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Chunk formation in immediate memory and how it relates to data compression

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ABSTRACT

This paper attempts to evaluate the capacity of immediate memory to cope with new situations in relation to the compressibility of information likely to allow the formation of chunks. We constructed a task in which untrained participants had to immediately recall sequences of stimuli with possible associations between them. Compressibility of information was used to measure the chunkability of each sequence on a single trial. Compressibility refers to the recoding of information in a more compact representation. Although compressibility has almost exclusively been used to study long-term memory, our theory suggests that a compression process relying on redundancies within the structure of the list materials can occur very rapidly in immediate memory. The results indicated a span of about three items when the list had no structure, but increased linearly as structure was added. The amount of information retained in immediate memory was maximal for the most compressible sequences, particularly when information was ordered in a way that facilitated the compression process. We discuss the role of immediate memory in the rapid formation of chunks made up of new associations that did not already exist in long-term memory, and we conclude that immediate memory is the starting place for the reorganization of information.

1. Introduction

Individuals have a tendency to make information easier to retain by recoding it into chunks (e.g., Cowan et al., 2004). The process of chunking simplifies memorization by taking advantage of knowledge to reduce the quantity of information to be retained (Miller, 1956). As a key learning mechanism, chunking (or grouping) has had considerable impact on the study of expertise (e.g., Chase and Simon, 1973; Ericsson et al., 1980; Hu and Ericsson, 2012), immediate recall (e.g., Chen and Cowan, 2005; Farrell et al., 2011), and memory development (e.g., Cowan et al., 2010; Gilchrist et al., 2009).

For chunking to benefit memory, people need to be able to retrieve the chunks they stored. One way people retrieve chunks is via long-term memory processes (French et al., 2011; Gobet et al., 2001; Guida et al., 2012; Reder et al., in press). Consider the letter string IBMCIAFBI. As Miller discussed, this letter string can be easily simplified to form three chunks if one uses long-term memory to recall the U.S. agencies (Miller, 1956) whose acronyms are IBM, CIA, and FBI.

Previous work on chunking has focused on how long-term memory aids chunk creation. However, immediate memory might also play a fundamental role in the creation of chunks. People may form chunks in immediate memory by rapidly encoding patterns before any consolidation in long-term memory occurs. For example, it is easy to remember the letter string AQAQAQ using a simple rule of repetition (e.g., AQ three times). This type of simplification does not necessarily depend on the use of long-term memory to recall past knowledge that relates items to each other.[1] Instead, this process depends on the apprehension of regularities inherent to the stimulus at hand, i.e., compression.

This idea that immediate memory might play a fundamental role in the creation of chunks has generally been overlooked. Some previous findings are consistent with the proposal that chunks can increase memory capacity (Brady et al., 2009; Feigenson and Halberda, 2008). However, these studies have mostly focused on how long-term-memory representations contribute to encoding

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[1] Long-term memory is needed to retrieve the individual items (e.g., A, Q, ×, and 3), but it is not needed to retrieve combinations of them.

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in immediate memory. In contrast, our goal is to provide a principled quantitative approach to how immediate memory relates to the formation of chunks. Getting a larger picture of chunking as a process originating in immediate memory needs a precise conceptualization, and the concept of compressibility could help in doing so.

We propose a two-factor theory of the formation of chunks in immediate memory. The first factor is compressibility (i.e., the idea that a more compact representation can be used to recode information in a lossless fashion[2]). Compressibility could predict chunking because it measures the degree to which the material is patterned, and hence the degree to which the material can be simplified. Memory for compressible sequences should be superior to memory for non-compressible sequences (the same way that studies in the domain of categorization have shown that compressible material is better learned over the long term; see Feldman (2000)).

The second factor is the order of the information to memorize. Presentation order might influence the ease with which patterns or regularities in the stimuli can be discovered, and compression algorithms typically depend on this kind of information. A presentation order that aligns with the process of simplifying the material may increase the likelihood that chunking occurs. In contrast, presentation orders that do not aid in the discovery of regularities, might result in failure to chunk compressible materials, causing them to be remembered in a way similar to non-compressible materials. Presentation order should therefore interact with compressibility. As a simple example, one can compress the set "2, 3, 4, 5, 6" with the rule, "all numbers between 2 and 6", whereas with the series "2, 4, 6, 3, 5", that same rule might not be noticed by the participant, so compression might not take place.

This two-factor theory is adapted from the domain of categorization, which has provided a framework for studying category formation in long-term memory, with explanations based on the compressibility of descriptions (Bradmetz and Mathy, 2008; Feldman, 2000, 2003; Goodwin and Johnson-Laird, 2013; Lafond et al., 2007; Vigo, 2006) using different types of presentation orders (based on rules, similarity, or dissimilarity; see Elio and Anderson (1981, 1984), Gagné (1950), Mathy and Feldman (2009) and Medin and Bettger (1994)). This framework nicely accounts for a wide range of categorization performance in long-term memory, but could in principle provide similar predictions for immediate memory. Our theory is that a compression model (e.g., Feldman, 2000) can be adapted to immediate memory. The rationale is that elementary structures, i.e., the redundancies that make a structure compressible, are simple enough to be used rapidly in immediate memory to cope with new situations.

We conducted an experiment to test the proposal outlined above, namely, that chunk formation occurs in immediate memory to optimize capacity before any consolidation process in long-term memory occurs. Our prediction is that immediate-memory span is proportional to stimulus compressibility, but only when the order of the information allows the participant to spontaneously detect redundancies such as pairs of similar features.

In the Discussion, we provide ample evidence that there are two major classes of concurrent models that cannot provide correct predictions for our results. The first class is Interference-based models of short-term memory, which predict poorer performance when participants see sequences containing similar features, whereas our model predicts that participants can take advantage of these similarities to compress information. The second class includes the minimal description length (MDL) approaches to long-term memory, which rely on the repetition of trials, and as such, offer no predictions about the compression process at play in our task.

2. Method

Two key aspects were investigated in the present experiment: compressibility of a sequence and presentation order within a sequence. These two factors were studied using categorizable multi-dimensional objects, with discrete features, such as small green spiral, large green spiral, small red square. The sequences used could not conform to already-learned chunks. Although the features themselves are part of basic knowledge, we are reasonably confident, for instance, that none of our participants had the exact sequence of items "a small green spiral followed by a large purple pentagon and a small yellow pentagon" in long-term memory before starting our experiment. The procedure used a serial recall task, which allowed to study the incremental encoding of chunks. The duration of the display of the memory items and the number of memory items were two other manipulated factors we thought would help us look into the incremental encoding of the chunks.

2.1. Participants

Sixty-seven students enrolled at the University of Franche-Comté, $M = 22$ years old ($sd = 2.7$), volunteered to participate in the experiment.

2.2. Stimuli

Our stimuli could vary according to three dimensions: shape, size and color. A combination of two shapes, colors, and sizes makes a set of eight different objects. There were eight different values for the shape dimension and the color dimension (Fig. 1, top panel). However, we restricted the size dimension to two values (large *vs.* small, or 280×280 pixels *vs.* 140×140 pixels). Shape, size and color are typically used by category learning researchers to build canonical stimulus sets because these dimensions can be easily and clearly partitioned.

For a given sequence, the program randomly chose two out of eight shapes and two out of eight colors (see Fig. 1, top panel), in order to create a set of eight objects. For example, if the values "triangle", "square", "white", and "black" were drawn, the program generated $2 \times 2 \times 2 = 8$ stimuli by combining three features for each stimulus (e.g., small white triangle, large white triangle, ..., large black square). These values allowed for 1568 possible sets of eight objects, so that the probability of a participant coming across two identical sets during the experiment would be very low. The stimuli were presented against a gray background.

2.3. Categories

We selected different categories of objects, which were to be displayed and recalled serially. An example is the sequence □ ■ □ ■ △ ▲, which can be represented by six individual exemplars (i.e., large white square, large black square, small white square, small black square, small white triangle, and small black triangle). Following Feldman (2000), this sequence can be redescribed accurately by a shorter logical rule provided that order does not matter ('squares or small', using inclusive disjunction, or 'not[large and triangle]' using conjunction, which by de Morgan's law are equivalent). Another example is the sequence ■ ▲ □ △ ('small black square, small black triangle, small white square, small white triangle'), which can be simplified by abstracting the feature common to

[2] By this, we mean a compression process without loss of information (the original data can be accurately reconstructed from the compressed data), and not a "lossy" form of compression (which brings to mind many of the applications in information technology used today to achieve a more substantial reduction of data); see Li and Vitányi (1997).