
Continual Lifelong Learning with Neural Networks: A Review

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Abstract

Humans and animals have the ability to continually acquire and fine-tune knowledge throughout their lifespan. This ability is mediated by a rich set of neurocognitive functions that together contribute to the early development and experience-driven specialization of our sensorimotor skills. Consequently, the ability to learn from continuous streams of information is crucial for computational learning systems and autonomous agents (inter)acting in the real world. However, continual lifelong learning remains a long-standing challenge for machine learning and neural network models since the incremental acquisition of new skills from non-stationary data distributions generally leads to catastrophic forgetting or interference. This limitation represents a major drawback also for state-of-the-art deep neural network models that typically learn representations from stationary batches of training data, thus without accounting for situations in which the number of tasks is not known a priori and the information becomes incrementally available over time. In this review, we critically summarize the main challenges linked to continual lifelong learning for artificial learning systems and compare existing neural network approaches that alleviate, to different extents, catastrophic interference. Although significant advances have been made in domain-specific continual lifelong learning with neural networks, extensive research efforts are required for the development of general-purpose artificial intelligence and autonomous agents. We discuss well-established research and recent methodological trends motivated by experimentally observed lifelong learning factors in biological systems. Such factors include principles of neurosynaptic stability-plasticity, critical developmental stages, intrinsically motivated exploration, transfer learning, and crossmodal integration.

1 Introduction

Computational systems operating in the real world are exposed to continuous streams of information and thus are required to learn and remember multiple tasks from dynamic data distributions. For instance, an autonomous agent interacting with the environment is required to learn from its own experiences. The agent must be capable of progressively acquiring and fine-tuning its knowledge over long time spans. The ability to continually learn over time by accommodating new knowledge while retaining previously learned experiences is referred to as *continual lifelong learning*. Such a continuous learning task has represented a long-standing challenge for machine learning and neural networks and, consequently, for the development of artificial intelligence (AI) systems (Hassabis et al., 2017; Thrun and Mitchell, 1995).

The main issue of computational models regarding continual learning is that they are prone to *catastrophic forgetting* or *catastrophic interference*, i.e., training a model with new information interferes with previously learned knowledge (McClelland et al., 1995; McCloskey and Cohen, 1989). This phenomenon typically leads to an abrupt performance decrease or, in the worst case, to the old

knowledge being completely overwritten by the new one. Current (deep) neural network learning models excel at a number of classification tasks by relying on a large batch of (partially) annotated training samples (see Guo et al., 2016; LeCun et al., 2015 for reviews). However, this learning scheme assumes that all samples are available during the training phase and, therefore, requires the retraining of the network parameters on the entire dataset in order to adapt to changes in the data distribution. When trained on sequential tasks with samples becoming progressively available over time, the performance of conventional neural network models significantly decreases on previously learned tasks as new tasks are learned (Kemker et al., 2018). Although retraining from scratch pragmatically avoids catastrophic interference, this methodology is very inefficient and hinders learning new data in real time. In scenarios of developmental learning, e.g., autonomous interactive agents, there may be no distinction between training and test phases, requiring the models to concurrently learn and timely trigger behavioural responses.

For overcoming catastrophic interference, learning systems must, on the one hand, show the ability to acquire new knowledge and fine-tune existing knowledge on the basis of the continuous input and, on the other hand, prevent the novel input from significantly interfering with existing knowledge. The extent to which a system must be plastic in order to integrate novel information and stable in order not to catastrophically interfere with consolidated knowledge is known as the *stability-plasticity dilemma* and has been widely studied in both biological systems and computational models (Ditzler et al., 2015; Mermillod et al., 2013). Due to the very challenging but high-impact aspects of continual learning, a large body of computational approaches have been proposed that take inspiration, to different extents, from the biological factors of learning from the mammalian brain.

Humans and other animals excel at learning in a continual lifelong manner, making the appropriate decisions on the basis of sensorimotor contingencies learned throughout their lifespan (Bremner et al., 2012; Calvert et al., 2004). Our ability to incrementally acquire and refine knowledge over sustained periods of time is mediated by a rich set of neurophysiological processing principles and cognitive functions that together contribute to the early development and experience-driven specialization of our perceptual and motor skills (Zenke et al., 2017a; Power and Schlaggar, 2017; Murray et al., 2016; Lewkowicz, 2014). In Section 2, we introduce a set of widely studied biological aspects of continual learning and their implications for the modelling of biologically-inspired neural network architectures. First, we focus on the mechanisms of neurosynaptic plasticity that regulate the stability-plasticity balance in multiple brain areas (Sec. 2.2 and 2.3). Plasticity is an essential feature of the brain for neural malleability at the level of cells and circuits (see Power and Schlaggar, 2017 for a survey). For a stable continuous lifelong process, two types of plasticity are required: i) Hebbian plasticity (Hebb, 1949) for positive feedback instability, and ii) compensatory homeostatic plasticity which stabilizes neural activity. For instance, it has been observed experimentally that specialized mechanisms protect knowledge about previously learned tasks from interference encountered during the learning of novel tasks by decreasing rates of synaptic plasticity (Cichon and Gan, 2015). The brain is particularly plastic during critical periods of early development and preserves a certain degree of plasticity for its reorganization at a smaller scale beyond such a critical developmental window (Hensch et al., 1998; Quadrato et al., 2014; Kiyota, 2017). Together, Hebbian learning and homeostatic plasticity stabilize neural circuits to shape optimal patterns of experience-driven connectivity, integration, and functionality (Zenke et al., 2017a; Abraham and Robins, 2005).

The brain must carry out two important, complementary tasks: generalize across experiences and retain specific memories. In Section 2.4, we summarize the complementary learning systems (CLS) theory (McClelland et al., 1995; Kumaran et al., 2016) which holds the means for effectively extracting the statistical structure of perceived events (generalization) while retaining episodic memories, i.e., the collection of experiences at a particular time and place. More specifically, the CLS theory defines the complementary contribution of the hippocampus and the neocortex in learning and memory, suggesting that there are specialized mechanisms in the human cognitive system for protecting consolidated knowledge. However, additional studies in learning tasks with human subjects (Mareschal et al., 2002; Pallier et al., 2003) observed that, under certain circumstances, catastrophic interference may still occur (see Sec. 2.5).

Studies on the neurophysiological aspects of continual lifelong learning have inspired a wide range of machine learning and neural network approaches. In Section 3, we introduce and compare computational approaches that alleviate, to different extents, catastrophic interference. We focus on recent (deep) learning models that i) regulate intrinsic levels of synaptic plasticity to protect consolidated knowledge (Sec. 3.2); ii) allocate additional neural resources to learn new information

(Sec. 3.3), and iii) use complementary learning systems for the consolidation of recent memories (Sec. 3.4). The vast majority of these approaches are designed to address continual supervised learning on annotated datasets of finite size and do not naturally extend to more complex scenarios such as the processing of (partially) unlabeled sequences (e.g., Zenke et al., 2017b; Kirkpatrick et al., 2017). Unsupervised continual learning, on the other hand, has been proposed mostly through the use of self-organizing neural networks (e.g., Parisi et al., 2017a; Richardson and Thomas, 2008) but without taking into account compensatory feedback which is crucial for stabilizing neural representations developed through bottom-up sensory drive. Although significant advances have been made in the design of learning methods with structural regularization or dynamic architectural update, considerably less attention has been given to the rigorous evaluation of these algorithms in continual lifelong learning tasks. Therefore, in Sec. 3.5 we discuss the importance of using and designing quantitative metrics to measure catastrophic interference in complex scenarios.

Continual learning has recently received increasing attention due to its implications in machine learning and general-purpose AI systems. Neural network approaches are typically designed to incrementally adapt to modality-specific, often synthetic, data samples collected in controlled environments, shown in isolation and random order. This differs significantly from the more ecological conditions humans and other animals are exposed to throughout their lifespan (Krueger and Dayan, 2009; Skinner, 1958). Agents operating in the real world must deal with sensory uncertainty, efficiently process continuous streams of crossmodal information, and effectively learn multiple tasks without catastrophically interfering with previously learned knowledge (Wermter et al., 2005). Intuitively, there is a huge gap between the above-mentioned neural network models and more sophisticated lifelong learning agents expected to incrementally learn from their continuous sensorimotor experiences.

In Section 4, we review computational approaches motivated by a set of biological aspects of learning. These aspects include well-established methods for learning through critical developmental stages and from samples that capture increasing degrees of complexity (Sec. 4.2) and reinforcement learning for the autonomous exploration of the environment driven by intrinsic motivation and self-supervision (Sec. 4.3). Then, we focus on experimental approaches that have received increasing attention due to the potential for their application in real-world domains where lifelong learning must go beyond the incremental accumulation of domain-specific knowledge. Therefore, it is crucial to embed systems with the ability to reuse consolidated knowledge in multiple domains. Humans excel at acquiring new skills and transferring knowledge across domains and tasks (Barnett and Ceci, 2002) while artificial systems are still in their infancy regarding what is referred to as *transfer learning* (Weiss et al., 2016). Furthermore, and in contrast with the predominant tendency to train neural network approaches with uni-sensory (e.g., visual or auditory) information, the brain benefits significantly from the integration of multisensory information, providing the means for an efficient interaction also in situations of sensory uncertainty (Stein et al., 2014; Bremner et al., 2012; Spence, 2010). The crossmodal aspects of early development and sensorimotor specialization in the brain have inspired a large body of research on autonomous embodied agents (Lewkowicz, 2014; Cangelosi and Schlesinger, 2015). In the last part of this section, we will review and discuss current findings and approaches of transfer learning for the reuse of knowledge in new task acquisition (Sec. 4.4) and multisensory systems for crossmodal continual learning (Sec. 4.5).

This review complements previous surveys on catastrophic forgetting in connectionist models (French, 1999; Goodfellow et al., 2013; Soltoggio et al., 2017) that do not critically compare recent experimental work (e.g., deep learning) or define clear guidelines on how to train and evaluate continual lifelong approaches on the basis of experimentally observed developmental mechanisms. Together, our and previous reviews highlight continual lifelong learning as a highly interdisciplinary challenge. Although the individual disciplines may have more open questions than answers, the combination of these findings may provide a breakthrough with respect to current ad-hoc approaches, with neural networks being the stepping stone towards the increasingly sophisticated cognitive abilities exhibited by AI systems. In Section 5, we summarize the key ideas presented in this review and provide a set of ongoing and future research directions.

2 Biological Aspects of Continual Lifelong Learning

2.1 The Stability-Plasticity Dilemma

Humans have an astonishing ability to adapt by effectively acquiring novel concepts, refining knowledge on the basis of new experiences and transferring consolidated knowledge across multiple domains (Bremner et al., 2012; Calvert et al., 2004; Barnett and Ceci, 2002). While it is true that we tend to gradually forget previously learned information throughout our lifespan, only rarely does the learning of novel information catastrophically interfere with consolidated knowledge (French, 1999). For instance, the human somatosensory cortex can assimilate new information during motor learning tasks without disrupting the stability of previously acquired motor skills (Braun et al., 2001).

Our ability to learn without catastrophically forgetting is mediated by a rich set of neurophysiological principles that regulate the stability-plasticity balance of the different brain areas and that contribute to the development and specialization of our cognitive system on the basis of our sensorimotor experiences (Zenke et al., 2017a; Power and Schlaggar, 2017; Murray et al., 2016; Lewkowicz, 2014). The stability-plasticity dilemma regards the extent to which a system must be prone to integrate and adapt to new knowledge and how this adaptation process should be compensated by internal mechanisms that stabilize neural activity, preventing catastrophic interference with consolidated knowledge (Ditzler et al., 2015; Mermillod et al., 2013).

Neurosynaptic plasticity is an essential feature of the brain yielding physical changes in the neural structure and allowing us to learn, remember, and adapt to dynamic environments (see Power and Schlaggar, 2017 for a survey). The brain is particularly plastic during critical periods of early development in which neural networks acquire their overarching structure driven by sensorimotor experiences. Plasticity becomes less prominent as the biological system stabilizes through a well-specified set of developmental stages, preserving a certain degree of plasticity for its adaptation and reorganisation at smaller scales (Hensch et al., 1998; Quadrato et al., 2014; Kiyota, 2017). The specific profiles of plasticity during critical and post-developmental periods vary across biological systems (Uylings, 2006), showing a consistent tendency to decreasing levels of plasticity with increasing age (Hensch, 2004). Plasticity plays a crucial role in the emergence of sensorimotor behaviour by complementing genetic information which provides a specific evolutionary path (Grossberg, 2012; Doidge, 2007). Genes or molecular gradients drive the initial development for granting a rudimentary level of performance from the start while extrinsic factors such as sensory experience complete this process for achieving higher complexity and performance (Hirsch and Spinelli, 1970; Shatz, 1996; Sur and Leamey, 2001). In this review, we focus on the developmental and learning aspects of brain organization while we refer the reader to Soltoggio et al. (2017) for a review of evolutionary imprinting.

2.2 Hebbian Plasticity and Stability

The ability of the brain to adapt to changes in its environment provides vital insight into how connectivity and function of the cortex are shaped. For instance, studies have shown that while rudimentary patterns of connectivity in the visual system are established in early development, normal visual input is required for the correct development of the visual cortex.

The seminal work of Hubel and Wiesel (1967) on the emergence of ocular dominance showed the importance of timing of experience on the development of normal patterns of cortical organization. The visual experience of newborn kittens was experimentally manipulated to study the effects of varied input on brain organization. They observed that the disruption of cortical organization was more severe when the deprivation of visual input began prior to ten weeks of age while no changes were observed in adult animals. Additional experiments showed that neural patterns of cortical organization can be driven by external environmental factors at least for a period early in development (Hubel and Wiesel, 1962, 1970; Hubel et al., 1977).

The most well-known theory describing the mechanisms of synaptic plasticity for the adaptation of neurons to external stimuli was first proposed by Hebb (1949), postulating that when one neuron drives the activity of another neuron, the connection between them is strengthened. More specifically, the Hebb's rule states that the repeated and persistent stimulation of the postsynaptic cell from the presynaptic cell leads to an increased synaptic efficacy. Throughout the process of development, neural systems stabilize to shape optimal functional patterns of neural connectivity. However,

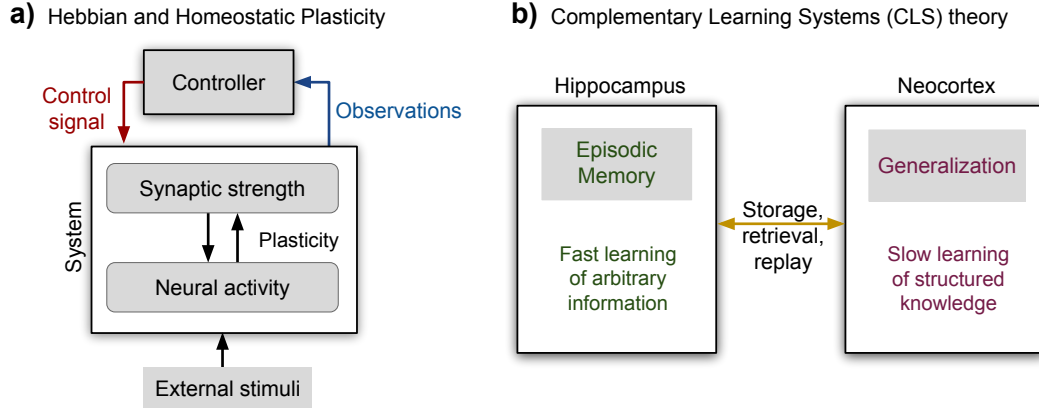


Figure 1: Schematic view of two aspects of neurosynaptic adaptation: a) Hebbian learning with homeostatic plasticity as a compensatory mechanism that uses observations to compute a feedback control signal (Adapted with permission from Zenke et al., 2017a). b) The complementary learning systems (CLS) theory (McClelland et al., 1995) comprising the hippocampus for the fast learning of episodic information and the neocortex for the slow learning of structured knowledge.

Hebbian plasticity alone is unstable and leads to runaway neural activity, thus requiring compensatory mechanisms to stabilize the learning process (Abott et al., 2000; Bienenstock et al., 1982).

Stability in Hebbian systems is typically achieved by augmenting Hebbian plasticity with additional constraints such as upper limits on the individual synaptic weights or average neural activity (Miller and MacKay, 1994; Song et al., 2000). Homeostatic mechanisms of plasticity include synaptic scaling and metaplasticity which directly affect synaptic strengths (Davis, 2006; Turrigiano, 2011). Without loss of generality, homeostatic plasticity can be viewed as a modulatory effect or feedback control signal that regulates the unstable dynamics of Hebbian plasticity (see Fig. 1.a). The feedback controller directly affects synaptic strength on the basis of the observed neural activity and must be fast in relation to the timescale of the unstable system (Aström and Murray, 2010). For a critical review of the temporal aspects of Hebbian and homeostatic plasticity, we refer the reader to Zenke et al. (2017a). Modulatory feedback in Hebbian neural networks has received increasing attention, with different approaches proposing biologically plausible learning through modulatory loops (Grant et al., 2017; Soltoggio et al., 2017).

Evidence on cortical function has shown that neural activity in multiple brain areas results from the combination of bottom-up sensory drive, top-down feedback, and prior knowledge and expectations (Heeger, 2017). In this setting, complex neurodynamic behaviour can emerge from the dense interaction of hierarchically arranged neural circuits in a self-organized manner (Tani, 2016). Input-driven self-organization plays a crucial role in the brain (Nelson, 2000), with topographic maps being a common feature of the cortex for processing sensory input (Willshaw and von der Malsburg, 1976). Different models of neural self-organization have been proposed that resemble the dynamics of basic biological findings on Hebbian-like learning and plasticity (Kohonen, 1990; Martinetz, 1993; Fritzke, 1995; Marsland 2002), demonstrating that neural map organization results from unsupervised, statistical learning with nonlinear approximations of the input distribution.

To stabilize the unsupervised learning process, neural network self-organization can be complemented with top-down feedback such as task-relevant signals that modulate the intrinsic map plasticity (Parisi et al., 2017a; Soltoggio et al., 2017). In a hierarchical processing regime, neural detectors have increasingly large spatio-temporal receptive fields to encode information over larger spatial and temporal scales (Taylor et al., 2015; Hasson et al., 2008). Thus, higher-level layers can provide the top-down context for modulating the bottom-up sensory drive in lower-level layers. For instance, bottom-up processing is responsible for encoding the co-occurrence statistics of the environment while error-driven signals modulate this feedforward process according to top-down task-specific factors (Murray et al., 2016). Together, these models contribute to a better understanding of the underlying neural mechanisms for the development of hierarchical cortical organization.

2.3 The Complementary Learning Systems

The brain learns and memorizes. The former task is characterized by the extraction of the statistical structure of the perceived events with the aim to generalize to novel situations. The latter, conversely, requires the collection of separated events occurring at a specific space and time. Consequently, the brain must comprise a mechanism to concurrently generalize across experiences while consolidating episodic memories.

Anatomical studies suggest that sophisticated cognitive functions rely on canonical neural circuits replicated across multiple areas (Douglas et al., 1995). However, although there are shared structural properties, different brain areas operate at multiple timescales and learning rates, thus differing significantly from each other in a functional way (Benna and Fusi, 2016; Fusi et al., 2005). A prominent example are the complementary contributions of the neocortex and the hippocampus in learning and memory (McClelland et al., 1995; O'Reilly et al., 2002; O'Reilly, 2004). This was formalized as the complementary learning systems (CLS) theory, holding that the hippocampal system exhibits short-term adaptation and allows for the rapid learning of novel information which will, in turn, be played back over time to the neocortical system for its long-term retention (see Fig. 1.b). More specifically, the hippocampus employs a rapid learning rate and encodes sparse representations of events to minimize interference. Conversely, the neocortex is characterized by a slow learning rate and builds overlapping representations of the learned knowledge. Therefore, the interplay of hippocampal and neocortical functionality is crucial to concurrently learn regularities (statistics of the environment) and specifics (episodic memories). Both brain areas are known to learn via Hebbian and error-driven mechanisms (O'Reilly and Rudy, 2001). In the neocortex, feedback signals will yield task-relevant representations while, in the case of the hippocampus, error-driven modulation can switch its functionality between pattern discrimination and completion for recalling information (O'Reilly, 2004).

Studies show that adult neurogenesis contributes to the formation of new memories (Altman, 1963; Eriksson, 1998; Cameron et al., 1993; Chunmei et al., 2008; Gage, 2000). During neurogenesis, the hippocampus' dentate gyrus uses new neural units to quickly assimilate and immediately recall new information (Altman, 1963; Eriksson, 1998). During initial memory formation, the new neural progenitor cells exhibit high levels of plasticity; and as time progresses, the plasticity decreases to make the new memory more stable (Deng et al., 2010). While the hippocampus is normally associated with the immediate recall of recent memories (i.e., short-term memories), the prefrontal cortex (PFC) is usually associated with the preservation and recall of remote memories (i.e., long-term memories) (Bontempi et al., 1999). Kitamura et al. (2017) showed that, when the brain learns something new, the hippocampus and PFC are both initially encoded with the corresponding memory; however, the hippocampus is primarily responsible for the recent recall of new information. Over time, they showed that the corresponding memory is consolidated over to PFC, which will then take over responsibility for recall of the (now) remote memory. It is believed that the consolidation of recent memories into long-term storage occurs during rapid eye movement (REM) sleep (Taupin and Gage, 2002; Gais et al., 2007).

Recently, the CLS theory was updated to incorporate additional findings from neuroscience (Kumaran et al., 2016). The first set of findings regards the role of the replaying of memories stored in the hippocampus as a mechanism that, in addition to the integration of new information, also supports the goal-oriented manipulation of experience statistics (O'Neill et al., 2010). The hippocampus rapidly encodes episodic experiences that can be reactivated during sleep or unconscious and conscious memory recall (Gelbard-Sagiv et al., 2008), thus consolidating information in the neocortex through the reactivation of encoded experiences through internally generated multiple replays (Ratcliff, 1990). Furthermore, evidence suggests that i) the hippocampus supports additional forms of generalization through the recurrent interaction of episodic memories (Kumaran and McClelland, 2012) and ii) if the new information is consistent with existing knowledge, then its integration into the neocortex is faster than originally suggested (Tse et al., 2011). Overall, the CLS theory holds the means for effectively generalizing across experiences while retaining specific memories in a lifelong manner.

2.4 Learning without Forgetting

The neuroscience findings described in Sec. 2.3 demonstrate that there are specialized mechanisms in the human cognitive system for protecting consolidated knowledge. Nevertheless, it has been observed that catastrophic interference may occur under specific circumstances. For instance, Mareschal et

al. (2002) found an asymmetric interference effect in a sequential category learning task with 3- and 4-month-old infants. The infants had to learn two categories, *dog* and *cat*, from a series of pictures and would have to later distinguish a novel animal in a subsequent preferential looking task. Surprisingly, it was observed that infants were able to retain the category *dog* only if it was learned before *cat*. This asymmetric effect is thought to reflect the relative similarity of the two categories in terms of perceptual structure.

Additional interference effects were observed for long-term knowledge. Pallier et al. (2003) studied the word recognition abilities of Korean-born adults whose language environment shifted completely from Korean to French after being adopted between the ages of 3 and 8 by French families. Behavioural tests showed that these subjects had no residual knowledge of the previously learned Korean vocabulary. Functional brain imaging data showed that the response of these subjects while listening to Korean was no different from the response while listening to other foreign languages that they had been exposed to, suggesting that their previous knowledge of Korean was completely overwritten. Interestingly, brain activations showed that Korean-born subjects produced weaker responses to French with respect to native French speakers. It was hypothesized that, while the adopted subjects did not show strong responses to transient exposures to the Korean vocabulary, prior knowledge of Korean may have had an impact during the formulation of language skills to facilitate the re-acquisition of the Korean language should the individuals be re-exposed to it in an immersive way.

Humans do not typically exhibit strong events of catastrophic interference because the kind of experiences we are exposed to are very often interleaved (Seidenberg and Zevin, 2006). Nevertheless, interference effects may be observed when new experiences are strongly immersive such as in the case of children drastically shifting from Korean to French. Together, these findings reveal a well-regulated balance in which, on the one hand, consolidated knowledge must be protected to ensure its long-term durability and avoid catastrophic interference during the learning of new tasks over long periods of time. On the other hand, under certain circumstances such as immersive long-term experiences, old knowledge can be overwritten in favor of the acquisition and refinement of new skills.

Taken together, the biological aspects of continual lifelong learning summarized in this section provide insights into how artificial models and agents could avoid catastrophic forgetting. In the next sections, we describe and compare an extensive set of neural network models and AI approaches that have taken inspiration from these principles. In the case of computational systems, however, additional challenges must be faced due to the limitations of learning in restricted scenarios that typically capture very few components of the processing richness of biological systems.

3 Continual Learning and Catastrophic Forgetting in Neural Networks

3.1 Continual Learning Systems

Continual lifelong learning represents a long-standing challenge for machine learning and neural network systems (Hassabis et al., 2017). This is due to the tendency of learning models to catastrophically interfere with existing knowledge when accommodating new information (Thrun and Mitchell, 1995). A continual lifelong learning system is defined as an adaptive algorithm capable of learning from a continuous stream of information, with such information becoming progressively available over time, and where the number of tasks to be learned (e.g., membership classes in a classification task) are not predefined. Critically, the accommodation of new information should occur without catastrophically interfering with previously learned task-relevant knowledge.

In connectionist models, catastrophic interference occurs when the new instances to be learned differ significantly from previously observed examples because this causes the new information to overwrite previously learned knowledge in the shared representational resources in the neural network (French, 1999; McCloskey and Cohen, 1989). When learning offline, this loss of knowledge can be recovered because the agent sees the same pseudo-randomly shuffled examples over and over, but this is not possible when the data cannot be shuffled and is observed as a continuous stream. The effects of catastrophic interference have been widely studied for over two decades, especially in networks learned using back-propagation (Ratcliff, 1990; Lewandowsky and Li, 1994) and in the Hopfield networks (Nadal et al., 1986; Burgess et al., 1991).

Early attempts to mitigate catastrophic interference often consisted of memory systems that store previous data and that regularly replay old samples interleaved with samples drawn from the new data (Robins, 1993; 1995), and these methods are still used today (Gepperth and Karaoguz, 2016; Rebuffi et al., 2017). However, a general drawback of memory-based systems is that they require explicit storage of old information, leading to large working memory requirements. Furthermore, in the case of a fixed amount of neural resources, specialized mechanisms should be designed that protect consolidated knowledge from being overwritten by the learning of novel information (e.g., Zenke et al., 2017b; Kirkpatrick et al., 2017). Intuitively, catastrophic interference can be strongly alleviated or completely overcome by allocating additional neural resources whenever they are required (e.g., Parisi et al., 2017a; Rusu et al., 2016; Hertz et al., 1991). This approach, however, may lead to scalability issues with significantly increased computational efforts for neural architectures that become very large. Conversely, since in a lifelong learning scenario the number of tasks and samples per task cannot be known a priori, it is non-trivial to predefine a sufficient amount of neural resources that will prevent catastrophic interference without strong assumptions on the distribution of the input. In this setting, three key aspects have been identified for avoiding catastrophic interference in connectionist models (Richardson and Thomas, 2008): i) allocating additional neural resources for new knowledge; ii) using non-overlapping representations if resources are fixed; and iii) interleaving the old knowledge as the new information is represented.

The brain has evolved mechanisms that enable continual lifelong learning such as neurosynaptic plasticity, critical post-natal developmental periods, and complex neurocognitive functions that process continuous streams of information in response to both short- and long-term changes in the environment (Zenke et al., 2017a; Power and Schlaggar, 2017; Murray et al., 2016; Lewkowicz, 2014). Consequently, the differences between biological and artificial systems go beyond architectural differences, and also include the way these artificial systems are exposed to external stimuli. Since birth, humans are immersed in a highly dynamic crossmodal world and, in response to this rich perceptual experience, our neurocognitive functions progressively develop to make sense of increasingly more complex events. We start with relatively limited capabilities for processing low-level features and incrementally develop towards the learning of higher-level perceptual, cognitive, and behavioural functions. We make massive use of the spatio-temporal relations and increasingly richer high-order associations of the sensory input to learn and trigger meaningful behavioural responses. Conversely, artificial systems are typically trained in batches, exposing the learning algorithm to multiple iterations of the same training samples in a (pseudo-)random order. After a fixed number of training epochs, it is expected that the learning algorithm has tuned its internal representations for being able to predict novel samples that follow a similar distribution with respect to the training dataset in a subsequent test phase. Clearly, this approach can be effective (and this is supported by the state-of-the-art performance of deep learning architectures for visual classification tasks; see Guo et al., 2016; LeCun et al., 2015 for reviews), but it does not reflect the kind of learning scheme that characterizes lifelong learning tasks.

In the next sections, we introduce and compare different neural network approaches for continual learning that mitigate, to different extents, catastrophic interference. Conceptually, these approaches can be divided into methods that retrain the whole network while regularizing to prevent catastrophic interference with previously learned tasks (Fig. 2.a; Sec. 3.2), methods that block changes to the network and expand it to represent new tasks (Fig. 2.b; Sec. 3.3), and methods that selectively train the network and expand it if necessary (Fig. 2.c). Additionally, a number of methods have modelled complementary learning systems to balance generalization and episodic memory (Sec. 3.4). However, considerably less attention has been given to the rigorous evaluation of these algorithms in continual lifelong learning tasks. In Sec. 3.5, we highlight the importance of using and designing new metrics to measure catastrophic interference in complex scenarios.

3.2 Regularization Approaches

Regularization refers to approaches that alleviate catastrophic interference by imposing constraints on the update of the neural weights. Conceptually, this approach is inspired by theoretical neuroscience models suggesting that consolidated knowledge can be protected from interference through synapses with a cascade of states yielding different levels of plasticity (Benna and Fusi, 2016; Fusi et al., 2005), which is typically modelled with additional regularization terms that penalize changes in the mapping function of a neural network. For instance, Li and Hoiem (2016) proposed a convolutional neural network (CNN) architecture in which the network with predictions of the previously learned tasks is

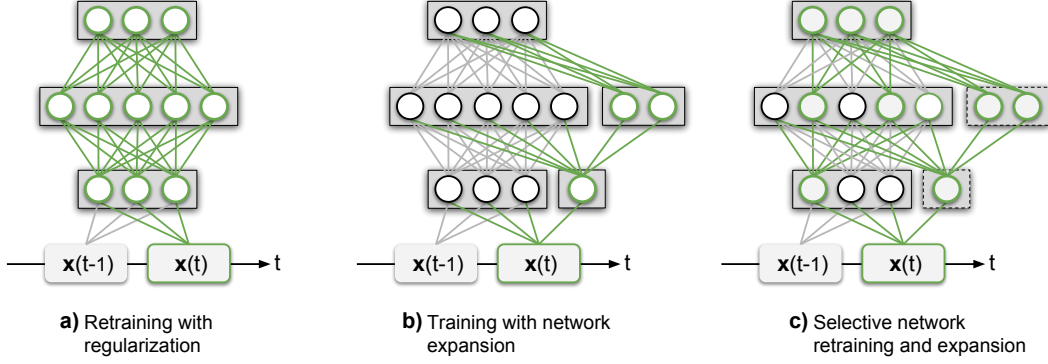


Figure 2: Schematic view of neural network approaches for continual learning: a) retraining while regularizing to prevent catastrophic interference with previously learned tasks, b) unchanged parameters with network extension for representing new tasks, and c) selective retraining with possible expansion.

enforced to be similar to the network with the current task by using knowledge distillation, i.e., the transferring of knowledge from a large, highly regularized model into a smaller model (Hinton et al., 2014). While distillation provides a potential solution to multi-task learning, it requires a reservoir of persistent data for each learned task. This approach, referred to as learning without forgetting (LwF), has the drawbacks of highly depending on the relevance of the tasks and that the training time for one task linearly increases with the number of old tasks. Jung et al. (2018) proposed to regularize the l_2 distance between the final hidden activations, preserving the previously learned input-output mappings by computing additional activations with the parameters of the old tasks. These approaches, however, are computationally expensive since they require to compute the old tasks' parameters for each novel data sample. Other approaches opt to either completely prevent the update of weights trained on old tasks (Razavian et al., 2014) or to reduce the learning rate in order to prevent significant changes in the network parameters while training with new data (Donahue et al., 2014).

Kirkpatrick et al. (2017) proposed elastic weight consolidation (EWC), which consists of adding a penalty to the loss function and constraining the weight parameters that are relevant to retain previously learned tasks. In other words, EWC slows down the learning for task-relevant weights that retain previous knowledge and can be used in supervised and reinforcement learning scenarios. However, this approach requires a diagonal weighting over the parameters of the learned tasks which is proportional to the diagonal of the Fisher information metric, with synaptic importance being computed offline and limiting its computational application to low-dimensional output spaces. Furthermore, additional experiments by Kemker et al. (2018) have shown that although EWC outperforms other methods for permutation tasks, it is not capable of learning new categories incrementally.

Zenke et al. (2017b) proposed to alleviate catastrophic forgetting by allowing individual synapses to estimate their importance for solving a learned task. Similar to Kirkpatrick et al. (2017), this approach penalizes changes to the most relevant synapses so that new tasks can be learned with minimal interference. In this case, the synaptic importance is computed in an online fashion over the learning trajectory in the parameter space. However, despite this substantial difference, the two approaches have shown similar results on the permuted MNIST benchmark (LeCun et al., 1998; see Fig. 3.a), whereas experiments on more complex and larger datasets have not been reported.

He and Jaeger (2018) introduced conceptor-aided backpropagation (CAB), which uses conceptors to shield gradients from forgetting prior knowledge. Thus, learning a new task should interfere only minimally with previously learned tasks. Furthermore, conceptors provide an analytical tool to discuss the relatedness and enabling conditions for continual learning in terms of the opportunities to re-use previously acquired functionality in subsequent learning episodes. Serrà et al., (2018) incorporated a hard attention (HAT) mask into the loss function and showed that this alleviated catastrophic forgetting in sequential task learning. The HAT adds a minimum number of weights to the base network and is trained together with the global model, with a minimal overhead using vanilla

stochastic gradient descent. Both CAB and HAT outperform EWC on a set of continual learning tasks using the MNIST dataset.

In summary, regularization approaches provide a way to alleviate catastrophic forgetting under certain conditions. However, this kind of approaches comprises additional loss terms for protecting consolidated knowledge which, with a limited amount of neural resources, may lead to a tradeoff on the performance of old and novel tasks.

3.3 Dynamic Architectures

The approaches introduced here change architectural properties in response to new information, either by dynamically accommodating novel neural resources or by re-training with an increased number of neurons or network layers. For instance, Rusu et al., (2016) proposed to block any changes to the network trained on previous knowledge and expand the architecture by allocating novel sub-networks with fixed capacity to be trained with the new information. This approach, referred to as progressive networks, retains a pool of pre-trained models during the training and learns lateral connections from these models to extract significant features for learning a new task. Experiments reported good results on a wide variety of reinforcement learning tasks, outperforming common baseline approaches that either pre-train or incrementally fine-tune the models by incorporating prior knowledge only at initialization. Intuitively, this approach prevents catastrophic forgetting but leads the complexity of the architecture to grow with the number of learned tasks.

Other approaches explored how to increase the capacity of the neural architecture more dynamically. Zhou et al., (2012) proposed the incremental training of a denoising autoencoder that adds additional neurons for samples with high loss and subsequently merges these neurons with existing ones to prevent redundancy. More specifically, the algorithm is composed of two processes for i) adding new features to minimize the residual of the objective function and ii) merging similar features to obtain a compact feature representation and in this way prevent overfitting. This model was shown to outperform non-incremental denoising autoencoders in classification tasks with the MNIST (LeCun et al., 1998) and the CIFAR-10 (Krizhevsky, 2009) benchmark datasets. Cortes et al. (2016) proposed to adapt both the structure of the network and its weights by balancing the model complexity and empirical risk minimization. In contrast to enforcing a pre-defined architecture, the algorithm learns the required model complexity in an adaptive fashion. The authors reported good results on several binary classification tasks extracted from the CIFAR-10 dataset. In contrast to previously introduced approaches that do not consider multi-task scenarios, Xiao et al. (2014) proposed a training algorithm with a network that incrementally grows in capacity and also in hierarchical fashion. Classes are grouped according to their similarity and self-organized into multiple levels, with models inheriting features from existing ones to speed up the learning. In this case, however, only the topmost layers can grow and the vanilla back-propagation training procedure is inefficient.

Part and Lemon (2016, 2017) proposed the combination of a pre-trained CNN with a self-organizing incremental neural network (SOINN) in order to take advantage of the good representational power of CNNs and at the same time, allow the classification network to grow according to the task requirements. An issue that arises from these types of approaches is scalability since the classification network grows with the number of classes that have been learned. Another problem that was identified through this approach is that by relying on fixed representations, e.g., pre-trained CNNs, the discrimination power will be conditioned by the dataset used to train the feature extractor. Rebuffi et al. (2017) deal with this problem by storing example data points that are used along with new data to dynamically adapt the weights of the feature extractor, a technique that is referred to as rehearsal. By combining new and old data, they prevent catastrophic forgetting but at the expense of a higher memory footprint.

Lopez-Paz and Ranzato (2017) proposed the Gradient Episodic Memory (GEM) model that alleviates catastrophic forgetting and transfers beneficial knowledge to past tasks. The model learns the subset of correlations common to a set of distributions or tasks, able to predict target values associated with previous or novel tasks without making use of task descriptors. However, similar to an issue shared with most of the approaches discussed in Sec. 3, the GEM model was evaluated on the MNIST and CIFAR100 datasets.

Ensemble methods have been proposed to alleviate catastrophic interference by training multiple classifiers and then using their combination to generate a prediction. Early attempts showed a

disadvantage linked to the intense use of storage memory which scales up with the number of sessions (Polikar et al., 2001; Dai et al., 2007), while more recent approaches restrict the size of the models through multiple strategies. For instance, Ren et al. (2017) proposed a model that can adaptively adjust to the changing data distribution by combining sub-models after a new training phase, learning new tasks without referring to previous training data. Coop et al. (2013) introduced a multi-layer perceptron (MLP) augmented with a fixed expansion layer (FEL) which embeds a sparsely encoding hidden layer to mitigate the interference of previously learned representations. Ensembles of FEL networks were used to control levels of plasticity, yielding incremental learning capabilities while requiring minimal storage memory. Fernando et al. (2017) proposed an ensemble method in which a genetic algorithm is used to find the optimal path through a neural network of fixed size for replication and mutation. This approach, referred to as PathNet, uses agents embedded in a neural network to discover which parts of the network can be reused for the learning of new tasks while freezing task-relevant paths for avoiding catastrophic interference. PathNet’s authors showed that incrementally learning new tasks sped up the training of subsequently learned supervised and reinforcement learning tasks; however, they did not measure performance on the original task to determine if catastrophic forgetting occurred. In addition, PathNet requires an independent output layer for each new task, which prevents it from learning new classes incrementally (Kemker et al., 2018).

There has been some recent work to develop neural networks that can assimilate new information while mitigating catastrophic forgetting by expanding the number of trainable parameters. Draelos et al. (2017) incrementally trained an autoencoder on new MNIST digits using the reconstruction error to show whether the older digits were retained. Their neurogenesis deep learning (NDL) model adds new neural units to the autoencoder to facilitate the addition of new MNIST digits, and it uses intrinsic replay (a generative model used for pseudo-rehearsal) to preserve the weights required to retain older information. Yoon et al., (2018) took this concept to the supervised learning paradigm and proposed a dynamically expanding network (DEN) that automatically increases the number of trainable parameters to incrementally learn new tasks. DEN is trained in an online manner by performing selective retraining which expands the network capacity using group sparse regularization to decide how many neurons to add at each layer.

So far, we have considered approaches designed for (or at least strictly evaluated on) the classification of annotated images. However, it is plausible to assume dealing with sequential input underlying spatio-temporal relations such as in the case of videos. Parisi et al. (2017a) showed that continual lifelong learning of spatio-temporal action sequences can be achieved in terms of prediction-driven neural dynamics with internal representations emerging in a hierarchy of recurrent self-organizing networks. Here, the networks can dynamically allocate neural resources and update connectivity patterns according to competitive Hebbian learning by computing the input based on its similarity with existing knowledge and minimizing interference by creating new neurons whenever they are required. This approach has shown competitive results with batch learning methods on the Weizmann (Gorelick et al., 2005) and the KTH (Schuldt et al., 2004) action benchmark datasets. Furthermore, it learns robust action-label mappings also in the case of occasionally missing or corrupted class labels. However, in this approach, neural growth and update are driven by the minimization of the bottom-up reconstruction error, without taking into account top-down task-relevant signals that can regulate the stability-plasticity balance.

3.4 Dual-Memory Learning Systems

A set of models have taken inspiration from the CLS theory (McClelland et al., 1995; Kumaran et al., 2016) providing the basis for a computational framework that effectively generalizes across experiences while retaining specific memories in a lifelong manner (see Sec. 2.3). An early computational example of this concept was proposed by Hinton and Plaut (1987) in which each synaptic connection has two weights: a plastic weight with slow change rate which stores long-term knowledge and a fast-changing weight for temporary knowledge. This dual-weight method reflects the properties of complementary learning systems to mitigate catastrophic forgetting during the sequential learning of tasks. French (1997) developed a pseudo-recurrent dual-memory framework, one for early processing and the other for long-term storage, that used pseudo-rehearsal (Robins, 1995) to transfer memories between memory centers. In pseudo-rehearsal, training samples are not explicitly kept in memory but drawn from a probabilistic or generative model (Robins, 1995; Lopez-Paz and Ranzato, 2017). During the next two decades, numerous neural network approaches based on CLS principles were

used to explain and predict results in different learning and memory domains (see O’Reilly et al., 2002 for a review). However, there is no empirical evidence that shows that these approaches can scale up to a large number of tasks or current image and video benchmark datasets (see Sec. 3.5).

More recently, Gepperth and Karaoguz (2016) proposed two approaches for incremental learning using i) a modified self-organizing map (SOM) and ii) a SOM extended with a short-term memory (STM). We refer to these two approaches as GeppNet and GeppNet+STM respectively. In the case of the GeppNet, task-relevant feedback from a regression layer is used to select whether learning in the self-organizing hidden layer should occur. In the GeppNet+STM case, the STM is used to store novel knowledge which is occasionally played back to the GeppNet layer during sleep phases interleaved with training phases. This latter approach yielded better performance and faster convergence in incremental learning tasks with the MNIST dataset. However, the STM has a limited capacity, thus learning new knowledge can overwrite old knowledge. In both cases, the learning process is divided into two phases, one for initialization and the other for actual incremental learning. Additional experiments showed that this approach performs significantly worse than EWC (Kirkpatrick et al., 2017) on different permutation tasks (see Sec. 3.6). Both GeppNet and GeppNet+STM require storing the entire training dataset during training.

Inspired by the generative role of the hippocampus for the replay of previously encoded experiences, Shin et al. (2017) proposed a dual-model architecture consisting of a deep generative model and a task solver. In this way, training data from previously learned tasks can be sampled in terms of generated pseudo-data and interleaved with information from the new tasks. Thus, it is not necessary to explicitly revise old training samples for experience replay, reducing the requirements of working memory. This approach is conceptually similar to previous ones using a pseudo-rehearsal method, i.e., interleaving information of a new task with internally generated samples from previously learned tasks. Robin (1995) showed that interleaving information of new experiences with internally generated patterns of previous experiences help consolidate existing knowledge without explicitly storing training samples. Pseudo-rehearsal was also used by Draelos et al. (2017) for the incremental training of an autoencoder, using the output statistics of the encoder to generate input for the decoder during the replay. However, similar to most of the above-described approaches, the use of pseudo-rehearsal methods was strictly evaluated on two datasets of relatively low complexity, e.g. the MNIST and the Street View House Number (SVHN) (Netzer et al., 2014). Consequently, the question arises whether this generative approach can scale up to more complex domains.

Kemker and Kanan (2018) proposed the FearNet model for incremental class learning that is inspired by studies of recall and consolidation in the mammalian brain during fear conditioning (Kitamura et al., 2017). FearNet uses a hippocampal network capable of immediately recalling new examples, a PFC network for long-term memories, and a third neural network inspired by the basolateral amygdala for determining whether the system should use the PFC or hippocampal network for a particular example. FearNet consolidates information from its hippocampal network to its PFC network during sleep phases. To do this, FearNet’s PFC model is a generative neural network that creates pseudo-samples that are then intermixed with recently observed examples stored in its hippocampal network. Kamra et al. (2018) presented a similar dual-memory framework for continual learning that also uses a variational autoencoder as a generative model for pseudo-rehearsal. Their framework generates a short-term memory module for each new task; however, prior to consolidation, predictions are made using an oracle (i.e., they know which module contains the associated memory).

Soltoggio (2015) proposed to deal with the plasticity-stability dilemma (see Sec. 2.1) through the use of short- and long-term plasticity for consolidating new information on the basis of a cause-effect hypothesis testing when learning with delayed rewards. In this case, the difference between the short- and long-term plasticity is not related to the duration of the memory but rather to the confidence of consistency of cause-effect relationships. This meta-plasticity rule, referred to as hypothesis testing plasticity (HTP), shows that such relationships can be extracted from ambiguous information flows, thus towards explaining the learning in more complex environments (see Sec. 4).

3.5 Benchmarks and Metrics of Catastrophic Interference

In Sec. 3.2-4, we critically summarized numerous approaches that alleviate catastrophic interference through different architectural or functional methods. However, a direct comparison of these methods is hindered by the highly heterogeneous and often limited experimental schemes used to evaluate them. Kemker et al. (2018) suggested more exhaustive guidelines for evaluating continual learning

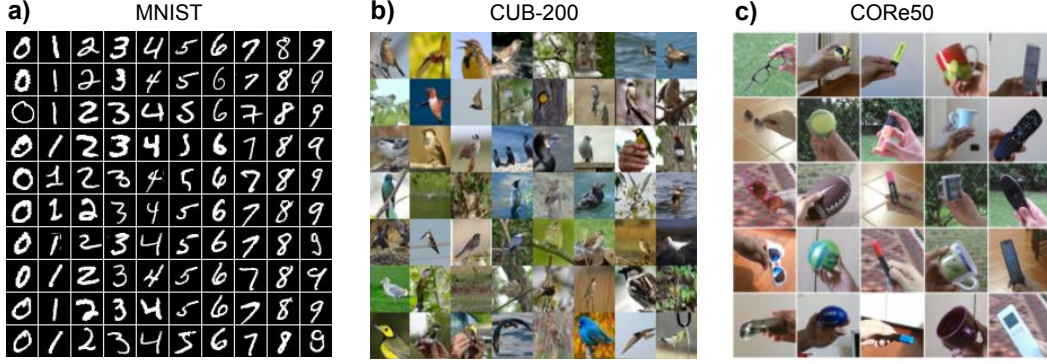


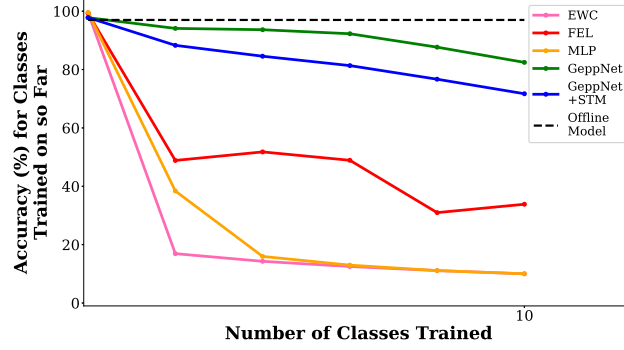
Figure 3: Example images from benchmark datasets used for the evaluation of continual learning approaches: a) the MNIST dataset with 10 digit classes (LeCun et al., 1998), b) the Caltech-UCSD Birds-200 (CUB-200) dataset composed of 200 different bird species (Wah et al., 2011), and c) the CORe50 containing 50 objects with variations in background, illumination, blurring, occlusion, pose, and scale (adapted with permission from Lomonaco and Meltoni, 2017).

approaches and performed complementary experiments that provide a direct quantitative comparison of a number of approaches. Such guidelines comprise the use of three benchmark experiments: i) data permutation, ii) incremental class learning, and iii) multimodal learning.

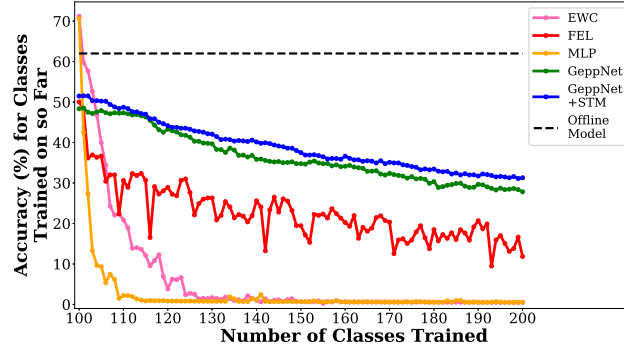
The data permutation experiment consists in training a model with a dataset along with a permuted version of the same dataset, which tests the model’s ability to incrementally learn new information with similar feature representations. It is then expected that the model prevents catastrophic interference with the original data during the subsequent learning of randomly permuted data samples. In the incremental class learning experiment, the model performance reflects its ability to retain previously learned information while incrementally learning one class at a time. Finally, in the multimodal learning experiment, the same model is sequentially trained with datasets of different modalities, which tests the model’s ability to incrementally learn new information with dramatically different feature representations (e.g., first learn an image classification dataset and then learn an audio classification dataset).

In addition to benchmark experimental procedures, quantitative metrics are required to assess the effects of catastrophic interference with the aim to provide a comparative evaluation of different methods. In the context of unsupervised self-organizing architectures, it has been proposed to assess the quality of the topological maps in terms of neural activity, discrimination, and organization (Richardson and Thomas, 2008; Oliver et al., 2000). Conversely, supervised methods generally compare the overall classification performance. Lopez-Paz and Ranzato (2017) introduced two metrics to measure how much influence previously learned tasks have on the current task (backwards transfer) and how much the current task will influence the learning of future tasks (forward transfer). Kemker et al. (2018) proposed three metrics to assess the ability of models to retain old knowledge and acquire new information.

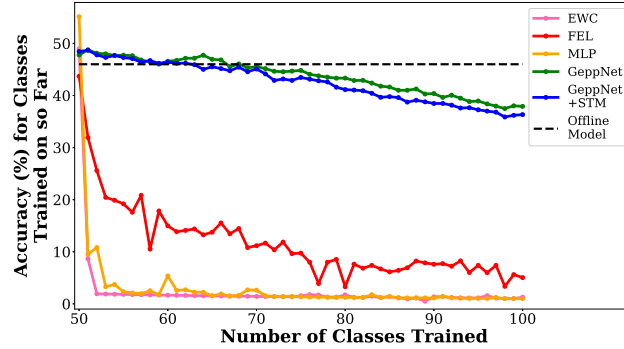
In contrast to the datasets typically proposed in the literature to evaluate continual learning approaches (e.g., MNIST containing 10 digit classes with low-resolution images), the above-mentioned experimental conditions were conducted using the Caltech-UCSD Birds-200 (CUB-200) dataset composed of 200 different bird species (Wah et al., 2011; see Fig. 3.b) and the AudioSet dataset, which is built from YouTube videos with 10-second sound clips from 632 classes and over 2 million annotations (Gemmeke et al., 2017). The approaches considered were supervised: a standard MLP trained online as a baseline, the EWC (Kirkpatrick et al., 2017), the PathNet (Fernando et al., 2017), the GeppNet and GeppNet+STM (Gepperth and Karaoguz, 2016), and the FEL (Coop et al., 2013). For the data permutation experiment, best results were obtained by PathNet followed by EWC, suggesting that models that use the ensembling and regularization mechanisms will work best at incrementally learning new tasks/datasets with similar feature distributions. In contrast, EWC performed better than PathNet on the multi-modal experiment because EWC does a better job on separating non-redundant (i.e., dissimilar) data. For the incremental learning task, best results were obtained with a combination of rehearsal and dual-memory systems (i.e. GeppNet+STM), yielding gradual adaptation and



(a) MNIST



(b) CUB-200



(c) AudioSet

Figure 4: Results of several continual learning approaches for the incremental class learning experiment. The mean-class test accuracy evaluated on the MNIST (a), CUB-200 (b), and AudioSet (c) is shown for the following approaches: FEL (red), MLP (yellow), GeppNet (green), GeppNet+STM (blue), EWC (pink), and offline model (dashed line). Adapted with permission from Kemker et al. (2018).

knowledge consolidation (see Fig.4). However, since rehearsal requires the storage of raw training examples, pseudo-rehearsal may be a better strategy for future work.

Perhaps not surprisingly, the evaluated models performed significantly worse when using datasets of higher complexity such as CUB-200 than when tested on the MNIST. This suggests that while there is a large number of approaches capable of alleviating catastrophic interference in highly controlled experimental conditions, continual lifelong learning has not been addressed for more complex scenarios. Recently, Lomonaco and Meltoni (2017) proposed a novel dataset named CORE50 for continual object recognition that includes 50 classes of objects observed from different perspectives and includes variations in background, illumination, blurring, occlusion, pose, and scale (see Fig. 3.c). With respect to the above-discussed datasets, CORE50 provides samples collected in experimental

conditions closer to what autonomous agents are exposed to in the real world (see Sec. 4). Therefore, additional research efforts are required to develop novel approaches that combine the advantages of multiple methodological strategies and that are subject to more exhaustive experimental scenarios.

4 Developmental Approaches and Autonomous Agents

4.1 Towards Autonomous Agents

Humans have the extraordinary ability to learn and progressively fine-tune their sensorimotor skills in a continual lifelong manner (Bremner et al., 2012; Calvert et al., 2004). Since the moment of birth, humans are immersed in a highly dynamic crossmodal environment which provides a wealth of experiences for shaping perception, cognition, and behaviour (Murray et al., 2016; Lewkowicz, 2014). A crucial component of lifelong learning in infants is their spontaneous capacity of autonomously generating goals and exploring their environment driven by intrinsic motivation (Gopnik et al., 1999). Consequently, the ability of learning new tasks autonomously through intrinsically motivated exploration is one of the main factors that differentiate biological lifelong learning from current artificial continual learning models.

While there has been significant progress in the development of models addressing incremental learning tasks (see Sec. 3), such models are designed to alleviate catastrophic forgetting from a set of annotated data samples. Typically, the complexity of the datasets used for the evaluation of continual learning tasks is very limited and does not reflect the richness and level of uncertainty of the stimuli that an artificial agent can be exposed to in the real world. Furthermore, models are often trained with data samples shown in isolation or presented in a random order. This significantly differs from the highly organized manner in which humans and animals efficiently learn from samples presented in a meaningful order for the shaping of increasingly complex concepts and skills (Krueger and Dayan, 2009; Skinner, 1958). Therefore, learning in a lifelong manner should go beyond the incremental accumulation of domain-specific knowledge, enabling to transfer generalized knowledge across domains and tasks (Barnett and Ceci, 2002) and benefiting from the interplay of crossmodal stimuli for the development and specialization of neurocognitive functions (Murray et al., 2016; Lewkowicz, 2014).

Intuitively, and in contrast with current continual learning approaches trained with limited amounts of annotated data, it is unrealistic to provide an artificial agent with all the necessary prior knowledge to effectively operate in real-world conditions (Thrun and Mitchell, 1995). Consequently, artificial agents must exhibit a richer set of learning capabilities enabling them to interact in complex environments with the aim to process and make sense of continuous streams of (often uncertain) information (Wermter et al., 2005). In the last decade, significant advances have been made to embed biological aspects of continual learning into neural network models. In this section, we summarize well-established and experimental neural network approaches driven by interdisciplinary research introducing knowledge from neuroscience, psychology, and cognitive sciences for developing lifelong learning autonomous agents (see Fig. 5). We focus on discussing models of critical developmental stages and staged training strategies such as curriculum learning (Sec. 4.2), autonomous exploration and choice of goals driven by curiosity and intrinsic motivation (Sec. 4.3), transfer learning for the reuse of consolidated knowledge in new task acquisition (Sec. 4.4), and the crossmodal aspects of continual lifelong learning for multisensory systems and embodied agents (Sec. 4.5).

4.2 Developmental and Curriculum Learning

Learning and development interact in a very intricate way (Elman, 1993). Humans show an exceptional capacity to learn throughout their lifespan and, with respect to other species, exhibit the lengthiest developmental process for reaching maturity. There is a limited time window in development in which infants are particularly sensitive to the effects of their experiences. This period is commonly referred to as the sensitive or critical period of development (Lenneberg, 1967) in which early experiences are particularly influential, sometimes with irreversible effects in behaviour (Senghas et al., 2004). During these critical periods, the brain is particularly plastic and neural networks acquire their overarching structure driven by sensorimotor experiences (see Power and Schlaggar, 2017 for a survey). Afterwards, plasticity becomes less prominent and the system stabilizes, preserving a certain degree of plasticity for its subsequent adaptation and reorganisation at smaller scales (Hensch et al., 1998; Quadrato et al., 2014; Kiyota, 2017).

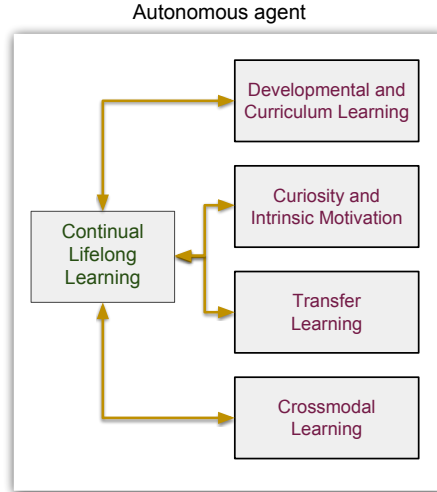


Figure 5: Schematic view of the main components for the development of autonomous agents able to learn over long periods of time in complex environments: Developmental and curriculum learning (Sec. 4.2), curiosity and intrinsic motivation (Sec. 4.3), transfer learning (Sec. 4.4), and crossmodal learning (Sec. 4.5).

The basic mechanisms of critical learning periods have been studied in connectionist models (Thomas and Johnson, 2006; Richardson and Thomas, 2008), in particular with the use of self-organizing learning systems which reduce the levels of functional plasticity through a two-phase training of the topographic neural map (Kohonen, 1982; 1995; Miikkulainen, 1997). In a first organization phase, the neural map is trained with a high learning rate and large (spatial) neighborhood size, allowing the network to reach an initial rough topological organization. In a second tuning phase, the learning rate and the neighborhood size are iteratively reduced for fine-tuning. Implementations of this kind have been used to develop models of early visual development (Miller et al., 1989), language acquisition (Lambon Ralph and Ehsan, 2006; Li et al., 2004) and recovery from brain injuries (Marchman, 1993). Recent studies on critical periods in deep neural networks showed that the initial rapid learning phase plays a key role in defining the final performance of the networks (Achille et al., 2017). The first few epochs of training are critical for the allocation of resources across different layers dictated by the initial input distribution. After such a critical period, the initially allocated neural resources can be re-distributed through additional learning phases.

Developmental learning strategies have been experimented on with embedded agents to regulate the real-time embodied interaction with the environment (Cangelosi and Schlesinger, 2015; Tani, 2016). In contrast with computational models that are fed with batches of information, developmental agents acquire an increasingly complex set of skills based on their sensorimotor experiences in an autonomous manner. Consequently, staged development becomes essential for bootstrapping cognitive skills with less amount of tutoring experience (Tani, 2016). However, the use of developmental strategies for artificial learning systems has shown to be a very complex practice. In particular, it is non-trivial to select a well-defined set of developmental stages that favors a good learning performance in highly dynamic environments. It has been argued that in the predictive coding framework (Adams et al., 2015; Rao and Ballard, 1999), the intention towards a goal can be generated through the prediction of the consequence of an action by means of the error regression with the prediction error. The use of generative models, which are implicit in predictive coding, is one component embedded in the framework of active inference (Friston et al., 2015). Such a framework aims to understand how to select the data that best discloses its causes in dynamic and uncertain environments through the bilateral use of action and perception. It remains unclear how to systematically define developmental stages on the basis of the interaction between innate structure, embodiment, and (active) inference.

Humans and animals exhibit better learning performance when examples are organized in a meaningful way, e.g., by making the learning tasks gradually more difficult (Krueger and Dayan, 2009). Following this observation, referred to as *curriculum learning*, Elman (1993) showed that having

a curriculum of progressively harder tasks leads to faster training performance in neural network systems. This has inspired similar approaches in robotics (Sanger, 1994) and more recent machine learning methods studying the effects of curriculum learning in the performance of learning (Bengio et al., 2009; Reed and de Freitas, 2015; Graves et al., 2016). Experiments on datasets of limited complexity showed that curriculum learning act as unsupervised pre-training, leading to improved generalization and faster speed of convergence of the training process towards the global minimum. However, the effectiveness of curriculum learning is highly sensitive with respect to the modality of progression through the tasks. Furthermore, this approach assumes that tasks can be ordered by a single axis of difficulty. Graves et al. (2017) proposed to treat the task selection problem as a stochastic policy over the tasks that maximizes the learning progress, leading to an improved efficiency in curriculum learning. In this case, it is necessary to introduce additional factors such as intrinsic motivation (Oudeyer et al., 2007; Barto, 2013), where indicators of learning progress are used as reward signals to encourage exploration (see Sec. 4.3). Curriculum strategies can be seen as a special case of transfer learning (Weiss et al., 2016), where the knowledge collected during the initial tasks is used to guide the learning process of more sophisticated ones (see Sec. 4.4).

4.3 Curiosity and Intrinsic Motivation

Computational models of intrinsic motivation have taken inspiration from how human children choose their goals and progressively acquire skills for defining developmental structures in lifelong learning frameworks (Baldassarre and Mirolli, 2013; see Gottlieb et al., 2013 for a review). Infants seem to select experiences that maximize an intrinsic learning reward through an empirical process of exploration (Gopnik et al., 1999). From a modelling perspective, it has been proposed that the intrinsically motivated exploration of the environment, e.g., driven by the maximization of the learning progress (Oudeyer et al., 2007; Schmidhuber, 1991), can lead to the self-organization of human-like developmental structures where the skills being acquired become progressively more complex.

Algorithms of intrinsic motivation collect data and acquire skills incrementally through the online (self-)generation of a learning curriculum (Baranes and Oudeyer, 2013; Forestier and Oudeyer, 2016). This allows the efficient stochastic selection of tasks to be learned with an active control of the growth of the complexity. Recent work in (deep) reinforcement learning has included mechanisms of curiosity and intrinsic motivation to address scenarios where the rewards are sparse or deceptive (Forestier et al., 2017; Pathak et al., 2017; Tanneberg et al., 2017; Bellemare et al., 2016; Kulkarni et al., 2016). In a scenario with very sparse extrinsic rewards, curiosity-driven exploration provides intrinsic reward signals that enable the agent to autonomously and progressively learn tasks of increasing complexity.

Pathak et al. (2017) proposed an approach to curiosity-driven exploration where curiosity is modelled as the error in an agent’s ability to predict the consequences of its own actions. This approach has shown to scale up to high-dimensional visual input, using the knowledge acquired from previous experiences for the faster exploration of unseen scenarios. However, the method relies on interaction episodes that convert unexpected interactions in intrinsic rewards, which does not extend to scenarios where interactions are rare. In this case, internally generated representations of the previous sparse interactions could be replayed and used to guide exploration (in a similar way to generative systems for memory replay; see Sec. 3.4).

4.4 Transfer Learning

Transfer learning refers to applying previously acquired knowledge in one context to solve a problem in a novel domain (Barnett and Ceci, 2002; Pan and Yang, 2010). While humans and animals excel at transferring generalized knowledge to novel domains (Holyoak and Thagard, 1997), transfer learning has remained an open challenge in machine learning and autonomous agents (see Weiss et al., 2016 for a survey). Specific neural mechanisms in the brain mediating the high-level transfer learning are poorly understood, although it has been argued that the transfer of abstract knowledge may be achieved through the use of conceptual representations that encode relational information invariant to individuals, objects, or scene elements (Doumas et al., 2008).

Transfer learning represents a significantly valuable feature of artificial systems for inferring general laws from (a limited amount of) particular samples, assuming the simultaneous availability of multiple

learning tasks with the aim to improve the performance at one specific task. Similarly, zero-shot learning (Lampert et al., 2009; Palatucci et al., 2009) and one-shot learning (Fei-Fei et al., 2003; Vinyals et al., 2016) aim at performing well on novel tasks but do not prevent catastrophic interference on previously learned tasks. An early attempt to realize continual learning through transfer learning was proposed by Ring (1997) through the use of a hierarchical neural network to solve increasingly complex reinforcement learning tasks by incrementally adding new neural units that encode the wider temporal context in which actions take place.

Recent deep learning approaches have attempted to tackle lifelong transfer learning in a variety of domains. For instance, Rusu et al. (2017) proposed the use of progressive neural networks (Rusu et al., 2016) to transfer learned low-level features and high-level policies from a simulated to a real environment. The task consists of learning pixel-to-action reinforcement learning policies with sparse rewards from raw visual input to a physical robot manipulator. Tessler et al. (2017) introduced a hierarchical deep reinforcement learning network that uses an array of skills and skill distillation to reuse and transfer knowledge between tasks. The approach was evaluated by teaching an agent to solve tasks in the Minecraft video game. However, skill networks need to be pre-trained and cannot be learned along with the overarching architecture in an end-to-end fashion. Lopez-Paz and Ranzato (2017) proposed the Gradient Episodic Memory (GEM) model that alleviates catastrophic forgetting and transfers beneficial knowledge to past tasks. The model learns the subset of correlations common to a set of distributions or tasks, able to predict target values associated with previous or novel tasks without making use of task descriptors. However, similar to an issue shared with most of the approaches discussed in Sec. 3, the GEM model was evaluated on the MNIST and CIFAR100 datasets. Therefore, the question remains whether GEM will scale up to more realistic scenarios.

4.5 Crossmodal Learning

The ability to integrate multisensory information is a crucial feature of the brain that yields a coherent, robust, and efficient interaction with the environment (Ernst and Bühlhoff, 2004; Stein and Meredith, 1993). Multisensory processing functions are the result of the interplay of the physical properties of the crossmodal stimuli and prior knowledge and expectations (e.g., in terms of learned associations), scaffolding perception, cognition, and behaviour (see Murray et al., 2016; Stein et al., 2014 for reviews). The process of crossmodal learning is dynamic across the lifespan and is subject to both short- and long-term changes. It consists of the dynamic reweighting of exogenous and endogenous factors that dictate to which extent multiple modalities interact with each other. Low-level stimulus characteristics (e.g., spatial proximity and temporal coincidence) are available before the formation of learned perceptual representations that bind increasingly complex higher-level characteristics (e.g., semantic congruency). Sophisticated perceptual mechanisms of multisensory integration emerge during development, starting from basic processing capabilities and progressively specializing towards more complex cognitive functions on the basis of sensorimotor experience (Lewkowicz, 2014).

From a computational perspective, modelling crossmodal learning can be useful for a number of reasons. First, multisensory functions aim at yielding robust responses in the case of uncertain and ambiguous sensory input. Models of causal inference have been applied to scenarios comprising the exposure to incongruent audio-visual information for solving crossmodal conflicts (Parisi et al., 2017b). Second, if trained with multisensory information, one modality can be reconstructed from available information in another modality. Moon et al. (2015) proposed multisensory processing for an audio-visual recognition task in which knowledge in a source modality can be transferred to a target modality. Abstract representations obtained from a network encoding the source modality can be used to fine-tune the network in the target modality, thereby relaxing the imbalance of the available data in the target modality. Barros et al. (2017) proposed a deep architecture modeling crossmodal expectation learning. After a training phase with multisensory information, unisensory network channels can reconstruct the expected output in the other modality. Finally, mechanisms of attention are essential in lifelong learning scenarios for processing relevant information in complex environments and efficiently triggering goal-directed behaviour from continuous streams of cross-modal information (Spence, 2014). Such mechanisms may model the combination of the exogenous properties of crossmodal input, learned associations and crossmodal correspondences, and internally generated expectations (Chen and Spence, 2017) with the aim of continually shaping perception, cognition, and behaviour in autonomous agents.

5 Conclusion

Continual lifelong learning represents an utterly interesting but challenging component of artificial systems and autonomous agents. A variety of biological factors of lifelong learning in humans and animals have inspired a wide range of machine learning and neural network approaches that alleviate the problem of catastrophic interference. Despite significant advances in this direction, current models of continual lifelong learning are still far from providing the flexibility, robustness, and scalability exhibited by biological systems.

The most successful (deep) learning models of continual learning are largely restricted to the supervised domain, relying on large amounts of annotated data collected in controlled environments or available on the internet (see Sec. 3). Such a domain-specific training scheme, however, cannot be applied directly to autonomous agents that operate in highly dynamic, unstructured environments. Consequently, additional research efforts are required to combine multiple methodologies that integrate a variety of factors observed in human learners. Basic mechanisms of critical periods of development (Sec. 4.2) can be modelled to empirically determine convenient (multilayered) neural network architectures and initial patterns of connectivity that improve the performance of the model for subsequent learning tasks. For agents learning autonomously, approaches using intrinsic motivation (Sec. 4.3) are crucial for the self-generation of goals, leading to an empirical process of exploration and the progressive acquisition of increasingly complex skills. Methods comprising transfer learning (Sec. 4.4) are a fundamental feature for reusing previously acquired skills to solve a problem in a novel domain by sharing low- and high-level knowledge, e.g., when the amount of available training samples for learning the new skill is very limited. Finally, the ability to efficiently integrate multisensory information (Sec. 4.5) is a key feature of autonomous agents operating in highly dynamic and noisy environment, leading to robust learning and behaviour also in situations of uncertainty.

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