

## Timing the “magical number seven”: Presentation rate and regularity affect verbal working memory performance

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The informative value of time and temporal structure often remains neglected in cognitive assessments. However, next to information about stimulus identity we can exploit temporal ordering principles, such as regularity, periodicity, or grouping to generate predictions about the timing of future events. Such predictions may improve cognitive performance by optimising adaptation to dynamic stimuli. Here, we investigated the influence of temporal structure on verbal working memory by assessing immediate recall performance for aurally presented digit sequences (forward digit span) as a function of standard (1000 ms stimulus-onset-asynchronies, SOAs), short (700 ms), long (1300 ms) and mixed (700–1300 ms) stimulus timing during the presentation phase. Participant’s digit spans were lower for short and mixed SOA presentation relative to standard SOAs. This confirms an impact of temporal structure on the classic “magical number seven,” suggesting that working memory performance can in part be regulated through the systematic application of temporal ordering principles.

**Keywords:** Working memory; Digit span; Timing; Temporal structure; Attention.

As we interact with our environment our minds engage in the continuous interplay between “echoes of the objects just past” and a “foretaste of those just to arrive” (James, 1890, p. 606). In other words, our brain must constantly bridge the divide of memory for, confrontation with, and prediction of sensory events. The processes underlying this mental capacity draw on limited resources, as expressed in (neuro-)cognitive constructs, such as executive functions, memory capacity, sensory acuity, or attention. As resources are limited, it is necessary to understand how these processes interact as events unfold in time to explain how we cope with an inherently dynamic environment.

One highly influential cognitive construct is the notion of a short-term storage for a limited amount of serial input as perhaps most famously discussed in terms of Miller’s (1956) “magical number seven” and Baddeley and Hitch’s (1974) model of “working memory,” conceived as “a system with limited capacity to temporarily maintain and

store information” (Baddeley, 2003). Time is inherent to this construct as the serial input is only stored for a short time before memory decays. However, it is still largely unknown how the temporal structure of the serial input itself factors into working memory (Teki, Gu, & Meck, 2017). The rate (tempo) of the input changes the storage time for input items prior to the recall and the time that is available to employ recall strategies, with some indications for higher performance at relatively fast rates with fixed recall order as opposed to higher performance at slower rates with reversed recall order (Posner, 1964) but also generally higher performance at slower rates (Laughery & Pinkus, 1966). However, in addition to presentation rate, factors such as temporal regularity or grouping may influence memory performance independent of the passage of time per se and the associated memory decay, that is, “time-based forgetting” or interference effects (Lewandowsky, Oberauer, & Brown, 2009). If this is the case, it would be necessary to determine whether this

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influence interacts with, or is at least compatible with, the proposed function of temporal structure in other cognitive constructs, most notably attention to gain a better understanding of the role of input dynamics in cognitive performance.

Already Bolton (1894) noted that attention can be conceived as a wave-like form or a series of pulses as it is impossible to attend continuously to an object that does not change (James, 1890). This notion of a “waxing and waning of attention” (Bolton, 1894, p. 155) is also central to the more recent dynamic attending theory (Large & Jones, 1999). Dynamic attending theory suggests that the allocation of attention is partly driven by the temporal structure of serial input. Coordination between input dynamics and resource allocation ensures that attention is directed in the right place at the right time, thereby amplifying sensitivity to inputs that occur at predicted points in time (McAuley, Jones, Holub, Johnston, & Miller, 2006; Morillon & Schroeder, 2015). An important implication of this theory is that the strength of the induced prediction is in part determined by uncertainty as indexed by temporal variability within a sequence. In other words, a high degree of temporal variability is associated with lower cognitive performance (Barnes & Jones, 2000). Low temporal variability would conversely improve cognitive performance. Although a theory of attention, this framework provides a rationale that can be adopted for explaining how temporal dynamics may factor into other cognitive constructs such as working memory.

Here, we investigate the influence of tempo and temporal variability on working memory and how this influence relates to cognitive performance through a systematic manipulation of stimulus-onset-asynchronies (SOAs) in a computerised version of a classic forward digit span test of verbal working memory with fixed recall order. Manipulations of temporal structure resulted in four experimental conditions presented in standard, short, long and mixed SOAs blocks. The maximal number of correctly recalled items for the standard condition, in which the digits were presented at a fixed rate of one item per second, was considered as baseline. Relative to this baseline, we expected lower performance for short SOAs due to reduced time to employ recall strategies (Posner, 1964) and difficulties to encode individual items and the same overall number of items in shorter time-windows. Similarly, we expected lower recall performance for mixed SOAs due to interference with the dynamic allocation of attention. Long SOAs prolong storage time prior to recall but give also more time to employ recall strategies. Relative to baseline, long SOAs were hence expected to either lower performance due to incipient memory decay and/or the additional recruitment of recall strategies, or enhance performance as more time becomes available for the encoding of individual items.

## METHOD

### Participants

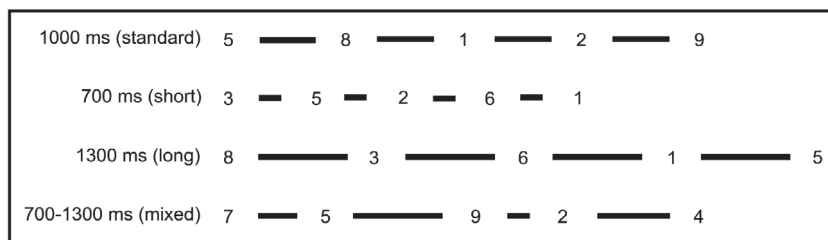
We expected to observe medium effect sizes with the relatively subtle timing manipulations employed in our study. Following power analyses for the planned analysis of variance (ANOVA) using the G\*Power 3.1 software package (Faul, Erdfelder, Buchner, & Lang, 2009; parameters: effect size  $f = 0.3$ , err prob. = 0.05, total calculated sample = 26) we tested 30 participants (mean age 20.2, *SD* 1.4 years, 20 female). None of the participants reported any history of hearing impairment or neuropsychological dysfunction. All participants were students of Maastricht University, gave their informed written consent, and received vouchers for compensation (5 € equivalents). The study was approved by the ethics committee of Maastricht University in accordance with the provisions of the World Medical Association Declaration of Helsinki.

### Stimuli

The stimulus material consisted of spoken digits. Each digit sound was generated individually by means of online text-to-speech synthesis software approximating a female speaker (<https://www.ibm.com/watson/services/text-to-speech/>). The duration of the respective sound files was equalised to 500 ms using the “change tempo without changing pitch” effect implemented in the Audacity package (<https://www.audacityteam.org>).

### Experimental procedure

The experimental setup closely followed the assessment of the forward digit span as implemented in the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008). During testing, participants sat in a quiet room in front of a computer screen. A microphone was placed in front of them to record their recall performance. Presentation (Neurobehavioral Systems Inc.) was used to present the stimuli through loudspeakers placed left and right of the computer screen in sequences increasing in length by one digit (ranging from two to nine digits). There were always two trials with the same sequence length but different digit orders (e.g., 5-8-1-2-9 vs. 3-5-2-6-1). Participants were instructed to first listen carefully to each sequence (presentation phase) and to then repeat it verbally (recall phase). The temporal manipulations were not mentioned to the participants. An asterisk was displayed at the centre of the screen during the presentation phase, while a question mark was displayed during the recall phase. The length of the recall phase was set to 3 seconds for the two-digit sequences and increased stepwise to 12 seconds for the nine-digit sequence. Performance was principally scored online by the experimenter applying the WAIS-IV



**Figure 1.** Example sequences across conditions (five digits; experimental trials varied from two to nine digits). The stimuli were presented in four conditions differing in the duration and variability of stimulus onset asynchronies comprising 1000 ms (standard), 700 ms (short), 1300 ms (long), and 700, 850, 1150, 1300 ms (mixed) intervals.

criteria. For some trials, this was done offline based on the audio recordings. Pseudo-randomization ensured that no digit was repeated and that no more than two ascending or descending adjacent digits were presented in each sequence. Extracted variables included the total raw score (maximum of 16 per condition; 1 per correctly reproduced sequence) and the maximal number of at least once correctly recalled items per condition. While the raw score reflects the WAIS-IV procedure to present two trials with the same sequence length, analyses focused on the maximal number of correctly recalled items that were expected to approximate the “magical number seven.”

The four conditions (Figure 1) were presented in separate blocks. Each block contained exclusively one of the following SOAs: standard (1000 ms), short (700 ms), long (1300 ms), mixed (700, 850, 1150, 1300 ms). The order in which these blocks were presented was balanced across participants to counter any potential effects of presentation order. The standard condition thus followed the WAIS-IV instruction to present one digit per second, while the other conditions were balanced around this standard rate ( $\pm 300$  ms;  $\pm 150$  ms). These SOAs were realised by adding fixed silent periods of 500, 200, 800 ms or mixed silent periods (200, 350, 650, 800 ms) to the respective sound stimuli. SOAs in the mixed condition were randomised with the constraints that no SOA was repeated and that the overall length of the sequence equalled the overall length of a standard sequence comprising the same number of digits.

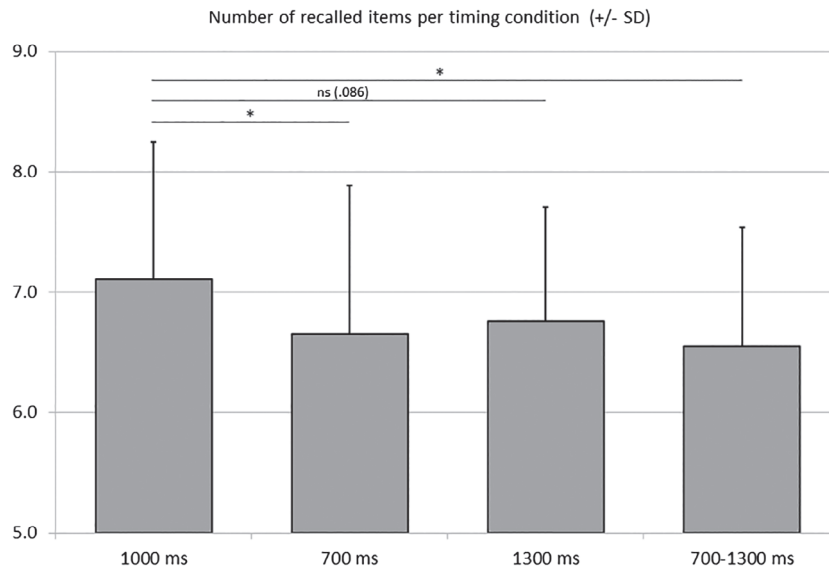
## RESULTS

Group means for total raw scores were 10.2 ( $SD$  2.3) for standard, 9.9 ( $SD$  2.0) for short, 10.1 ( $SD$  2.0) for long and 9.9 ( $SD$  1.9) for mixed SOAs. The maximal number of correctly recalled items per condition was 7.2 ( $SD$  1.2) for standard, 6.7 ( $SD$  1.2) for short, 6.8 ( $SD$  1.0) for long and 6.6 ( $SD$  1.1) for mixed SOAs. One 19-year-old female participant consistently performed more than two  $SD$ s above the group mean in terms of total raw scores for each condition and was hence excluded from the final analyses, changing the above results for raw scores to 10.1 ( $SD$

2.2) for standard, 9.7 ( $SD$  1.9) for short, 10.0 ( $SD$  1.8) for long and 9.8 ( $SD$  1.7) for mixed SOAs, while the maximal number of correctly recalled items per condition changed to 7.1 ( $SD$  1.1) for standard, 6.7 ( $SD$  1.2) for short, 6.8 ( $SD$  1.0) for long and 6.6 ( $SD$  1.0) for mixed SOAs (Figure 2).

These results were compared by means of a one-way ANOVA using the within-subject factor *timing condition* and applying Greenhouse–Geisser correction. Results for the standard condition were then compared to all other conditions using paired-samples *t*-tests. The sequentially rejective Holm–Bonferroni method was applied to address the problem of multiple comparisons, resulting in adjusted alpha levels of .017 for the most significant, 0.025 for the intermediate and 0.05 for the least significant *p*-value (Holm, 1979).

For the full group (including the outlier), the ANOVA yielded a significant main effect of timing condition  $F(2.89, 83.81) = 3.20$ ,  $p < .03$ ,  $\eta^2 = 0.99$ . Exclusion of the outlier led to a comparable result, that is, a significant main effect of timing condition,  $F(2.87, 80.44) = 3.09$ ,  $p < .04$ ,  $\eta^2 = 0.99$ . The subsequent planned comparisons for the full group confirmed significantly better recall performance for standard compared to mixed,  $t(29) = 2.72$ ,  $p < .02$ , Cohen’s  $d = 0.49$  and for standard compared to short SOAs,  $t(29) = 2.54$ ,  $p < .02$ ,  $d = 0.40$ , next to a non-significant trend in the same direction for standard compared to long SOAs,  $t(29) = 1.78$ ,  $p = .086$ ,  $d = 0.32$ . Similar findings were obtained after exclusion of the outlier, again confirming significantly better recall performance for standard compared to mixed,  $t(28) = 2.73$ ,  $p < .02$ ,  $d = 0.52$ , and for standard compared to short SOAs,  $t(28) = 2.37$ ,  $p < .03$ ,  $d = 0.37$ , and a trend in this direction for standard compared to long SOAs,  $t(28) = 1.78$ ,  $p = .086$ ,  $d = 0.32$ . Figures for the highest and lowest performing 20% of the group ( $N = 6$ ) in terms of the mean maximal number of correctly recalled items per condition indicate that the standard tempo led to the highest performance in both the former (mean 8.7,  $SD$  0.5 vs. mean 8.0 across conditions) and the latter (mean 6.0,  $SD$  0.6 vs. 5.6 mean across conditions) subgroup, suggesting that this tempo leads to optimal performance independent of overall memory capacity. Taken together,



**Figure 2.** Working memory capacity in terms of the maximal number of correctly recalled items (forward digit span). Results show the maximal number of correctly recalled items for each timing condition (standard 1000 ms, short 700 ms, long 1300 ms and mixed 700–1300 ms stimulus-onset asynchronies). Error bars indicate standard deviations.

these findings confirm a differential influence of temporal structure on working memory. They suggest optimal recall at the fixed standard rate, with rate manipulations in both directions negatively impacting recall performance and mixed SOAs leading to the lowest performance.

## DISCUSSION

This study investigated if and how the temporal structure of sequence presentation influences immediate serial recall performance in the forward digit span test, a classical assessment of short-term memory (Richardson, 2007). Once more, the results confirm a mean of seven items for the longest number of correctly recalled digits at the standard rate (Miller, 1956) and deterioration of performance at variable or faster presentation rates. This pattern was obtained using a blocked design. This approach counters potential effects of condition order while it minimises the chances that the results reflect a special status of a global mean rate extracted across the experiment (McAuley & Miller, 2007). The finding for the standard rate is compatible with dynamic attending theory but calls for further investigation as it stands in contrast to studies which did not find such effect for pseudowords (Kunert & Jongman, 2017).

Next to the effect of regularity the results confirm an influence of specific characteristics of temporal structure. Lower performance with short SOAs may be explained by limitations in encoding speed, that is, the more rapid stimulus presentation in this condition interferes with

encoding quality as it limits the time to encode the identity of individual items and to employ rehearsal, association and other recall strategies (Posner, 1964). However, the trend towards lower performance also with long SOAs suggests an inverted U-shaped function for the influence of presentation rate on working memory in this range, potentially reflecting both stronger trace decay and recruitment of recall strategies at long SOAs. Since short- and long-SOA conditions are fully predictable in time, it is unlikely that problems with attention allocation could explain the differences between these conditions and the standard condition. Conversely, lower performance in the mixed condition may reflect the combined influence of short and long SOAs on encoding and problems allocating attention in time. In line with dynamic attending theory, the absence of coherent temporal structure in this condition should compromise the ability to predict the timing of successive stimulus events.

Finally, it seems noteworthy that the time-window within which SOAs were manipulated was relatively short (600 ms; from 700 to 1300 ms). Significant differences were obtained from this range, which calls for computerised testing at fixed presentation rates to keep findings comparable. The widespread application of verbal working memory assessments offers numerous starting points to explore the informative value of temporal structure in working memory in particular, and memory formation in general. This is especially true for clinical settings, as a lack of adequate coordination between the temporal structure of the environment and resource allocation puts individuals at risk of missing relevant information, potentially contributing to cognitive decline (McAuley et al., 2006).



## CONCLUSIONS

The identified impact of temporal structure on verbal working memory assessed in the form of the classic “magical number seven” illustrates the fundamental role of time and temporal structure in cognition. This impact points to the general opportunity to influence cognitive performance through temporal manipulations. Temporal ordering principles, such as rate, regularity and grouping should hence not only be considered as by-products of our adaptation to a dynamic environment but as crucial to our understanding of this process.

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