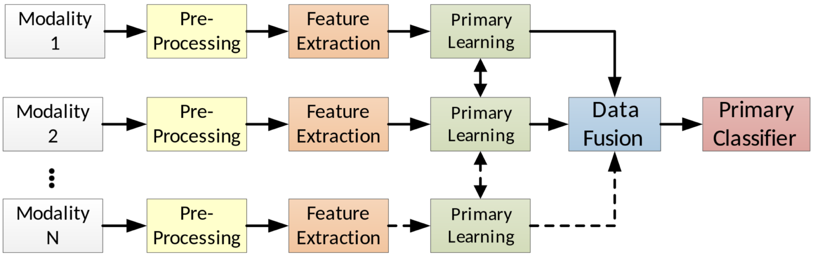


Fig. 3. An example cross-modality architecture with a single data-sharing operation.

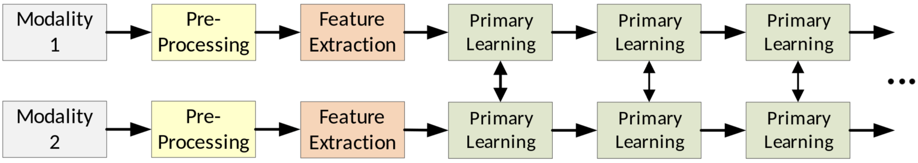
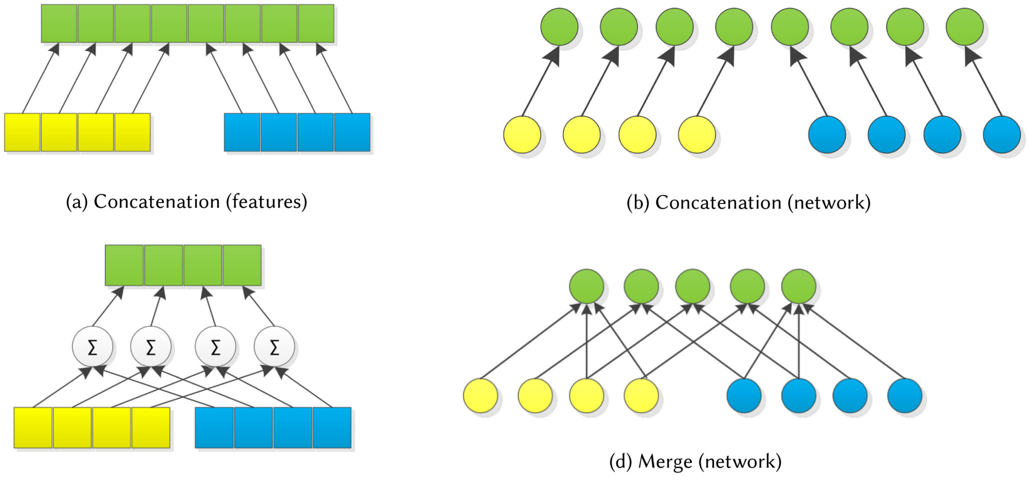


Fig. 4. The first part of a sample cross-modality architecture where data between modalities is shared multiple times during the learning process.

a promising direction for solving multimodal problems. In one work classifying satellite images [39], each modality was partially trained using a CNN, and the results were merged with the original data from the other modality. Another set of CNNs was used to continue the learning of those combined features, and results were merged again before performing the final classification. Similar to the sharing style shown in Figure 4, the model presented by Gao et al. [26] shared partially learned features between parallel CNN networks multiple times for Alzheimer's disease classification. The results from the last stage of each modality-specific network was concatenated before making predictions. This cross-modality fusion architecture is often also used with **deep belief network (DBN)** or autoencoder-style networks [25, 32, 59].

3.3.2 Data Fusion Technique. Based on our review of previous works, we have separated data fusion techniques into concatenation and merge fusion techniques. Figure 5 shows visual representations of these commonly used styles.

Concatenation: This data fusion method simply concatenates modality data to form a single feature vector. When using this technique, the input data can be raw features, class likelihood vectors, or neural network nodes. Examples of concatenation are shown in Figure 5(a) for traditional machine learning features and in Figure 5(b) for neural network nodes.



(a) Concatenation (features)

(b) Concatenation (network)

(c) Merge (features)

(d) Merge (network)

Fig. 5. A depiction of the main data fusion techniques (concatenation, merge) with two modalities (yellow, blue) and the final result (green). Traditional machine learning features are depicted as squares, neural network nodes as circles, and feature merging operators as Σ.

Merge: This approach combines modality data with business logic more complicated than simple concatenation. The merging process is often performed for traditional features with an arithmetic operator (represented as Σ) that transforms the input values into a new feature vector, as shown in Figure 5(c). Neural network merging connects modality-specific nodes to an output merged layer that utilizes the network weights and biases to combine features, as shown in Figure 5(d). Although the merge technique usually produces fewer output features or nodes as with an encoder, it could also be used as part of a decoding operation.

3.4 Primary Learner

Each traditional machine learning or deep learning system is designed to extract knowledge from the training data, often as network weights, decision boundaries, or splitting criteria. Multimodal pipelines can perform this learning process several ways, which requires clear explanation to support future advancements and the replication of experiments. For example, early fusion models produce a single joined data source so the learning process can happen all at once for all modalities. However, late fusion performs independent learning for each modality, and cross-modality models can perform the learning process multiple times. The work performed by the *Primary Learner* stage can also be shared with either the *Feature Extraction* or *Final Classifier* stage, which is further discussed in Section 3.6.

3.5 Final Classifier

Unlike the *Primary Learner* stage, the *Final Classifier* is used to produce the end result of the multimodal pipeline, usually predicted labels or class likelihood vectors. The algorithm used for this stage can be the same as the one used for *Primary Learner*, a completely different algorithm, or the work could be shared between the two stages. The algorithms used at this stage can range from a single softmax layer to entire ensemble models. We believe that explicitly defining this stage makes it easier to describe the overall multimodal architecture of a new model that can be implemented by future researchers.

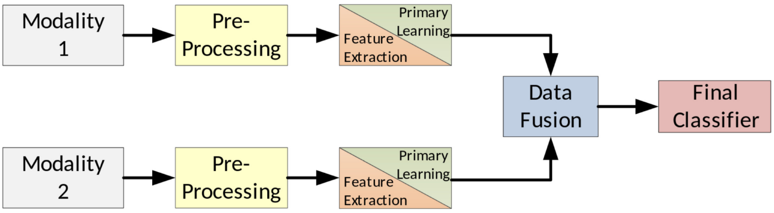


Fig. 6. An example multimodal architecture using late fusion with the feature extraction and learning tasks performed with a shared model.

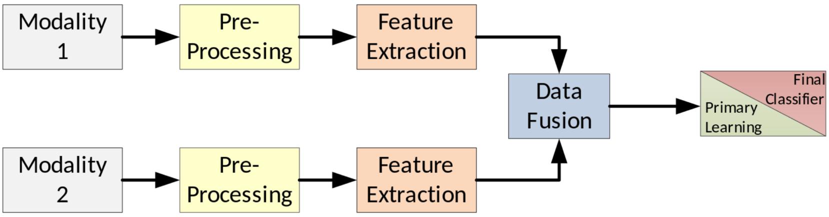


Fig. 7. An example multimodal architecture using early fusion with the learning and classification tasks performed with a shared model.

3.6 Stage Sharing

There are many real-world scenarios where individual stages in our taxonomy use the same model. Figure 6 shows an example of a late fusion architecture where each modality performs the feature extraction and learning with the same model. This is often done with CNNs, as later shown in Table 5. Figure 7 shows an early fusion architecture where the learning and classification is performed with a single model. This is done in the majority of traditional machine learning models as extracted features are concatenated and passed to a single classifier.

4 REVIEW OF RECENT MULTIMODAL CLASSIFICATION RESEARCH

In this section, we review recent works on multimodal classification. Tables 4 and 5 provide a selection of models and their architectural design using the previously defined taxonomy. This review process was used to discover patterns and commonalities between different multimodal classification approaches so the taxonomy could be created. We have separated the traditional machine learning and deep learning works, as they tended to use different types of architectures. Section 4.3 discusses these differences and other observations in more detail.

Only papers published since 2017 were considered to keep this proposed taxonomy focused on the state-of-the-art works, especially relevant for the quickly evolving field of deep learning. We considered over 400 papers during our literature search and eventually selected 121 papers, which included surveys, multimodal classification models, and topics related to future challenges. Published models that lacked the required details for decomposition were excluded. In cases where a paper presented multiple models, we chose the one that gave the best overall results, and for clarity some model types like CNNs were given their generic name instead of their specific implementation or the pre-trained model used. Determining the exact model configuration of these models may be open to different interpretations, but we chose descriptions that best fit our proposed definitions. In these tables (Tables 4 and 5), the * marker is used to identify cases where two of the stages are shared by the same model.

Table 4. An Overview of Publications Using Traditional Machine Learning Methods for Multimodal Classification

Multimodal Classification with Traditional Machine Learning Techniques						
Reference	**Feature Extraction**	**Fusion Architecture**	**Data Fusion Technique**	**Primary Learner**	**Final Classifier**	**Modalities**
Usman and Rajpoot [103]	manual	early	concatenation (features)	RF*	RF*	image
Huddar et al. [43]	manual/WE	early	concatenation (features)	ensemble	score merge	audio/text/video
Li et al. [55]	SVM*	early	concatenation (features)	SVM*	SVM	signal
Liang et al. [61]	manual	early	concatenation (features)	GBT*	GBT*	image
Elola et al. [20]	manual	early	concatenation (features)	RF*	RF*	signal
Ieracitano et al. [45]	manual	early	concatenation (features)	MLP*	MLP*	signal
Kautzky et al. [52]	manual	early	concatenation (features)	RF*	RF*	image/tabular
Li et al. [60]	manual	early	concatenation (features)	LR*	LR*	image
Panda et al. [73]	manual	early	concatenation (features)	RF*	RF*	tabular/text
Syed et al. [94]	SVD/WE	early	concatenation (features)	RF*	RF*	image/text
Sorinas et al. [91]	manual	early	concatenation (features)	*k*NN*	*k*NN*	signal
Zhou et al. [125]	manual	early	concatenation (features)	RF*	RF*	image
Gupta et al. [33]	manual	early	concatenation (features)	MKL	MKL	image/tabular
Qureshi et al. [75]	manual	early	concatenation (features)	ELM*	ELM*	image
Lee et al. [54]	SVM*	late	concatenation (scores)	SVM*	SVM	image/tabular
Guggenmos et al. [31]	manual	late	concatenation (scores)	SVM	score merge	image
Lin et al. [63]	manual	late	concatenation (scores)	ELM	ELM	image/tabular
Uddin and Canavan [102]	XGBoost	cross-modality	concatenation (features)	XGBoost	XGBoost	tabular

The * marker is used to identify cases where two of the stages are shared by the same model.

4.1 Traditional Machine Learning

4.1.1 Early Fusion. Since many of the traditional machine learning classifiers are susceptible to the Curse of Dimensionality [10], explicit feature extraction is often performed for high dimensional data. This approach allows for the use of 2-D and 3-D imaging data that shows up often in the recently proposed multimodal models. For example, Usman and Rajpoot [103] used the Random Forest classifier with extracted imaging features from four MRI modalities to predict brain tumor status, and Zhou et al. [125] used MRI-based features for genotyping brain tumors. Kautzky et al. [52] developed an **attention-deficit and hyperactivity disorder (ADHD)** diagnostic tool by using 49 **regions of interest (ROI)** features with **positron emission tomography (PET)** images and 30 **single nucleotide polymorphisms (SNP)**-based features. Syed et al. [94] built a predictive model for the automatic standardization of **Digital Imaging and Communications in Medicine (DICOM)** structure sets used in the Radiation Oncology field. The 3-D representation of each delineated structure was reduced to 50 features using **singular value decomposition (SVD)** and combined with word embedding features from the associated text annotations. Both sets of feature vectors were concatenated before using the Random Forest classifier. Random Forest was also used with data from automated external defibrillators that provided **electrocardiogram (ECG)**, **thoracic impedance (TI)**, and the capnogram information [20]. This proposed model was time series-based and manual feature engineering was performed before data fusion. Panda et al. [73] used **electroencephalogram (EEG)** and customer review text to predict emotional response. Data from both modalities were encoded into a shared feature space before being passed to the Random Forest classifier.

Although Random Forest was the most commonly used traditional classifier, other algorithms were shown to be effective. For example, Li et al. [60] extracted 396 CT and MRI radiomic features from patients with locally advanced rectal cancer using the Linear Regression classifier for predicting therapeutic response after neoadjuvant chemotherapy. With the **Gradient Boost Tree (GBT)** classifier, Liang et al. [61] predicted individuals with schizophrenia using **structural magnetic resonance imaging (sMRI)** and diffusion tensor imaging-based features. Li et al. [55] developed a **Support Vector Machine (SVM)**-based multimodal model for human activity and fall detection using an **inertial measurement unit (IMU)** and radar. However, this work used a hierarchical classification approach where sub-groups of features were grouped for predicting sub-activities. To differentiate between patients with Mild Cognitive Impairment, Alzheimer's disease, or

Table 5. An Overview of Publications Using Deep Learning Methods for Multimodal Classification

Multimodal Classification with Deep Learning						
Reference	**Feature Extraction**	**Fusion Architecture**	**Data Fusion Technique**	**Primary Learner**	**Final Classifier**	**Modalities**
Jafari et al. [47]	CNN*	early	concatenation (features)	CNN*	FCNN	signal
Li et al. [57]	manual	early	concatenation (features)	DBN	SVM	image
Garillos-Manliguez and Chiang [28]	CNN*	early	concatenation (features)	CNN*	FCNN	image
Chancellor et al. [13]	WE/CNN*	late	concatenation (network)	WE/CNN*	FCNN	image/text
Gallo et al. [24]	WE/CNN	late	concatenation (scores)	SVM/RF	score merge	image/text
Kang and Kang [51]	DNN/CNN	late	concatenation (network)	FCNN	FCNN	image/tabular
Tan et al. [98]	CNN	late	concatenation (network)	RNN	FCNN	video
Vielzeuf et al. [105]	CNN/LSTM*	late	concatenation (score)	CNN/LSTM*	score merge	image/signal
Liu et al. [66]	DNN/CNN*	late	concatenation (network)	DNN/CNN*	FCNN	image/tabular
Liu and Li [65]	CNN*	late	concatenation (network)	CNN*	*k*-NN	image/tabular
Oramas et al. [71]	CNN*	late	concatenation (network)	CNN*	FCNN	audio/image
Suzuki et al. [93]	CNN	late	concatenation (network)	CNN	FCNN	image
Vijay and Indumathi [106]	manual	late	concatenation (scores)	Multi-SVNN	score merge	image
Yap et al. [117]	CNN	late	concatenation (network)	FCNN*	FCNN*	image/tabular
Aceto et al. [1]	CNN/GRU*	late	concatenation (network)	CNN/GRU*	FCNN	tabular
Choi et al. [17]	CNN	late	merge (scores)	FCNN*	FCNN*	tabular
Illendula and Sheth [46]	CNN/BiLSTM*	late	concatenation (network)	CNN/BiLSTM*	FCNN	image/text
Jaiswal et al. [48]	CNN/GRU*	late	concatenation (network)	CNN/GRU*	FCNN	audio/text
Ma and Jia [69]	CNN*	late	concatenation (network)	CNN*	LR	image
Shen et al. [84]	LSTM/CNN*	late	concatenation (network)	LSTM/CNN*	FCNN	image/text
Tian et al. [101]	AE/CNN/WE	late	merge (network)	LSTM/WE	FCNN/CNN	audio/image/text
Xu et al. [111]	CNN/LSTM/DT*	late	concatenation (scores)	CNN/LSTM/DT*	score merge	tabular/text
Agbley et al. [3]	FCNN/CNN*	late	concatenation (network)	FCNN/CNN*	FCNN	tabular/signal
Alay and Al-Baity [6]	CNN*	late	concatenation (scores)	CNN*	score merge	image
Erickson et al. [21]	DNN/CNN	late	concatenation (network)	DNN *	DNN *	image
Gadiraju et al. [23]	CNN/LSTM*	late	concatenation (scores)	CNN/LSTM*	SVM	image/signal
Zhai et al. [121]	CNN/LSTM*	late	concatenation (scores)	CNN/LSTM*	score merge	signal
Ahmad et al. [4]	CNN	late	merge (network)	CNN	SVM	signal
Aceto et al. [2]	CNN/GRU	late	concatenation (network)	CNN/GRU	FCNN	tabular
Felipe et al. [22]	manual/CNN	late	concatenation (scores)	CNN/SVM	score merge	image
Liang et al. [62]	CNN	late	concatenation (network)	CNN	FCNN	text
Liu et al. [67]	CNN/DNN*	late	concatenation (scores)	CNN/DNN*	score merge	image/tabular
Song et al. [90]	CNN*	late	concatenation (network)	CNN*	FCNN	image
Syed et al. [95]	CNN/WE	late	concatenation (scores)	LR	score merge	audio/image/text
Venugopalan et al. [104]	CNN*/manual	late	concatenation (network)	FCNN/CNN*	FCNN	tabular/image
Vijay and Indumathi [107]	manual	late	concatenation (scores)	Multi-SVNN	DBN	image
Xu et al. [113]	CNN	late	concatenation (scores)	CNN/GBT	GBT	image/tabular
Zehtab-Salmasi et al. [120]	CNN*	late	concatenation (network)	CNN*	FCNN	image/tabular
Said et al. [82]	AE*	cross-modality	merge (network)	AE*	FCNN	signal
Liu et al. [64]	DNN/CNN	cross-modality	concatenation (network)	DNN	FCNN	image/tabular
Xu et al. [112]	BiLSTM/CNN	cross-modality	concatenation (network)	GRU	FCNN	image/text
Yu et al. [119]	CNN/LSTM*	cross-modality	concatenation (network)	CNN/LSTM*	FCNN	image/text
Hong et al. [39]	CNN	cross-modality	merge (network)	CNN	FCNN	image
Huddar et al. [44]	BiLSTM/GGA	cross-modality	concatenation (network)	BiLSTM	FCNN	audio/text/video
Yang et al. [116]	CNN/WE	cross-modality	concatenation (network)	AN	DNN/CNN	image/text
Gao et al. [26]	CNN*	cross-modality	concatenation (network)	CNN*	FCNN	image

The * marker is used to identify cases where two of the stages are shared by the same model.

without a neurological condition, Ieracitano et al. [45] used both **Continuous Wavelet Transform (CWT)** and **bispectrum (BiS)** data from EEG recordings. The experimental results showed that MLP outperformed AE, LR, and SVM classifiers with these concatenated features. Instead of using a single classifier, Huddar et al. [43] built an ensemble of five individual classifiers. This work used transcription, audio, and video data for which a significant amount of preprocessing and feature selection was performed. Because the primary learning was done with the fused multimodal data, we have chosen to treat this as an early fusion architecture.

Using the **Extreme Learning Machine (ELM)** classifier, Qureshi et al. [75] built a model to assist in the diagnosis of schizophrenia. Features extracted from structural and functional MRI scans were grouped together to create new data modalities that were trained individually. Based on their respective predictive power, each modality was given a weight used at the final multimodal classification step. Gupta et al. [33] created a predictive model for distinguishing healthy patients from those with Alzheimer's disease or mild cognitive impairment where transformed image and **apolipoprotein (APOE)** genotype-based features were shaped into kernel space before classification with the **multiple kernel learning (MKL)** algorithm [5]. Sorinas et al. [91] also used the ***k*-Nearest Neighbor (*k*NN)** classifier with manually extracted features from EEG, ECG, and skin temperature data to predict emotional response to videos.

4.1.2 Late Fusion. In the work by Guggenmos et al. [31], five neuroimaging modalities were used for classifying psychiatric disorders. Each modality was trained independently using both SVM and the **weighted robust distance (WeiRD)** classifiers. This model also used an optimization approach where the best classifier and hyperparameters were chosen for each modality. The final classification was performed using a weighted average of the results from each modality-specific classifier. Lee et al. [54] also used SVMs for feature extraction and classification for predicting clinical pain states using brain imaging and heart rate data. To differentiate between healthy patients and those with either Alzheimer's disease or mild cognitive impairment, Lin et al. [63] developed a predictive model using MRI, **fluorodeoxyglucose positron emission tomography (FDG-PET)**, **cerebrospinal fluid (CSF)**, and APOE $\epsilon 4$ gene data. Unlike the previous two methods, this model used the ELM classifier [41], which is a variant of the traditional SVM algorithm.

4.1.3 Cross-modality Fusion. Using a multi-layer model with XGBoost, Uddin et al. [102] built a predictor for the presence of chronic back pain as part of the EmoPain 2020 Challenge [8]. At each layer, some aspect of back pain was classified and the resulting class probabilities were then merged with the existing feature vectors. This fusion method shares some similarity to both early and late fusion architectures but has the unique property of progressively updating the feature vectors.

4.2 Deep Learning

4.2.1 Early Fusion. Using both **application-specific integrated circuit (ASIC)** and **field-programmable gate array (FPGA)**-based hardware platforms, Jafari et al. [47] used time series data from wearable sensors to detect human activity with a CNN. The sensor data was converted into a single channel image with one row per sensor and each column as a time series point. Using visible light and hyperspectral imaging, Garillos-Manliguez and Chiang [28] created a multimodal network for classifying papaya fruit maturity. The resulting RGB and hyperspectral image data was stacked as separate columns before being trained using a CNN. Li et al. [57] used multimodal satellite imagery to predict land cover types. Preprocessing was performed on each image modality, and the resulting pixels were stacked into a single input vector for a DBN. Classification was then performed using SVM with the learned deep features.

4.2.2 Late Fusion. Biometric identification systems can improve security with multiple verification methods. In the work by Vijay and Indumathi [106], ear and palm vein images were used, and feature extraction was performed with the **Multi-Support Vector Neural Network (Multi-SVNN)** classifier for each modality. The final identification check was performed with the sum of the modality-specific scores after optimizing the model weights. This work was later extended [107] using finger knuckle, ear, and iris image data. Although Mutli-SVNN was used again for learning each modality, a DBN was used for classification. Alay and Al-Baity [6] also built a biometric classifier with iris, face, and finger vein images. All three modalities were trained with CNNs and their outputs passed through a softmax layer. These values were normalized before being combined using either an arithmetic mean or product rule, and the highest value was chosen for the predicted class.

In the work of Aceto et al. [1], the authors developed a multimodal framework called MIMETIC for classifying network traffic. From each modality, data was extracted from network traces and independently trained with a CNN or **gated recurrent unit (GRU)** model. Final layers were concatenated and classified with FCNN layers. This work was later extended to support multi-task classification with a new framework called DISTILLER [2]. This approach trained on shared FCNN layers after the initial modal concatenation but the features were split again for training task-specific layers.

The field of medicine uses data from many potential sources, including imaging, textual notes, and discrete information, making it a natural domain for multimodal learning. In the work of Said et al. [82], an AE network was built for classifying EEG and **electromyography (EMG)** data. Each modality had its own AE that were merged, and classification was performed by fine-tuning a softmax function as the network bottleneck. Tan et al. [98] predicted cognitive events from EEG and optical flow temporal data. Both modalities are trained with CNNs and reshaped into a 2-D feature vector before being classified with an RNN. Venugopalan et al. [104] used MRI, SNP, and clinical data for predicting cognitive disorders. The modalities were trained with CNNs and AEs with their output layers concatenated and classified with a two-layer FCNN.

Using cardiovascular and actigraphy sensing, Zhai et al. [121] built an ensemble model for predicting sleep cycles. Three different time windows were chosen for both sensor types, and the combined data was trained on CNN and LSTM models, respectively, resulting in an ensemble of six total classifiers. All posterior probabilities were added to a classification matrix, and the final classification was made with the highest average or argmax value. Using three derived image modalities from ECG data, Ahmad et al. [4] developed a model for heartbeat classification. Each modality was trained on a CNN, the results were summed, and an SVM was chosen for the final classification. Clinical and cough audio data were used by Agbley et al. [3] to predict COVID-19 infections. The audio data was converted to a 2-D scalogram and trained with a CNN, while the clinical data was encoded using an FCNN. The final layers were merged, and classification was performed with a dense layer and softmax.

Liu et al. [67] used genomic data and pathology images to predict breast cancer subtypes. The genomic data was trained with an FCNN and the image data with a CNN after **principal component analysis (PCA)** performed feature reduction. Song et al. [90] used two image modalities from **contrast-enhanced spectral mammography (CESM)** scans for breast cancer detection. Each modality was trained with a CNN and the final layers were concatenated for classification with two FCNN layers. For skin lesion classification, Yap et al. [117] combined CNN-generated features with tabular clinical data and performed classification with a three-layer FCNN. Ma and Jia [69] used MRI and pathology images to predict the cancer stage of brain tumors. Both modalities were classified with CNNs and their final layers were concatenated and classified using an LR classifier.

Using ground-based cloud cover images and weather information, Liu et al. [66] created a **joint fusion convolutional neural network (JFCNN)**. Image data was trained with a CNN, and the weather data was trained with a decoder style FCNN for feature learning. The final layers were concatenated and classified with a joint FCNN layer. JFCNN was later used with GAN-generated artificial examples to increase the training dataset size [65]. Suzuki et al. [93] used airborne imagery and geospatial features to classify forest cover. Each modality was trained with a CNN, and the results were classified with CNN and FCNN layers. Xu et al. [113] used image and tabular visit data for urban functional area classification. Learned features from the image and area visit information were trained with a GBT, and their class probabilities were classified with a softmax layer.

Chancellor et al. [13] used text and image data to detect pro-eating disorder policy violations on Tumblr. The text was trained using tag embedding with a fully connected layer and image data with a CNN. The resulting layers were concatenated and classified with a two-layer FCNN. In the work by Illendula and Sheth [46], a model was built to predict emotion from social media posts using image and text. The image data was classified with ResNet [37], the textual data with BiLSTM, and the final classification was performed with a softmax layer. Syed et al. [95], used audio, text, and image data to predict levels of public trust in politicians. Using CNN and word embedding models for each modality, the final classification was performed using either majority vote or the summed confidence scores.

Gallo et al. [24] predicted real-world objects using image and text tags. A CNN was used to learn image features, and the bag-of-words method was used for text. Experiments showed that SVM with images and Random Forest for text led to best performance. Visual and near-infrared spectroscopy images were used by Erickson et al. [21] for helping robots interact with objects. The image data was trained with an FCNN and the final layers were concatenated before classification with another two-layer FCNN.

Vielzeuf et al. [105] used video frames and audio data to classify the expressed emotion in video clips. Using CNN and RNN-based networks, the final values for each modality were scored with a weighted mean. In the work by Oramas et al. [71], audio and album cover art were used to predict music genres. Each modality was trained with a CNN and two FCNN layers, with the final results classified with a cosine loss function. Tian et al. [101] used audio, video frames, and text descriptions to identify different types of natural disasters. Feature extraction was performed with AENet [97] for audio, Inception v3 [96] for video data, and text embedding with GloVe [74]. The audio and video features were trained using an LSTM with the SVM-based **Sequential Minimal Optimization (SMO)** algorithm, the text features were trained using a 1-D CNN, and a softmax layer for classification. Because some video concepts were not present in many of the video frames, the textual model was used for less common concepts instead of the joint audio-video.

An FCNN multimodal network was built by Kang et al. [51] to predict crime occurrences with spatial, temporal, and environmental data. Each modality was trained with an FCNN, and the final layers were concatenated and classification was performed using two dense layers with softmax. Using text and the visual presentation of Wikipedia documents, Shen et al. [84] built a model to predict document quality. Text data was classified using BiSTLM and image data with Inception v3 for the image data. Final results were combined using a dense layer and softmax. Zehtab-Salmasi et al. [120] predicted smartphone prices with images of the devices and their discrete properties. Each modality was trained with CNNs, and the output layers were flattened, concatenated, and classified with three more FCNN layers. The EmbraceNet [17] framework was designed to accept data from any kind of input modality. This method embeds data from modality-specific networks in a common length vector using *docking* layers. A single *embraced* vector is built from the *docking* output using multinomial distribution so each feature is only populated by a single modality.

Another approach to multimodal learning is to create different feature sets from the same training data. For example, Liang et al. [62] represented text as different modalities by splitting the data into phrases, words, n-grams, or other granularities using the **Spatial View Attention Convolutional Neural Network (SVA-CNN)** framework. This architecture was designed for preserving the relationships between these textual representations. Using context attention, parallel connection, and serial connection CNN sub-networks, the output convolutional layers were concatenated and classified with an FCNN. Similarly, Felipe et al. [22] also created several data modalities from Enteric Nervous System images of rats. Using a combination of handcrafted and model-generated image features, several chronic degenerative diseases were classified.

4.2.3 Cross-modality Fusion. Using both image and discrete weather station data, Liu et al. [64] built a system to predict cloud types. Low-level features were learned with a CNN for images and a fully connected network for the discrete data. These features were combined for further learning with another fully connected network, and the resulting new features were combined with prior learned features before final classification. This network design included a multimodal skip connection, similar to what is found within neural network architectures like ResNet [37].

Yu et al. [119] built a classification network for social media-based sentiment analysis using image and text. First, an LSTM with average pooling was used to extract target entity information from the text. These results were combined with a CNN trained on the image data and with the textual context information trained on two other LSTMs. Several different combinations of fused features were concatenated for softmax classification. This approach allowed for different modalities to learn with information from the other modalities.

Different image modalities were used by Hong et al. [39] to predict land cover and they tested multiple fusion network architectures. In addition to versions of early and late fusion, more advanced architectures were also investigated using both encoder-decoder and modality sharing schemes. The best results came from the latter methods, which also used the merge fusion style that compacted the multimodal data instead of concatenation.

A text-and-image-based sentiment analysis network was built by Yang et al. [116]. Text embedding and extracted image features were combined and trained on multi-modal CNN-LSTM-based attention networks. Results from these networks were concatenated and classified with softmax to predict the emotion expressed in a social media post.

For predicting brain diseases such as Alzheimer's, Gao et al. [26] used imaging data with a pathwise transfer network where partially extracted features were shared between modalities. At each layer of the network, weights from each modality were concatenated and convoluted before being concatenated again with the original modality outputs. This process allowed for the continuous sharing of information between each modality-specific network. At the classification step, the final results from each modality were again concatenated and fine-tuned with CNN, dense, and softmax layers. In addition, this work used a GAN to create artificial examples to address cases where one of the image modalities was missing.

In one work by Huddar et al. [44], a multimodal network was created for sentiment analysis using audio, video, and text data. Feature selection was performed on each modality independently with a **greedy search-based genetic algorithm (GGA)** followed by context extraction with a BiLSTM model. The unimodal results were then concatenated to form three new bimodal feature vectors representing the audio-video, text-video, and text-audio combinations. The same GGA/BiLSTM process was performed on those three modalities, and the resulting vectors were again concatenated into a single feature vector. Finally, the combined vector was processed again with a GGA/BiLSTM followed by a softmax classifier.

The **Multi-Interactive Memory Network (MIMN)** [112] was developed to predict sentiment labels from associated image and text information. Feature extraction was performed with word and phrase embedding for text data and a CNN for image data. Features from each modality were further processed by their own LSTM before being used by two parallel memory networks, one for text and another for image data. Each network had multiple blocks that included a GRU and an attention mechanism. The first block accepts its matching image or text LSTM feature vector as well as the average pool from the aspect vector and returns the output of the GRU. In the following blocks, the input is the matching LSTM vector and the GRU output vector from the other parallel network, providing context from the other modality. The final classification is performed by concatenating the output of both networks followed by a softmax layer.

4.3 Observations

From our literature search, we have identified some trends including the use of feature extraction, fusion architectures, and model sharing. It was also clear that the current focus of multimodal classification is with deep learning, although new research based on traditional machine learning is still being produced. Table 6 provides some comparisons between machine learning and

Table 6. A Comparison between Recent ML and DL Multimodal Classification Architectures Based on Some of Their Primary Features

Comparison of ML and DL Multimodal Architectures

Occurrence of Modalities (%)

	Audio	Image	Signal	Tabular	Text	Video
ML	5.6	55.6	22.2	33.3	16.7	5.6
DL	10.9	71.7	15.2	30.4	28.3	2.2

Fusion Architecture Frequency (%)

	Early	Late	Cross-modality
ML	77.8	16.6	5.6
DL	6.5	76.1	17.4

Data Fusion Technique Frequency (%)

	Feature Concatenation	Score Concatenation	Feature Merge	Score Merge
ML	83.3	16.7	0.0	0.0
DL	60.9	26.1	10.7	2.3

Model Sharing Frequency (%)

	Extraction/Primary Learner	Primary Learner/Final Classifier	No Model Sharing
ML	11.1	52.2	27.8
DL	61.1	6.5	41.3

deep learning models with the frequency that each modality, fusion method, and model sharing approach was used.

Compared to deep learning, the traditional machine learning models primarily use the manual feature extraction. The early fusion type was used in 14 of the 18 traditional machine learning models, likely because these classifiers expect a single feature vector or matrix as input and do not provide a way to further augment the data during training. For the same reason, those models all used simple multimodal feature concatenation. Most works also used the same algorithm for learning and classification unless it was a multi-task problem or used an ensemble, as *Primary Learner - Final Classifier* stages were shared in 11 of the 18 models compared to only twice for the *Feature Extraction - Primary Learner* stages. Tree base algorithms, such as Random Forest, GBT, and XGBoost, were the most popular classifiers. All of the major data types were used in the machine learning models but images were most common.

Among the deep learning–related publications, 3 used early fusion, 8 used cross-modality fusion, and 35 used late fusion, a reversal from the traditional machine learning works. Feature extraction was usually data-type dependent, and CNN was by far the most popular method followed by RNNs, such as LSTM and GRU. The architectural design of the deep learning early fusion models were similar to those using machine learning, with the biggest difference being the individual algorithms used.

Models using late fusion perform the bulk of modality training independently, which allows for the use of pre-trained models in deep learning solutions. This also supports the use of fundamentally different models for each specific modality, such as CNN for images and LSTM for text. The concatenation was still the most popular data fusion technique, but node merging was also used. In most late fusion models, a shallow neural network followed by a softmax layer was used as the final classifier.

While cross-modality fusion is still not the most common method, its popularity may be increasing, as it was more prominent in the deep learning models. These architectures tend to be more complicated than early or late fusion, but it has been shown that the performance may be superior.

At this time, multimodal learning lacks large pre-trained networks that are available for unimodal learning such as ResNet, Inception v3, or VGG [87]. If the best performing cross-modality architectures could be pre-trained on very large datasets, then the resulting models would provide a significant benefit for future work.

Several sub-network patterns have also emerged from these prior works. The most common architecture was a shared CNN for *Feature Extraction* - *Primary Learner* stages, followed by an FCNN and softmax classifier. Unlike traditional machine learning, the deep learning architectures tended to use the *Feature Extraction* - *Primary Learner* stage sharing, which occurred 24 times compared to only 3 times for the *Primary Learner* - *Final Classifier* combination. In cases where different network types were used for each modality, CNN and RNN networks were often paired.

Architectures using the *Primary Learner* stage model as full classifiers were more likely to use score merge as the *Final Classifier* method instead of an FCNN. This approach may have been often used because it is convenient to simply apply a single softmax layer to the pre-trained model outputs. However, future work is needed to determine if that method is superior to using earlier layers as input for the fusion stage.

5 APPLYING THE TAXONOMY

5.1 Challenges with Model Descriptions

While depictions of early and late fusion styles have been relatively consistent across multiple papers [9, 18, 38, 42, 77, 86, 123], there are still cases where other terms have been used. In the work by Guo et al. [32], one network architecture described as *multi-view-one-network* is essentially early fusion, and *one-view-one-network* could be considered late fusion. Li et al. [58] provided a view-wise feature extraction architecture that could be mapped to our late fusion taxonomy with the use of different learner and classifier models. Gao et al. [25] described early fusion as *shadow multiple modality* and late fusion as *deep multiple modality*. For the cross-modality style architectures, Ramachandram and Taylor [77] and Syed et al. [94] used the term *intermediate*, while Gao et al. [25] used *deep shared modality*. In the survey by Gao et al. [25], the authors also used *deep cross-modality* to describe multitask architectures, but these terms were used in the context of generative models such as **restricted Boltzmann machines (RBM)**. Even more specific models were described by Oloyede and Hancke [70] including *Fusion at the Decision Level* (late fusion, score merge), *Fusion at the Matching Score Level* (late fusion, using different learners/classifiers), *Biometric Traits at the Sensor Level* (early fusion), and *Fusion at the Feature Level* (late fusion, feature concatenation). In a similar manner, Yaman et al. [114] used the terms *data fusion* (early fusion), *feature fusion* (late fusion, feature merge), and *score fusion* (late fusion, score merge).

The term *intermediate* has been used for cross-modality fusion but can also refer to fusion occurring somewhere between feature extraction and classification [17]. Terms such as *middle* [39], *joint* [42], and *hybrid* [123] have also been used to describe this kind of fusion. Since our proposed taxonomy is based on the five processing stages, the middle fusion concept can be captured by early or late fusion style architectures. This allows for the cross-modality fusion to describe only the inter-modality data sharing concept. These examples only cover a small portion of all existing works, and so it is likely that many other depictions of multimodal classification architectures exist. Using our proposed taxonomy, we are able to label a wide range of models with consistent terms.

5.2 Describing Multimodal Classification Models

One of the challenges we faced when reviewing the previous works is that in addition to inconsistent terms, many publications did not provide enough information to confidently recreate their process. To address this issue, we have provided a checklist in Table 7 that could help ensure that the critical aspects of a multimodal classification model are fully presented with well-defined terms.

Table 7. A Checklist of Topics that Should Be Discussed when Describing Multimodal Classification Architectures

Checklist for Describing Multimodal Classification Architectures	
Model Property	**Description**
Input Data	Describe the data type and properties of each modality and its potential benefit to model performance
Preprocessing	On a case-by-case basis, detail any preprocessing performed on each modality
	Discuss any dataset-level modifications such as class balancing, normalization, or imputation
Feature Extraction	List the method of feature extraction (e.g., manual feature engineering, model learned features) and the purpose of this choice
	Description of the model used for the primary learner step, including any relevant setting such as hyperparameters, dropout rate, or regularization
Data Fusion	Describe when data fusion is performed within the architecture (early, late, cross-modality)
	Describe how data fusion is performed (concatenation, merge)
Cross-Fusion	If cross-modality fusion is performed, then provide a detailed description of this process with a matching diagram
Primary Learner	Description of the model used for the primary model step, including any relevant setting such as hyperparameters, dropout rate, or regularization
Final Classifier	Description of the model used for the classifier step, including any relevant setting such as hyperparameters, dropout rate, or regularization
	Explain the output format (binary or multi-class labels, class probabilities)
Shared Stages	Describe any models shared between multiple architecture stages

In addition to describing model architectures with text, visual depictions can also be useful. In Figures 8 and 9, we show how the taxonomy defined in Section 3 could be applied to previously published models using a network architecture diagram. Figure 8 shows an ML architecture developed by Syed et al. [94] that predicted radiotherapy structure set names based on 3-D volumes and physician provided labels. The *Preprocessing* and *Feature Extraction* steps show different techniques for each modality. *Data Fusion* was then performed using concatenation, and the Random Forest algorithm was shared between the *Primary Learner* and *Final Classifier* steps. Figure 9 shows a DL method presented by Song et al. [90] for classifying breast cancer. All four input data modalities were different representations of a patient's medical imaging, and they all received the same *Preprocessing* operations. The *Feature Extraction* and *Primary Learner* steps were performed independently for each modality using Res2Net50 models. The output nodes were concatenated for the *Data Fusion* step before applying the *Final Classifier* with a shallow full connected neural network. When presenting models like these in a manuscript, additional details applicable to the specific case should be provided, as suggested in Table 7.

6 DISCUSSION OF OPEN PROBLEMS

While there has been much progress in the recent years with multimodal data classification, there are still several important areas that have not been adequately addressed. In this section, we discuss open problems related to the ever growing size of datasets, difficult classification tasks, and the lack of general tools for multimodel classification.

6.1 Big Data

The emergence of Big Data has led to new opportunities and challenges. While there have been many effective solutions for classification on large datasets, little has been done specifically for

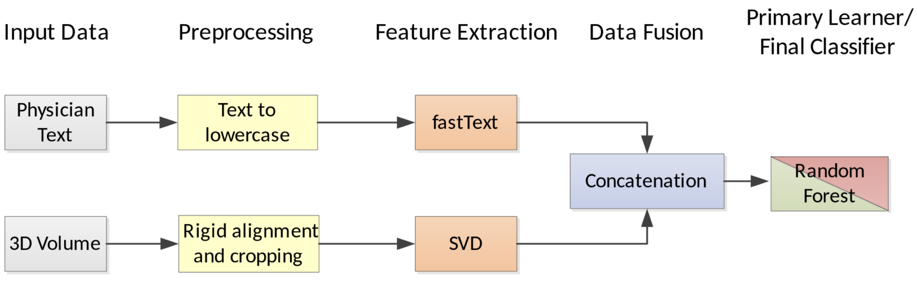


Fig. 8. The model architecture by Syed et al. [94] as described by our multimodal taxonomy.

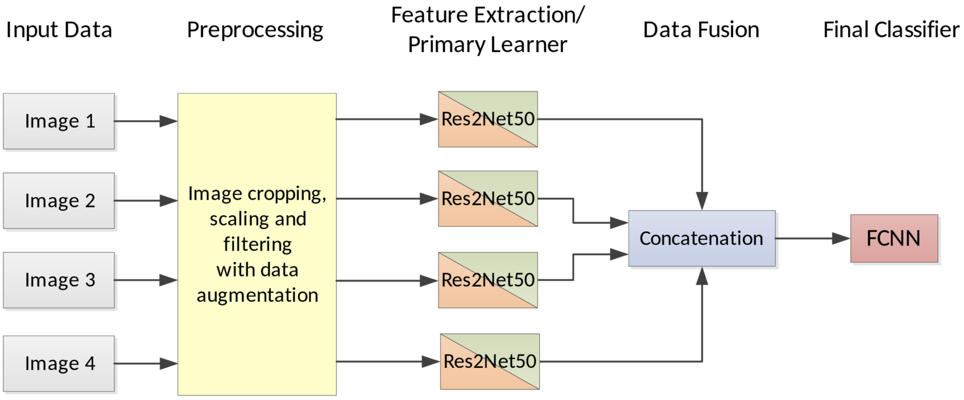


Fig. 9. The model architecture by Song et al. [90] as described by our multimodal taxonomy.

multimodal data, as unimodal has been the focus up to this point. One of the major limitations with multimodal learning research is the lack of large, publicly available datasets. The vast majority of experiments carried out in the reviewed papers used small datasets with only tens to thousands of examples. The private datasets, often containing medical imaging, also were small, as collecting healthcare data can be time-consuming, expensive, and often comes with ethical and legal restrictions on its use.

Deep learning networks are currently the most popular way of performing multimodal classification, and this technology works best with large training datasets. Although Illendula and Sheth [46] used a dataset with approximately 500,000 examples, the majority of other works used significantly fewer. The challenge of limited data is further compounded when presented with multiclass datasets, as the total number of examples per class will be even further reduced. The creation of large benchmark datasets that cover different modality combinations will be a significant benefit for future multimodal research.

While the lack of data may negatively affect these models, its impact on multimodal classification has not been fully investigated. Transfer learning with pre-trained models may help with limited training data, and this approach has been used in a number of the reviewed papers. Data augmentation is a common method for inserting new training examples such as image shifts or rotations. GANs have also been used to add synthetic examples to increase the size of multimodal datasets [56, 65].

Large datasets are often not fully curated and can have missing or erroneous values. Since these issues can exist independently for each modality, it is likely that a higher percentage of training examples will require data cleaning. In additional to traditional data imputation, it was also shown that GANs can be used to add data missing from one of the modalities [26]. However, even if GAN-generated or cleaned examples appear to be realistic, it is important to ensure that inter-modality relationships are also representative of the original dataset. Future work is needed to provide methods that discover these relationships and how the training data can be safely modified.

6.2 Imbalanced Data

Many machine learning algorithms were designed with the assumption that class distributions are balanced in the training dataset. However, this is often not the case and class imbalance may introduce a bias that could negatively affect classifier performance [36]. In many real-world datasets, there may be a majority class that is significantly larger than the other minority class. The same problem is magnified with multiclass datasets, as there may be many majority-minority class relationships.

Class imbalanced data can be addressed by modifying the data itself, using algorithms inherently designed for addressing this issue, or a combination of both [53]. Data-level methods have been most popular with unimodal datasets and was the only method found within the multimodal models included in this literature review. Random oversampling is one of the most common data-level methods, where random examples are simply replicated until the desired level of class balance is achieved. Random undersampling has been used but may run the risk of removing useful examples or producing a final training dataset that is too small overall. Another popular method is the **synthetic minority over-sampling technique (SMOTE)** [16], which generates new examples from a combination of nearby examples of the same class. This approach has inspired the development of many other oversampling algorithms and has been shown to outperform random sampling methods in many cases.

While there has been limited work done on multimodal imbalanced learning, it was addressed in a few of the reviewed papers. For example, two works [51, 103] used random undersampling while another [20] used random oversampling. The more advanced SMOTE method was also used by Li et al. [60] and Uddin and Canavan [102]. Since SMOTE is based on the k-NN algorithm, it is important that the individual features are normalized or weighed by importance. Without performing this step, the generation of synthetic examples may be over-influenced by noisy or less impactful features and thus resulting in lower-quality examples.

GANs have become a popular method for data augmentation [85] and have already been used with multimodal datasets. In one work [72], a GAN was used for adding missing text modality data that was paired with image data. Moreover, Li et al. [56] generated completely new synthetic examples instead of just imputing missing modality data. Future work is needed to better understand how methods such as SMOTE and GANs could be best utilized with multimodal datasets.

6.3 Instance-level Difficulty

Poor classifier performance cannot always be blamed on class imbalance, especially if classes are well separated. Some examples are harder to learn from, because they exist in a region contaminated with examples from other classes or are close to decision boundaries [81]. The difficulty of learning from such examples increases with more classes or a higher level of class imbalance, as both can lead to more regional contamination. These challenges have been well researched in traditional unimodal learning, and a number of solutions have been proposed to address this issue, especially when presented with class imbalance.

Popular oversampling methods such as random oversampling and SMOTE have been shown to do well at addressing class imbalance but do not consider which examples are more important for classification. Algorithms such as Save Level SMOTE [12] and Borderline SMOTE [34] favor specific types of examples during oversampling to add more emphasis on certain parts of the feature space, such as safe class regions and decision boundaries. However, no such method has been designed that includes these learning concepts with multimodal datasets.

These unimodal solutions may not directly translate to multimodal problems, as individual modalities could exhibit different levels of learning difficulty. Embedding each modality to a shared latent space may help solve this problem, but more experimentation is required to identify the best solutions.

6.4 Parallel and Distributed Computing

The relatively small datasets used in current multimodal research has not required distributed computing solutions. However, classification models on larger datasets will need more resources than are available with a single CPU or GPU. Distributed systems such as Apache Hadoop, Apache Spark, and GPU clusters are potential solutions but currently do not have direct multimodal learning support. Although this omission may have been caused by the lack of historical use cases, there will be a need for multimodal frameworks compatible with large datasets in the coming years.

Distributed computing provides a new challenge for multimodal learning, because model performance may be affected by how data is shared between computational nodes. If the distribution of class instances or sub-concepts are not carefully considered, then partial results generated at each node may not properly reflect the global properties of the training data [88]. While this has been shown to be a potential issue with unimodal learning, it has not yet been determined how this would affect multimodal models.

Two possible patterns for multimodal distributed solutions include each modality being processed together (early fusion) or processed independently and then reduced at the end (late fusion). In the early fusion case, data at a particular node may be well proportioned for one modality but not for the other. This can introduce learning challenges similar to class imbalance or instance-level difficulty as found in traditional unimodal models. The late fusion architectures could have additional issues if the data distributions between the modality-specific models are different. Further work is needed to better understand the potential challenges with distributed multimodal learning and the best architectures for addressing them.

6.5 Evaluation Metrics

Classification models must be evaluated to determine their performance, and the specific metrics used are dependent on the desired results. True positive rate, precision, recall, and F_1 scores are often used, especially for binary class datasets. The macro and micro average of F_1 is also used for multiclass datasets, but these metrics may provide over-optimistic results when presented with imbalanced data, as it may hide poor performance on minority classes. As reported by Branco et al. [11], there are a number of other metrics that are better suited for dealing with imbalanced data, such as **Average Accuracy (AvAcc)** of classes, the Geometric **Macro Average of recall in each class (MAvG)**, and **Class Balance Accuracy (CBA)**.

These existing metrics were designed for unimodal problems, and we are unaware of any metrics designed specifically for evaluating multimodal classifiers. While these metrics are addressing performance related to the predicted classes, there may be value in knowing how well each model does with each individual modality. Going further, the performance of each class may be affected differently by each modality. New metrics designed for multimodal classification could help identify areas in which a modality-specific model is under-performing as well as provide a better understanding of the relationships between classes and each modality.

6.6 Universal Models and Benchmarks

As shown in previous research, traditional machine learning algorithms and deep learning architectures can be successfully used for multimodal classification. However, the general usability of these models is limited as most are tailored for their domain-specific input modalities and may not work directly on different data combinations. Although the EmbraceNet [17] partially addresses this issue, it was only designed for late fusion style networks and may lose some shared context between modalities, depending on how the fused feature vector is constructed. Ideally, future multimodal frameworks will be configurable to support arbitrary input types using well-defined architectural rules. This will allow for a straightforward manual or automated construction of a complicated model or network. With the success of transfer learning and an ever-increasing number of pre-trained models, providing plug-and-play support for these networks will simplify the process of constructing powerful multimodal models.

Unimodal learning has benefited from large, publicly available datasets such as those from the **Modified National Institute of Standards and Technology (MNIST)** and ImageNet. These datasets are needed for training large models that could be used for transfer learning and providing benchmarks for evaluating different approaches. The creation of such datasets will be an important step for advancing multimodal learning.

7 CONCLUSIONS

Although unimodal learning has dominated the machine learning field, there is a growing interest in multimodal problems. New methods for combining data from multiple sources, the large collection of social media and customer reviews, and the aggregation of healthcare-related information are all providing more valuable use cases for multimodal learning. We have also seen cases where unimodal datasets can be treated as multimodal problems and thus utilize these novel learning methods. The general consensus from the reviewed papers is that multimodal-based architectures have the potential of outperforming the traditional unimodal models. However, the lack of consistent terminology for the primary aspects of multimodal-based learning and classification architectures has made it difficult to compare or evaluate different approaches. Many of the most difficult problems facing classification, such as big data, class imbalance, and instance-level difficulty, have not yet been fully addressed in this context.

As discussed in Section 1, we were motivated to address four outstanding issues related to multimodal classification problems. First, a taxonomy specific to multimodal classification was presented in Section 3 to make it easier to describe such models. In Section 4, the taxonomy was applied to 64 previously published multimodal models to highlight recent trends in these architectures. Section 5 gave examples of how to apply this taxonomy to new models and provided a checklist that could be used to guide model descriptions in manuscripts. Finally, future challenges were discussed in Section 6.

There are a number of other important challenges not addressed in this article that will require further research. Regression models have successfully been used for mutlimodal datasets [54, 108, 109] but have gotten much less focus than classification. A future survey on this topic could help identify if the general challenges and our proposed taxonomy for classification translates well to regression models. Generative models, such as GANs and AEs, have been well represented in multimodal survey papers but were used in only a few of the reviewed classification models. In a similar manner, **Canonical Correlation Analysis (CCA)** has been commonly discussed in the context of multimodal learning but is less often used with classification models. An in-depth discussion of how or when to use such methods for multimodal classification would be a benefit to the research community.

In summary, we have proposed a new multimodal classification taxonomy for describing both the overall model architectures and the style in which data fusion is performed. Unlike previous taxonomies, we focus solely on classification problems and guided our definitions based on common patterns from prior works. We believe this kind of taxonomy will be helpful when describing multimodal models that tend to be more complicated than their unimodal counterparts.

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