Executive Control Operations for Updating Verbal Working Memory

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Abstract

The maintenance and updating of temporary stored information in verbal working memory (VWM) has typically been studied through popular procedures like the immediate serial recall and N-back recognition tasks. However, these procedures are problematic because they confound memory-updating operations with other processes such as encoding, rehearsal, and retrieval. To help solve this problem, we have developed new procedures that enable various types of updating (e.g., appending and deleting ordered items in working memory) to be isolated and characterized through analytical measurements of "cumulative" and "rolling" forward or backward overt rehearsal. Mean response latencies, durations and error rates based on these measurements reveal that simple "append" operations are relatively easy and invariant with changes in memory load, whereas memory load strongly affects more difficult combinations of "delete" and "append" operations. Our findings have potentially significant implications for theoretical modeling of updating and other related executive control operations in verbal working memory.

Updating Operations

VWM updating is the intentional modification of the current contents of verbal working memory. In terms of Baddeley's (2000) model this involves the central executive interacting with the phonological loop.

Types of updating operations may include:

- Addition: "a b c" → "a b c **d**"
- Deletion: "a b c" → "b c"
- Replacement: "a b c" → "a **f** c"
- Reordering: "a b c" → "a **c b**"

Operations can occur at the start, middle, or end of the list of items. Some operations may be primitive, while others are composite, e.g.:

Replacement: "a b c" → "a **f** c"

versus

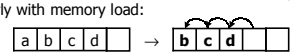
Deletion and insertion: "a b c" → "a c" → "a **f** c"

The relationship between the time taken to perform an operation and memory load depends on both the particular operation and the storage mechanism for serial order. For example, consider deletion of the first item in a list, e.g. "a b c d" → "b c d".

In a 'pointer' model of serial order, the number of operations is constant:

$$\Downarrow \qquad\qquad \Downarrow$$
$$a \Rightarrow b \Rightarrow c \Rightarrow d \quad \rightarrow \quad \mathbf{a} \Rightarrow b \Rightarrow c \Rightarrow d$$

While in a 'slot' model of serial order, the number of operations varies linearly with memory load:

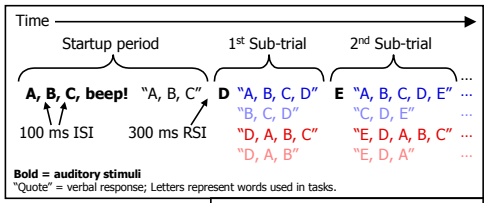


Benefits of New Rehearsal Tasks

New rehearsal tasks were designed that have distinct advantages over existing tasks for studying the updating of serial VWM:

- Use of chronometric analysis (RTs and articulation times) with speeded responses encouraged by performance bonuses
- Control over rehearsal strategy by overt rehearsal and short response stimulus intervals (RSIs)
- Localization of errors in memory contents by way of full overt rehearsal after each memory update
- Comparison of different updating operations (See methods)
- Application of results to other VWM tasks (See Expt. 1 results)

Methods for New Rehearsal Tasks



Startup period:

- Auditory presentation of n = 2, 3, 4, or 5 words with 100 ms inter-stimulus interval (ISI)
- After signal, participant recites the entire sequence

Cumulative forward rehearsal (CFR)
Rolling forward rehearsal (RFR)
Cumulative backward rehearsal (CBR)
Rolling backward rehearsal (RBR)

Sequence of sub-trials:

- On each sub-trial, auditory presentation of one word
- Participant immediately recites updated sequence
- Next sub-trial begins after a 300 ms RSI

Trial details:

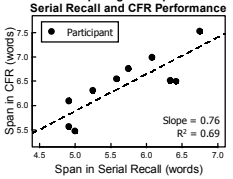
- Trial ends after recital when an error occurs, or when maximum number of sub-trials is completed
- Participants monetarily encouraged to start response promptly and recite sequence quickly and accurately
- Accuracy, RT, and articulation time recorded for startup period and each sub-trial

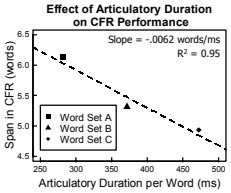
Word sets:

- 3 word sets (A, B, and C) of 10 short, medium, or long words
- Equated on mean phonological onset dissimilarity, using PSIMETRICA (Mueller et al., 2003)
- Varying in mean articulatory duration, determined experimentally using articulatory duration technique of Mueller et al. (2003)
- Task, word-set and n were blocked, within-subject
- Order of tasks and word-sets counterbalanced across subjects

Experiment 1: Serial Recall and CFR

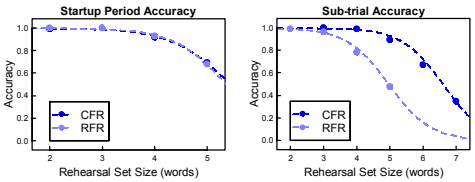
- Participants performed both the serial recall task and the CFR task.
- Memory span in serial recall was a significant predictor of span in CFR.
- These results suggest the phonological loop contributes to performance on both tasks.





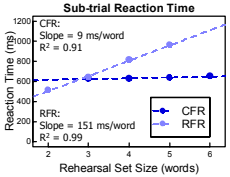
- Word sets with greater measured articulatory duration per word produced smaller spans for the CFR task.
- The cost in span for increased articulatory duration (0.0062 words/ms) was similar to that reported for serial recall (0.0057 words/ms) (Mueller et al., 2003).

Experiment 2: CFR and RFR



- Accuracy decreased significantly with rehearsal set size.
- No effect of task on accuracy during startup period suggests similar initial states before updates began.
- Significantly lower accuracy in RFR than CFR during sub-trials indicates significant effects of different updating operations.

- No effect of rehearsal set size on reaction time for CFR task.
- Significant linear increase in reaction time with increasing rehearsal set size for RFR task.
- This pattern suggests constant time updating operations for CFR, and linear time updating operations for RFR.



Why the qualitative difference in the pattern of RTs between tasks?

1st Option – Type of operation: deletion vs. addition

- Deleting an item in a list requires rebuilding the list.

2nd Option – Location of operation: beginning vs. end

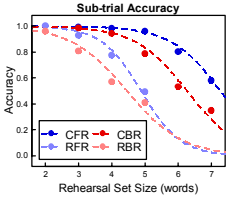
- Modifications to the beginning of a list require manipulation of all items in the list.

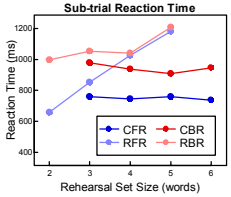
Using "backward" rehearsal tasks unconfounds the type and location of updating operation:

Update type	Update location: Beginning	Update location: End
Addition	CBR, RBR	CFR, RFR
Deletion	RFR	RBR

Experiment 3: CFR, RFR, CBR, & RBR

- Sub-trial accuracy decreased significantly with rehearsal set size for all four tasks.
- Main effects on sub-trial accuracy of rolling vs. cumulative and backward vs. forward tasks.
- Both update type and update location influenced accuracy.

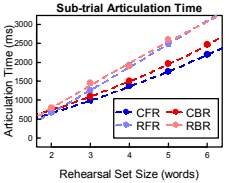


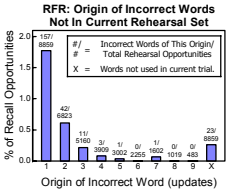


- Sub-trial reaction times for CBR showed no effect of rehearsal set size, but significant constant cost compared to CFR.
- Sub-trial reaction times for RBR are more difficult to interpret, with RTs significantly longer than RFR at small set sizes, and equivalent at larger set sizes.

Experiment 3: Further Analysis

- Articulation times measured from first utterance to end of recital.
- Longer articulation times and greater slopes in rolling tasks than cumulative tasks.
- Suggests that RT patterns are not due simply to a trade-off between RT and articulation time.

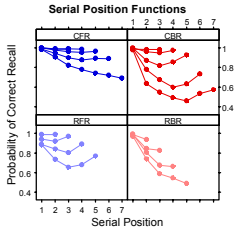




- Most incorrect words are transpositions within the current rehearsal set (not shown).
- However, in RFR and RBR, some incorrect words are intrusions from past updates.
- Intrusions are most frequently from the most recent update, with progressively fewer from older updates.

Recall advantages at extreme serial positions are considered in terms of item presentation time:

- CFR and RFR show primacy effects at the start of the list.
- RFR also shows a recency effect at the end of the list.
- CBR and RBR show recency effects at the start of the list.
- CBR also shows a primacy effect at the end of the list.



Conclusions

- The new rehearsal tasks provide insight into verbal working memory updating operations.
- Adding items to a list is a constant time operation that does not depend on memory load.
- There is an extra constant cost in reaction time and accuracy associated with adding items to the beginning of a list compared with adding items to the end of a list.
- Deleting items from a list is a linear time operation that does depend on memory load.
- Deleting items from a list does not involve completely removing them from memory, since recently deleted items are more likely to intrude into a list than items not used in the current trial.

References

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