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Precursors to Chunking Vanish when Working Memory Capacity is Exceeded

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ABSTRACT

Free recall of 500 Russian college students was measured using the Tarnow Unchunkable Test consisting of sets of 3 and 4 double digit items. The average working memory capacity is exceeded with four items. In the three item test, even though items were constructed to be unchunkable, there were asymmetric associations: recalling item N was more sensitive to whether item N-1 is recalled than the other way around. These asymmetric associations are presumably precursors of learning. The asymmetric associations between items 1 and 2 and items 2 and 3 were similar. As the working memory capacity is exceeded in the four item test, the asymmetric association for the subject group halved from item 1 to item 2 (p=0.32) and disappeared completely from items 2 to 3 (large effect size: η2=0.79, p=0.001) and from items 3 to 4. This finding suggests that if asymmetric associations are precursors to learning, it may be important to not overload working memory during learning; this may be of importance for design of textbooks and other teaching tools. The symmetric associations allow us to separate out the importance of attention. These stays the same roughly the same with trial and with increases from 3 to 4 items and were a little larger than 0.3. This also suggests that attention, presumably extending over three TUT items, is not the major factor limiting the symmetric associations (if it were, the symmetric associations should be close to 1). The removal of asymmetric associations does not manifest itself in the output order: it is usually the same as the display order. Thus asymmetric associations ("chaining order") do not constitute memory for order.

Keywords: Memory Binding, Learning, Free Recall, Working Memory Capacity, Forward Associations

INTRODUCTION

"Theorizing at this stage is like skating on thin ice - keep moving, or drown" [1,2].

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Aristotle and the British Empiricists assumed that the human brain starts out as a tabula rasa (blank slate) and that, among the acquired content, contiguous stimuli create associations; this is referred to as the Law of Contiguity [3,4].

The brain contains a hundred billion neurons yet our working memory capacity (WMC) is limited to 3-7 items [5,6] and citations therein and thereof). If the reader attempts to remember four unrelated double digit integers after a single visual exposure [1]) it is very probable that one of the integers vanishes, no matter how hard the reader tries; a partial destruction of the memories occurs as the fourth item is added [7].

Working memory is not that well defined (it did originate in a flawed attempt to compare the human brain to the workings of a computer) but it is thought of consisting of currently activated long term memories, the difference between working memory and short term memory is not clear, indeed there might not be any [8]. Nevertheless, whether it is short term memory or working memory there is a limit on how many new items can be remembered at any one time, without using the method of loci (in which case short term memory can be drastically improved [9], and it is often thought to be 3-7 similar items for the majority of people (not rare examples such as described in [10]). The limited WMC is presumably important when learning perhaps for elaboration of the items to be remembered - elaboration being one way of enhancing the probability of an item becoming a long term memory. (Textbooks might be designed more efficiently with this limit in mind, contrary to the modern tendency of a multitude of colors, fonts and focus points on each page.)

Here we report the results of a very simple, well-defined experiment on working memory capacity using relatively unchunkable double-digit integers [1]. We have previously published the working memory structure used for TUT showing that integers are stored in base 10 representations and that rather than slots, working memory may consist of pointers [11]. We also investigated the interference from the fourth item and found that the mechanism was not displacement of an item by a subsequent item but rather the destruction of the item memories [7] and other results remain to be published. In this contribution we will discuss the interdependencies of the working memory items.

There are several types of interdependencies of recalled items. The simplest one is the correlation between the various items: if one item is recalled, the correlation tells you whether the other item will be recalled and vice versa. The simplest form of learning should include some correlation between the various items. However, if somebody remembers all the items on one list and none of the items on another list, this correlation may only indicate that attention was paid to the first list but not to the second list. Beyond simple item-item correlations, which we refer to as symmetric associations, we also investigate asymmetric associations: i.e. whether remembering one item makes it more likely to remember another item than vice versa. These asymmetric associations would seem to be precursors to forming "chunks" between the items. If one wants to measure the potential of forming chunks it is then necessary to have a symmetric association between the items but not sufficient; an asymmetric association is both necessary and sufficient.

In this contribution we will examine how the limited WMC impacts the symmetric and asymmetric associations between displayed items after single exposures to the item lists.

Previous work on inter-item associations in free recall has been focused on static associations, i.e. the probability of one item eliciting another as a free associate (see [12] and citations thereof), on fMRI studies of recognition probes of dynamic associations uncovering correlations between activity of different brain structures and current inter-item associations (see, for example, [13]). Here we will examine averages of dynamic associations created by the items (double digit integers without any obvious relationships) appearing in the displayed list and probed indirectly by free recall. In particular, we are going to examine the size of these associations as WMC is exceeded.

METHOD

We present data from a study of university students aged 17 to 24.

The Tarnow Unchunkable Test (TUT) used in this study separates out the working memory (WM) component of free recall by using particular double-digit combinations which lack intra-item relationships [1]. It does not contain any explicit WM operations. The TUT was given via the internet using client-based JAVAScript to eliminate any network delays. The instructions and the memory items were displayed in the middle of the screen. Items were displayed for two seconds without pause. The trials consisted of 3 or 4 items after which the subject was asked to enter each number remembered separately, press the keyboard enter button between each

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entry and repeat until all the numbers remembered had been entered. Pressing the enter button without any number was considered a "no entry". The next trial started immediately after the last entry or after a "no entry". There was no time limit for number entry. Each subject was given six three item trials and three four item trials in which the items are particular double-digit integers.

For each consecutive pair of items, we calculate two associations:

Forward association= probability that item N+1 is recalled given that item N is recalled - probability that item N+1 is recalled given item N is not recalled.

Backward association= probability that item N is recalled given that item N+1 is recalled - probability that item N is recalled given item N+1 is not recalled.

We define Symmetric association=Average (Forward association, Backward association) and Asymmetric association=Forward association – Backward association.

Note that in our experiment the items are overwhelmingly recalled in order.

Sample

500 Russian undergraduate students of the State University of Humanities and Social Studies (121 (63%) females and 71 (37%) males, mean age was 18.8 years) participated in the study for extra credit. Each participant was tested individually in a quiet room. An experimenter was present throughout each session.

One record was discarded – the student had only responded once out of a possible thirty times.

In this result we do not report the results of the first trial.

RESULTS

The values of the symmetric and asymmetric associations for the 3-item and 4-item tests are displayed in Figure 1. While the average symmetric association is similar for both the 3-item and 4-item tests (ANOVA yields p=0.61 for item 1 to item 2 and p=0.76 for item 2 to item 3), the asymmetric association is much larger in the 3-item test than in the 4-item test: the asymmetric association is halved from item 1 to item 2 (however p=0.32) and disappears completely from items 2 to 3 (large effect size: $\eta 2=0.79$, $p=0.001$) and from items 3 to 4. As we would have hoped, the asymmetric associations are positive, i.e. they go in the forward direction.

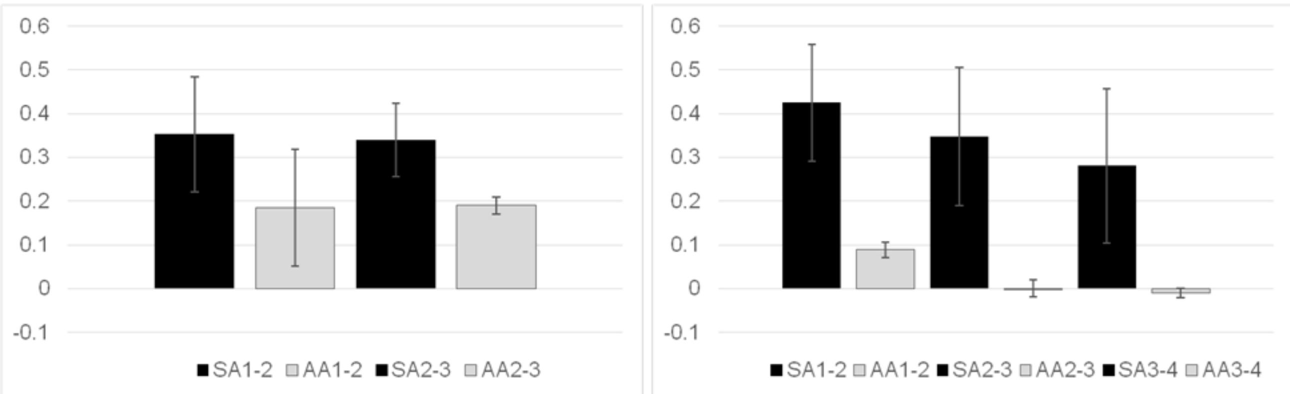

Figure 1. Symmetric association and asymmetric association for the 3-item (left) and 4-item (right) tests. SAM-N indicates the symmetric association between items M and N; AAM-N indicates the asymmetric association between items M and N. The error bars are the standard deviation of the results for the different trials.

The trial by trial symmetric and asymmetric associations for the 3-item and 4-item tests are displayed in Figure 2.

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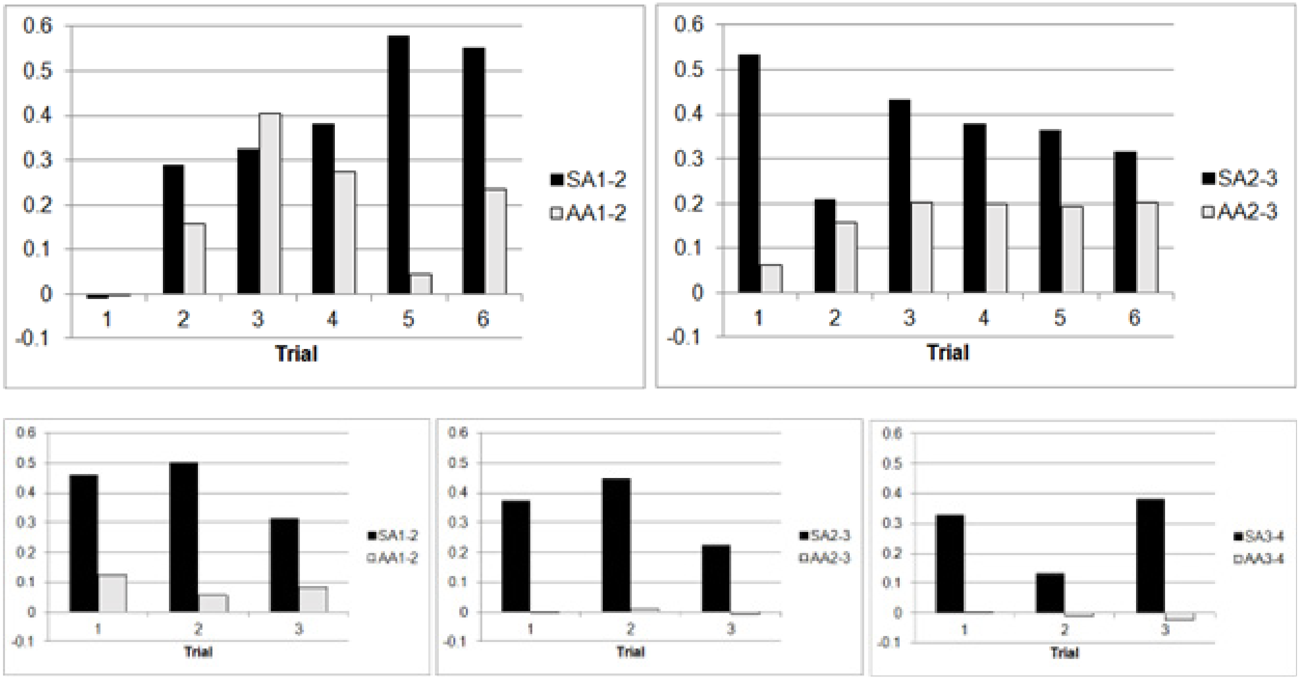

Figure 2. Symmetric and asymmetric association for the six 3-item trials for items 1 and 2 (upper left) and items 2 and 3 (upper right); for the three 4-item trials for items 1 and 2 (lower left), items 2 and 3 (lower center) and items 3 and 4 (lower right).

If the asymmetric association disappears, does that mean the memory for item order disappears? In Figure 3 is displayed the output order of subsequently displayed items. Display order is defined as +1 and reverse display order is -1. The graph shows that the vast majority of items are displayed in order, even for items 2-3 and 3-4 in the 4-item trials.

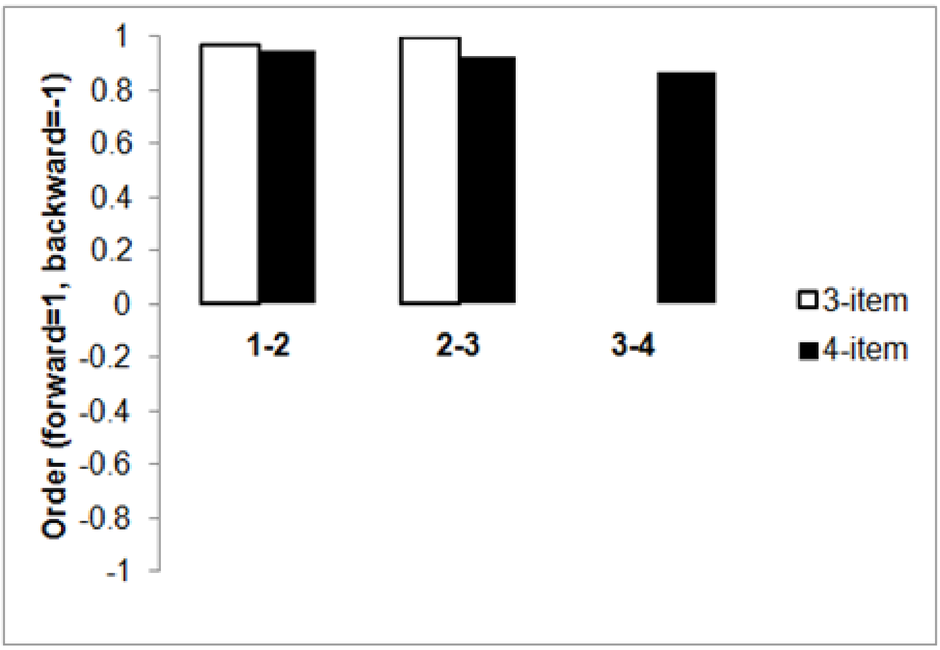

Figure 3. Recall order of subsequently displayed items.

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DISCUSSION

We found before that WMC is limited to three TUT items [14]. In the present contribution we found that once the WMC is exceeded, the asymmetric associations between items disappear even while the symmetric associations remain in size. The effect size of our finding is very large with $\eta 2 = 0.79$. That the symmetric associations remain about the same is not that interesting – they can be an artifact of attention – if the attention of a subject lasts for at least two consecutive items there should be a symmetric association between the items. What is interesting is that the asymmetric associations disappear at the same time as the working memory capacity is exceeded going from three to four TUT items. It lends credibility to information overload leading to confusion.

The finding also provides yet another clue as to how working memory capacity is limited. We found earlier that the fourth item destroys the memory of the previous items [7] – here we find that the extra item also removes the asymmetric associations.

The disappearance of asymmetric association curiously does not manifest itself in removing the item order in the output (Figure 3). Others have noted that the memory for item order, as seen in an analysis of errors, is arguably not tied to a "chaining" algorithm [15]; our result proves these findings in a very clear experiment.

General Discussion

Our findings are of fundamental importance to pedagogy. It is known that cognitive overload negatively affects learning and we have discovered one very specific mechanism for this: exceeding WMC removes asymmetric associations between the items.

Where is the asymmetric association coming from? After all, a displayed item is not cueing the next displayed item? The presented items in the TUT are displayed on a screen and attended to. While the display is external, the attention given to the displayed item is internal presumably providing the item with meaning. This process takes time [16] the more meaning the item has. When the displayed item changes, the attention has to provide the new item with meaning. This internal movement of item meaning may be what causes the asymmetric association but how that happens is not obvious to us.

We also found that the output order remains largely intact even though the asymmetric association disappears. That order can be conserved without asymmetric association shows that the order memory originates elsewhere, at least for short lists.

This allows us to construct a sensitivity chart for what happens when WMC is exceeded:

1. Most sensitive: Asymmetric associations between items disappear.
2. Sensitive: No more items can be recalled and some disappear.
3. Least sensitive: Order memory diminishes a little but similar to before WMC was exceeded.

This may have implications for AI [17,18]: since AI is limitless in its working memory, perhaps new types of thinking will occur. The authors have no competing interests other than that ET owns the rights to the TUT.

COMPLIANCE WITH ETHICAL STANDARDS

CONFLICT OF INTEREST

Author RE declares no conflict of interest. Author ET owns the rights to the TUT.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

INFORMED CONSENT

Informed consent was obtained from all individual participants included in the study.

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