CNN – MNIST Digits Classification

Objectif : entraîner un CNN sur MNIST (10 chiffres) et analyser l'impact du nombre de convolutions (2 vs 3).

In [13]:
```
# Import des librairies necessaires pour le traitement des images,
# la creation du CNN, l'entrainement du modele et le suivi des ressources
import numpy as np
import matplotlib.pyplot as plt
import os
from tensorflow import keras
from tensorflow.keras.models import Sequential
from tensorflow.keras.layers import Conv2D, MaxPooling2D, Flatten, Dense, Dropou
from tensorflow.keras.callbacks import EarlyStopping, ModelCheckpoint, Callback
import time
import GPUtil
import psutil
```

In [14]:
```
# Parametres globaux pour la taille des images, le batch et le nombre d'epochs
IMG_SIZE = (28, 28)
BATCH_SIZE = 32
EPOCHS = 20
```

In [15]:
```
# Chargement du dataset MNIST, normalisation des images et mise en forme des don
# Les labels sont convertis en format categoriel pour la classification multi-cl
(x_train, y_train), (x_test, y_test) = keras.datasets.mnist.load_data()

x_train = x_train.astype("float32") / 255.0
x_test  = x_test.astype("float32") / 255.0

x_train = np.expand_dims(x_train, axis=-1)  # (60000, 28, 28, 1)
x_test  = np.expand_dims(x_test, axis=-1)   # (10000, 28, 28, 1)

y_train_cat = keras.utils.to_categorical(y_train, num_classes=10)
y_test_cat  = keras.utils.to_categorical(y_test, num_classes=10)
```

In [16]:
```
# Fonction qui construit un CNN pour le dataset MNIST
# Le modele peut avoir 2 ou 3 convolutions selon le parametre nb_conv
def build_cnn(nb_conv):
    model = Sequential()

    # 1ère convolution
    model.add(Conv2D(32, (3,3), activation='relu', input_shape=(28,28,1)))
    model.add(MaxPooling2D((2,2)))

    # 2ème convolution
    model.add(Conv2D(32, (3,3), activation='relu'))
    model.add(MaxPooling2D((2,2)))

    # 3ème convolution optionnelle
    if nb_conv == 3:
        model.add(Conv2D(64, (3,3), activation='relu'))
        model.add(MaxPooling2D((2,2)))

    # Passage en vecteur et couches denses pour la classification
```

```
    model.add(Flatten())
    model.add(Dense(128, activation='relu'))
    model.add(Dropout(0.5))
    model.add(Dense(10, activation='softmax'))  # 10 classes (0..9)

    # Compilation du modele
    model.compile(
        optimizer='adam',
        loss='categorical_crossentropy',
        metrics=['accuracy']
    )

    return model
```

In [17]:
```
# Fonctions pour recuperer l'utilisation du CPU, de la RAM et du GPU pendant l'e
def get_cpu_ram():
    cpu_percent = psutil.cpu_percent(interval=1)
    ram = psutil.virtual_memory()
    ram_used_mb = ram.used / (1024 ** 2)
    return cpu_percent, ram_used_mb

def get_gpu_stats():
    try:
        gpus = GPUtil.getGPUs()
        if not gpus:
            return None, None, None
        gpu = gpus[0]
        return gpu.load * 100, gpu.memoryUsed, gpu.memoryTotal
    except:
        return None, None, None
```

In [18]:
```
# Callback pour afficher le temps et l'utilisation des ressources
# + fonction pour creer les callbacks (early stopping et sauvegarde des meilleur
class PerformanceCallback(Callback):
    def on_epoch_begin(self, epoch, logs=None):
        self.start_time = time.time()

    def on_epoch_end(self, epoch, logs=None):
        cpu, ram = get_cpu_ram()
        gpu, vram_used, vram_total = get_gpu_stats()
        duration = time.time() - self.start_time

        msg = f" | CPU: {cpu:.1f}% | RAM: {ram:.0f} MB | Time: {duration:.1f}s"
        if gpu is not None:
            msg += f" | GPU: {gpu:.1f}% | VRAM: {vram_used}/{vram_total} MB"
        print(msg)


def get_callbacks(nb_conv):
    # Creation du dossier pour stocker les poids du modele
    ckpt_dir = f"checkpoints_mnist_cnn_{nb_conv}"
    os.makedirs(ckpt_dir, exist_ok=True)

    # Sauvegarde des meilleurs poids selon la validation
    checkpoint = ModelCheckpoint(
        filepath=os.path.join(ckpt_dir, "weights_epoch_{epoch:02d}.h5"),
        monitor="val_accuracy",
        save_weights_only=True,
        save_best_only=True,
```

```
        verbose=1
    )

    # Early stopping pour arreter l'entrainement si la validation n'amelior plus
    early_stop = EarlyStopping(
        monitor="val_accuracy",
        patience=5,
        restore_best_weights=True,
        verbose=1
    )

    return checkpoint, early_stop, ckpt_dir
```

In [19]:
```
# Creation et entrainement du modele CNN a 2 convolutions sur le dataset MNIST
model_2 = build_cnn(nb_conv=2)
checkpoint, early_stop, ckpt_dir = get_callbacks(2)

history_2 = model_2.fit(
    x_train, y_train_cat,
    batch_size=BATCH_SIZE,
    epochs=EPOCHS,
    validation_data=(x_test, y_test_cat),
    callbacks=[checkpoint, early_stop, PerformanceCallback()],
    verbose=1
)
```

```
Epoch 1/20
1871/1875 [============================>.] - ETA: 0s - loss: 0.2265 - accuracy:
0.9303
Epoch 1: val_accuracy improved from -inf to 0.98330, saving model to checkpoints_
mnist_cnn_2\weights_epoch_01.h5
 | CPU: 2.6% | RAM: 15916 MB | Time: 11.8s | GPU: 4.0% | VRAM: 846.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.2262 - accura
cy: 0.9304 - val_loss: 0.0496 - val_accuracy: 0.9833
Epoch 2/20
1869/1875 [============================>.] - ETA: 0s - loss: 0.0858 - accuracy:
0.9747
Epoch 2: val_accuracy improved from 0.98330 to 0.98630, saving model to checkpoin
ts_mnist_cnn_2\weights_epoch_02.h5
 | CPU: 4.7% | RAM: 15972 MB | Time: 11.5s | GPU: 5.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0856 - accura
cy: 0.9748 - val_loss: 0.0387 - val_accuracy: 0.9863
Epoch 3/20
1869/1875 [============================>.] - ETA: 0s - loss: 0.0643 - accuracy:
0.9807
Epoch 3: val_accuracy improved from 0.98630 to 0.98870, saving model to checkpoin
ts_mnist_cnn_2\weights_epoch_03.h5
 | CPU: 2.3% | RAM: 15959 MB | Time: 11.7s | GPU: 5.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0643 - accura
cy: 0.9808 - val_loss: 0.0340 - val_accuracy: 0.9887
Epoch 4/20
1874/1875 [============================>.] - ETA: 0s - loss: 0.0525 - accuracy:
0.9841
Epoch 4: val_accuracy did not improve from 0.98870
 | CPU: 1.2% | RAM: 15973 MB | Time: 11.6s | GPU: 10.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0525 - accura
cy: 0.9841 - val_loss: 0.0323 - val_accuracy: 0.9886
Epoch 5/20
1868/1875 [============================>.] - ETA: 0s - loss: 0.0456 - accuracy:
0.9865
Epoch 5: val_accuracy improved from 0.98870 to 0.99120, saving model to checkpoin
ts_mnist_cnn_2\weights_epoch_05.h5
 | CPU: 3.1% | RAM: 16017 MB | Time: 11.6s | GPU: 4.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0457 - accura
cy: 0.9864 - val_loss: 0.0267 - val_accuracy: 0.9912
Epoch 6/20
1870/1875 [============================>.] - ETA: 0s - loss: 0.0381 - accuracy:
0.9886
Epoch 6: val_accuracy did not improve from 0.99120
 | CPU: 2.4% | RAM: 15995 MB | Time: 11.7s | GPU: 2.0% | VRAM: 846.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0382 - accura
cy: 0.9886 - val_loss: 0.0281 - val_accuracy: 0.9907
Epoch 7/20
1868/1875 [============================>.] - ETA: 0s - loss: 0.0340 - accuracy:
0.9894
Epoch 7: val_accuracy improved from 0.99120 to 0.99240, saving model to checkpoin
ts_mnist_cnn_2\weights_epoch_07.h5
 | CPU: 1.6% | RAM: 16013 MB | Time: 11.6s | GPU: 3.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0340 - accura
cy: 0.9894 - val_loss: 0.0257 - val_accuracy: 0.9924
Epoch 8/20
1867/1875 [============================>.] - ETA: 0s - loss: 0.0307 - accuracy:
0.9904
Epoch 8: val_accuracy did not improve from 0.99240
 | CPU: 1.7% | RAM: 16013 MB | Time: 11.5s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0306 - accura
```

```
cy: 0.9905 - val_loss: 0.0254 - val_accuracy: 0.9916
Epoch 9/20
1868/1875 [============================>.] - ETA: 0s - loss: 0.0267 - accuracy:
0.9917
Epoch 9: val_accuracy did not improve from 0.99240
 | CPU: 2.5% | RAM: 16020 MB | Time: 11.5s | GPU: 6.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0268 - accura
cy: 0.9916 - val_loss: 0.0284 - val_accuracy: 0.9919
Epoch 10/20
1872/1875 [============================>.] - ETA: 0s - loss: 0.0244 - accuracy:
0.9916
Epoch 10: val_accuracy did not improve from 0.99240
 | CPU: 3.1% | RAM: 16024 MB | Time: 11.7s | GPU: 6.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0244 - accura
cy: 0.9916 - val_loss: 0.0296 - val_accuracy: 0.9905
Epoch 11/20
1872/1875 [============================>.] - ETA: 0s - loss: 0.0207 - accuracy:
0.9936
Epoch 11: val_accuracy did not improve from 0.99240
 | CPU: 1.3% | RAM: 15995 MB | Time: 11.6s | GPU: 6.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0208 - accura
cy: 0.9936 - val_loss: 0.0258 - val_accuracy: 0.9922
Epoch 12/20
1873/1875 [============================>.] - ETA: 0s - loss: 0.0217 - accuracy:
0.9930
Epoch 12: val_accuracy improved from 0.99240 to 0.99280, saving model to checkpoi
nts_mnist_cnn_2\weights_epoch_12.h5
 | CPU: 3.1% | RAM: 16011 MB | Time: 11.7s | GPU: 3.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0217 - accura
cy: 0.9930 - val_loss: 0.0251 - val_accuracy: 0.9928
Epoch 13/20
1866/1875 [============================>.] - ETA: 0s - loss: 0.0187 - accuracy:
0.9935
Epoch 13: val_accuracy did not improve from 0.99280
 | CPU: 2.0% | RAM: 15996 MB | Time: 11.6s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0187 - accura
cy: 0.9935 - val_loss: 0.0276 - val_accuracy: 0.9920
Epoch 14/20
1867/1875 [============================>.] - ETA: 0s - loss: 0.0183 - accuracy:
0.9941
Epoch 14: val_accuracy did not improve from 0.99280
 | CPU: 2.7% | RAM: 15999 MB | Time: 11.6s | GPU: 6.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0183 - accura
cy: 0.9941 - val_loss: 0.0257 - val_accuracy: 0.9921
Epoch 15/20
1866/1875 [============================>.] - ETA: 0s - loss: 0.0167 - accuracy:
0.9946
Epoch 15: val_accuracy did not improve from 0.99280
 | CPU: 1.9% | RAM: 16008 MB | Time: 11.7s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0167 - accura
cy: 0.9946 - val_loss: 0.0279 - val_accuracy: 0.9922
Epoch 16/20
1866/1875 [============================>.] - ETA: 0s - loss: 0.0166 - accuracy:
0.9946
Epoch 16: val_accuracy improved from 0.99280 to 0.99300, saving model to checkpoi
nts_mnist_cnn_2\weights_epoch_16.h5
 | CPU: 1.2% | RAM: 15963 MB | Time: 11.7s | GPU: 1.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0165 - accura
cy: 0.9947 - val_loss: 0.0286 - val_accuracy: 0.9930
Epoch 17/20
```

```
1875/1875 [==============================] - ETA: 0s - loss: 0.0160 - accuracy:
0.9948
Epoch 17: val_accuracy did not improve from 0.99300
 | CPU: 3.1% | RAM: 15966 MB | Time: 11.6s | GPU: 6.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0160 - accura
cy: 0.9948 - val_loss: 0.0327 - val_accuracy: 0.9921
Epoch 18/20
1872/1875 [============================>.] - ETA: 0s - loss: 0.0143 - accuracy:
0.9955
Epoch 18: val_accuracy did not improve from 0.99300
 | CPU: 3.0% | RAM: 15979 MB | Time: 11.7s | GPU: 4.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0143 - accura
cy: 0.9955 - val_loss: 0.0347 - val_accuracy: 0.9928
Epoch 19/20
1867/1875 [============================>.] - ETA: 0s - loss: 0.0152 - accuracy:
0.9950
Epoch 19: val_accuracy did not improve from 0.99300
 | CPU: 2.9% | RAM: 15961 MB | Time: 11.6s | GPU: 5.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0152 - accura
cy: 0.9950 - val_loss: 0.0283 - val_accuracy: 0.9929
Epoch 20/20
1875/1875 [==============================] - ETA: 0s - loss: 0.0129 - accuracy:
0.9956
Epoch 20: val_accuracy did not improve from 0.99300
 | CPU: 2.2% | RAM: 15941 MB | Time: 11.6s | GPU: 4.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0129 - accura
cy: 0.9956 - val_loss: 0.0321 - val_accuracy: 0.9919
```

In [20]:

```python
# Creation et entrainement du modele CNN a 3 convolutions sur le dataset MNIST
model_3 = build_cnn(nb_conv=3)
checkpoint, early_stop, ckpt_dir = get_callbacks(3)

history_3 = model_3.fit(
    x_train, y_train_cat,
    batch_size=BATCH_SIZE,
    epochs=EPOCHS,
    validation_data=(x_test, y_test_cat),
    callbacks=[checkpoint, early_stop, PerformanceCallback()],
    verbose=1
)
```

```
Epoch 1/20
1868/1875 [============================>.] - ETA: 0s - loss: 0.2999 - accuracy:
0.9080
Epoch 1: val_accuracy improved from -inf to 0.97490, saving model to checkpoints_
mnist_cnn_3\weights_epoch_01.h5
 | CPU: 2.9% | RAM: 16021 MB | Time: 12.1s | GPU: 3.0% | VRAM: 846.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.2994 - accura
cy: 0.9081 - val_loss: 0.0834 - val_accuracy: 0.9749
Epoch 2/20
1875/1875 [==============================] - ETA: 0s - loss: 0.1054 - accuracy:
0.9703
Epoch 2: val_accuracy improved from 0.97490 to 0.97860, saving model to checkpoin
ts_mnist_cnn_3\weights_epoch_02.h5
 | CPU: 2.4% | RAM: 16029 MB | Time: 11.7s | GPU: 3.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.1054 - accura
cy: 0.9703 - val_loss: 0.0747 - val_accuracy: 0.9786
Epoch 3/20
1875/1875 [==============================] - ETA: 0s - loss: 0.0783 - accuracy:
0.9777
Epoch 3: val_accuracy improved from 0.97860 to 0.98150, saving model to checkpoin
ts_mnist_cnn_3\weights_epoch_03.h5
 | CPU: 2.2% | RAM: 16061 MB | Time: 11.8s | GPU: 5.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0783 - accura
cy: 0.9777 - val_loss: 0.0603 - val_accuracy: 0.9815
Epoch 4/20
1872/1875 [============================>.] - ETA: 0s - loss: 0.0639 - accuracy:
0.9811
Epoch 4: val_accuracy improved from 0.98150 to 0.98620, saving model to checkpoin
ts_mnist_cnn_3\weights_epoch_04.h5
 | CPU: 2.0% | RAM: 16021 MB | Time: 11.9s | GPU: 4.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0639 - accura
cy: 0.9811 - val_loss: 0.0451 - val_accuracy: 0.9862
Epoch 5/20
1872/1875 [============================>.] - ETA: 0s - loss: 0.0513 - accuracy:
0.9849
Epoch 5: val_accuracy did not improve from 0.98620
 | CPU: 2.6% | RAM: 16027 MB | Time: 11.8s | GPU: 3.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0515 - accura
cy: 0.9849 - val_loss: 0.0534 - val_accuracy: 0.9857
Epoch 6/20
1867/1875 [============================>.] - ETA: 0s - loss: 0.0459 - accuracy:
0.9862
Epoch 6: val_accuracy improved from 0.98620 to 0.98780, saving model to checkpoin
ts_mnist_cnn_3\weights_epoch_06.h5
 | CPU: 2.5% | RAM: 16054 MB | Time: 12.0s | GPU: 4.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0457 - accura
cy: 0.9862 - val_loss: 0.0418 - val_accuracy: 0.9878
Epoch 7/20
1872/1875 [============================>.] - ETA: 0s - loss: 0.0416 - accuracy:
0.9881
Epoch 7: val_accuracy did not improve from 0.98780
 | CPU: 2.5% | RAM: 16054 MB | Time: 11.7s | GPU: 3.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0415 - accura
cy: 0.9882 - val_loss: 0.0516 - val_accuracy: 0.9872
Epoch 8/20
1874/1875 [============================>.] - ETA: 0s - loss: 0.0359 - accuracy:
0.9891
Epoch 8: val_accuracy did not improve from 0.98780
 | CPU: 1.6% | RAM: 16023 MB | Time: 11.7s | GPU: 1.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0358 - accura
```

```
cy: 0.9891 - val_loss: 0.0591 - val_accuracy: 0.9850
Epoch 9/20
1870/1875 [============================>.] - ETA: 0s - loss: 0.0332 - accuracy:
0.9900
Epoch 9: val_accuracy improved from 0.98780 to 0.98820, saving model to checkpoin
ts_mnist_cnn_3\weights_epoch_09.h5
 | CPU: 2.2% | RAM: 16041 MB | Time: 11.8s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0332 - accura
cy: 0.9900 - val_loss: 0.0461 - val_accuracy: 0.9882
Epoch 10/20
1875/1875 [==============================] - ETA: 0s - loss: 0.0295 - accuracy:
0.9911
Epoch 10: val_accuracy did not improve from 0.98820
 | CPU: 2.1% | RAM: 16085 MB | Time: 11.8s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0295 - accura
cy: 0.9911 - val_loss: 0.0512 - val_accuracy: 0.9877
Epoch 11/20
1875/1875 [==============================] - ETA: 0s - loss: 0.0248 - accuracy:
0.9923
Epoch 11: val_accuracy improved from 0.98820 to 0.98940, saving model to checkpoi
nts_mnist_cnn_3\weights_epoch_11.h5
 | CPU: 2.3% | RAM: 16047 MB | Time: 11.8s | GPU: 5.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0248 - accura
cy: 0.9923 - val_loss: 0.0537 - val_accuracy: 0.9894
Epoch 12/20
1875/1875 [==============================] - ETA: 0s - loss: 0.0249 - accuracy:
0.9925
Epoch 12: val_accuracy did not improve from 0.98940
 | CPU: 2.7% | RAM: 16059 MB | Time: 11.7s | GPU: 3.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0249 - accura
cy: 0.9925 - val_loss: 0.0497 - val_accuracy: 0.9867
Epoch 13/20
1869/1875 [============================>.] - ETA: 0s - loss: 0.0222 - accuracy:
0.9929
Epoch 13: val_accuracy did not improve from 0.98940
 | CPU: 1.6% | RAM: 16057 MB | Time: 11.7s | GPU: 3.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0222 - accura
cy: 0.9929 - val_loss: 0.0511 - val_accuracy: 0.9885
Epoch 14/20
1871/1875 [============================>.] - ETA: 0s - loss: 0.0199 - accuracy:
0.9936
Epoch 14: val_accuracy did not improve from 0.98940
 | CPU: 1.3% | RAM: 16051 MB | Time: 11.6s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0199 - accura
cy: 0.9936 - val_loss: 0.0580 - val_accuracy: 0.9885
Epoch 15/20
1870/1875 [============================>.] - ETA: 0s - loss: 0.0202 - accuracy:
0.9942
Epoch 15: val_accuracy did not improve from 0.98940
 | CPU: 1.3% | RAM: 16039 MB | Time: 11.6s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0202 - accura
cy: 0.9942 - val_loss: 0.0570 - val_accuracy: 0.9885
Epoch 16/20
1874/1875 [============================>.] - ETA: 0s - loss: 0.0179 - accuracy:
0.9944
Epoch 16: val_accuracy did not improve from 0.98940
Restoring model weights from the end of the best epoch: 11.
 | CPU: 2.2% | RAM: 16000 MB | Time: 11.6s | GPU: 2.0% | VRAM: 794.0/16303.0 MB
1875/1875 [==============================] - 12s 6ms/step - loss: 0.0181 - accura
```

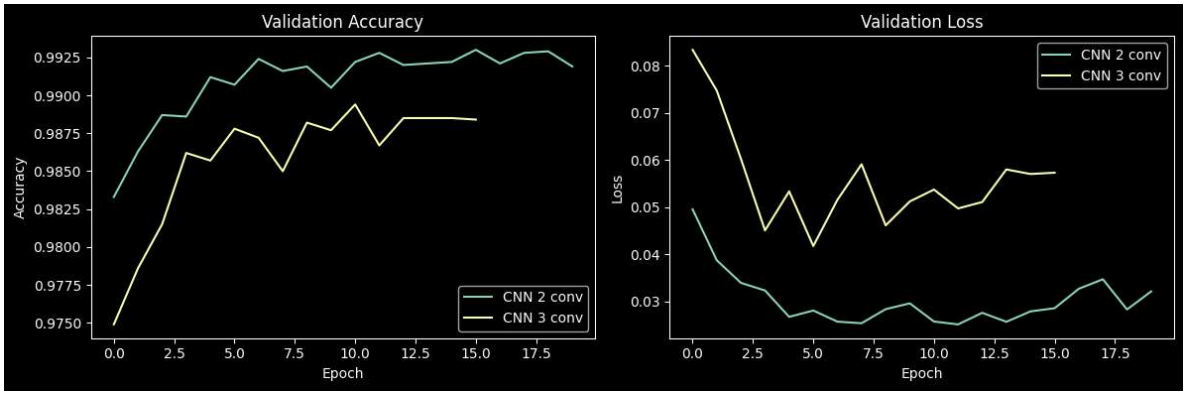
```
cy: 0.9944 - val_loss: 0.0573 - val_accuracy: 0.9884
Epoch 16: early stopping
```

In [21]:
```python
plt.figure(figsize=(12,4))

plt.subplot(1,2,1)
plt.plot(history_2.history["val_accuracy"], label="CNN 2 conv")
plt.plot(history_3.history["val_accuracy"], label="CNN 3 conv")
plt.title("Validation Accuracy")
plt.xlabel("Epoch")
plt.ylabel("Accuracy")
plt.legend()

plt.subplot(1,2,2)
plt.plot(history_2.history["val_loss"], label="CNN 2 conv")
plt.plot(history_3.history["val_loss"], label="CNN 3 conv")
plt.title("Validation Loss")
plt.xlabel("Epoch")
plt.ylabel("Loss")
plt.legend()

plt.tight_layout()
plt.show()
```



Conclusion

L'entraînement des deux architectures convolutionnelles sur le dataset MNIST met en évidence un comportement différent de celui observé sur les datasets d'images plus complexes. Dans ce cas, les deux modèles atteignent des performances très élevées, mais l'augmentation de la profondeur du réseau n'apporte pas d'amélioration significative.

CNN à 2 convolutions :

- Précision maximale sur l'ensemble de validation : 99,30 % (epoch 16)
- Perte de validation minimale : ≈ 0,025
- Entraînement stable sur 20 epochs, avec des performances très élevées dès les premières itérations

CNN à 3 convolutions :

- Précision maximale sur l'ensemble de validation : 98,94 % (epoch 11)
- Perte de validation minimale : ≈ 0,042
- Early stopping déclenché à l'epoch 16, meilleur modèle restauré à l'epoch 11

Les courbes de précision et de perte de validation montrent que le CNN à 2 convolutions converge plus rapidement et atteint une précision légèrement supérieure à celle du CNN à 3 convolutions. Sur ce dataset simple et bien structuré, l'ajout d'une couche convolutionnelle supplémentaire n'améliore pas la généralisation du modèle et peut même introduire une complexité inutile.

Ainsi, contrairement aux résultats obtenus sur les deux autre dataset, précédent, le modèle le plus simple (CNN à 2 convolutions) est ici le plus efficace. Cela confirme que le choix de l'architecture doit être adapté à la complexité du dataset, et qu'un réseau plus profond n'est pas systématiquement synonyme de meilleures performances.

Sur MNIST, les deux entraînements sont très légers côté ressources : CPU ~1–5%, RAM ~15,9–16,1 Go, VRAM ~794–846 Mo, et GPU ~1–10% (avec un pic à 10% sur le modèle 2 conv). Chaque epoch dure ~11,5–12 s. En perf, le 2 conv atteint une val_accuracy max = 0,9930 (99,30%) vers l'epoch 16, tandis que le 3 conv monte à 0,9894 (98,94%) (meilleur epoch 11, puis early stopping à 16). Donc ici, le 2 conv est légèrement meilleur, tout en gardant une consommation CPU/GPU/RAM/VRAM comparable au 3 conv.

In [21]: