Working Memory for Sequences of Verbal Stimuli: The Impact of Stimulus Type and Presentation Mode

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Abstract. Previous studies have shown that the use of a static or dynamic mode of presenting a non-verbal series (a sequence of strokes that make up a broken line, like an open polygonal chain), as well as varying the retention time of this information in working memory, can affect the accuracy and temporal characteristics of the sequence reproduction. The present study aims to investigate the effects of the presentation mode and the retention time on the memorization and reproduction of a sequence of verbal items. For this purpose, adult subjects were asked to memorize and reproduce sequences of letters and digits which were visually presented either simultaneously (statically) or sequentially (dynamically). The response delay time (500 or 3000 ms) and the length of the sequences (from 3 to 5 elements) were varied. As dependent variables, the accuracy of stimulus reproduction and the reaction time were computed. It turned out that the memorization of verbal sequences depended on the presentation mode (static or dynamic), and the static mode seemed to lead to a more complete representation of the memorized sequences. It was shown that the sequences of letters and digits are memorized differently. It is assumed that, unlike sequences of letters, sequences of digits are stored in working memory not as a sequence of individual elements but as shorter sequences of larger chunks or even as a whole. In contrast to the situation of reproducing a broken line, in the case of reproducing verbal sequences, no significant change in the reaction time was revealed when the time of information retention in working memory was varied.

Keywords: working memory, verbal sequences, digits, letters, reaction time, internal representation

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Introduction

In order to carry out daily activities, we often need to memorize relatively short series of items like objects and actions of different kinds. The short-term retention of a short series of items is an aspect of working memory (WM), which is modeled as several domain-specific buffers controlled by the central executive (Baddeley & Hitch, 1974).

This work is a continuation of a series of our studies aimed at uncovering specifics of the brain representation of serial visual information presented either statically (as in a snapshot) or dynamically (as in a movie). The rationale for this approach is grounded in some known literature data. It has been shown that patterns of brain activation during the construction of static and dynamic internal representations differ: in the first case, zones in the posterior parietal cortex PPC are activated (Lehnert & Zimmer, 2008), and in the second case, motion-sensitive neurons of the MT/MST regions are activated (Kriegeskorte et al., 2003; D'Esposito & Postle, 2015; Donato, Pavan & Campana, 2020; Curtis & Sprague, 2021). The possible transformation of representations in the process of retaining them in WM is discussed, for example, in the framework of the dynamic-processing model of WM, according to which the transformation of a representation can also depend on the task (Rose, 2020).

Previously, we studied whether and how a representation of a series of non-verbal items (linear strokes constituting a broken line [an open polygonal chain]) is affected by the presentation mode (static, i. e., simultaneous presentation, or dynamic, i. e., sequential presentation) and the retention time varying from 0 to 3 seconds (Korneev & Kurganskii, 2014a). It was found that

(i) the accuracy and timing of the memorized sequence production was affected by the presentation mode: dynamically presented broken lines were reproduced less accurately and required a longer latent preparation time (i. e., reaction time; RT), and

(ii) RT decreased as the retention time increased, with the rate of RT changes being different for the static vs. dynamic modes.

These results, which were confirmed in follow-up studies (Antonova, Absatova, Korneev & Kurgansky, 2015), led us to suggest that, with the passage of time, the representation of a sequence of visuospatial elements, which are set to be reproduced motorically, undergo a spontaneous transformation (not caused by any external agent but proceeding as time goes by due to internal causes) from a domain-specific form to a more abstract one (Korneev & Kurganskii, 2014a; Korneev, Lomakin & Kurganskii, 2017).

The present work is aimed at applying a similar approach: manipulating the presentation mode (static vs. dynamic) and varying the retention time in WM to study the memorization of sequences of verbal items. Specifically, we use the accuracy of reproduction and the reaction time as two dependent variables to investigate how and to what extent the representation of a verbal sequence is affected by the stimuli presentation mode and the retention time.

The difference in the representation of verbal and non-verbal information in WM is reflected in the Baddeley and Hitch model (Baddeley & Hitch, 1974; Baddeley, 1981), which contains a phonological loop responsible for encoding and storing verbal information and a visuospatial sketchpad that holds non-verbal information. This difference in representation is supported by more recent results, including those concerning the encoding and retention of a series of elements.

It is worth mentioning here a review devoted to the similarities and differences in the experimental effects obtained on the material of short-term storage and the reproduction of verbal, visual and spatial serial information (Hurlstone, Hitch & Baddeley, 2014). Consideration of the results of various experiments allowed the authors to conclude that, despite the possibility of both serial order retention mechanisms described by the competitive queuing (CQ) model, many effects obtained on the verbal material are not reproduced or simply have not yet been studied in the case of memorizing visual and spatial information (see Hurlstone et al., 2014 for review). According to the CQ model, a sequence of N motor responses is represented internally by N simultaneously pre-activated nodes (parallel planning layer). The order in which the responses are executed is determined by the activation gradient across the nodes. Which response to execute at a given time is determined through competition among the activation levels of all nodes (this competition takes place in yet another set of nodes: the competitive choice layer). As soon as the activation level of a response that has won the competition exceeds a certain predefined threshold, the response is physically executed.

A study by Ginsburg and co-authors (Ginsburg, Archambeau, van Dijck, Chetail & Gevers, 2017) showed the difference in positional effects while memorizing verbal versus non-verbal (visuospatial) sequences. In their study, the positional effect was observed only for verbal sequences whilst the positional effect was absent for the spatial sequences (sets of dots). The authors concluded that these results supported the idea of dissociable mechanisms of coding of a serial order in verbal and visuospatial domains.

The presence of different mechanisms for storing verbal versus non-verbal information are supported by the results of experiments (Alloway, Kerr & Langheinrich, 2010) in which participants have to memorize either verbal (numerical) or visual-spatial stimuli sequences while solving a secondary task that also could be verbal or non-verbal. It was found that a reduction in recall efficiency was observed only if a secondary task was of the same modality as the primary stimulus.

The results of a fMRI study (Rothmayr et al., 2007) point to a dissociation between the cortical sites involved in verbal and non-verbal WM for long and short delays. In that study, the subjects performed the delayed discrimination of two Gabor stimuli of different orientations while coding the relative orientation of the stimuli either verbally or non-verbally with memory delays of short (2 s) or long (8 s) durations. More activity was found for the short verbal condition compared to the short non-verbal one in the bilateral superior temporal gyrus, insula and supramarginal gyrus. At the same time, the activity in the long verbal condition was higher than in the long non-verbal condition in left language-associated areas (STG) and bilateral posterior parietal areas. Finally, the right DLPFC and bilateral superior frontal gyrus was more active in the non-verbal long delay condition than in the long verbal condition.

A study conducted by Roberts and co-authors (Roberts, Englund Strait & Decker, 2018) showed that the developmental trajectories of verbal and visual-spatial WM were different. The verbal WM was characterized by a linear trend of the WM span across ages from 6 to 25 years, while the similar developmental trajectory of the visual-spatial WM was rather curvilinear. The WM span for dynamic visual spatial information increased linearly up to 12–13 years of age, remained almost unchanged after that and resumed its growth at around the age of 20 years. The WM span for the static visual spatial information increased linearly up to 18 years of age, reaching a plateau after that age.

In studies of WM, the issue of general and modal-specific mechanisms of its organization is widely discussed. This concerns not only the dichotomy of verbal vs. nonverbal, but also intra-modal differences. The difference in visual non-verbal WM organization for two types of retained information (object vs. spatial) has been known for a long time (Ruchkin et al., 1997), which is not the case for verbal WM. Although some studies point to a different organization of WM when holding sequences of letters versus digits, this is limited to auditory sequences. For example, it has been shown that when solving problems of recalling a sequence of digits and letters in a direct order, the reproduction accuracy is higher for numbers than for letters (Zirk-Sadowski, Szucs & Holmes, 2013).

When memorizing series of elements, it is not only the modality of its elements but also the presentation mode that influences the accuracy and timing of a subject's response. The literature data (Logie, 2011; Wansard et al., 2015) as well as our previous studies (Korneev & Kurgansky, 2014a, 2014b) suggest the presence of different storage systems for dynamic and static information in WM, at least in relation to visual-spatial information.

As for verbal sequences, their dynamic presentation is used mainly in studies of reading (e.g., Sharmin, Špakov & Räihä, 2015). We were unable to find experimental works in which the memorization of verbal sequences presented statically or dynamically is directly compared. Thus, it is still unclear whether the presentation mode affects the way verbal information is stored.

These data, in our opinion, could contribute to understanding the general mechanisms of the coding, retention and transformation of verbal information in WM as well as those mechanisms that are specific to the case when relevant verbal information is presented simultaneously or sequentially. In addition, such a study may be relevant in light of the widespread use of computer technologies, in which a variety of combinations of one-time and sequential presentations of information, including verbal information, is possible. This issue is discussed both in the context of cognitive testing (Carpenter & Alloway, 2019) and in the context of e-learning (Burin, González, Martínez & Marrujo, 2021). The goal of this work was to study the organization of visual verbal WM, and, in particular, how it is affected by the visual stimuli presentation mode and the duration of information retention. As visual verbal stimuli, we used sequences of letters and numbers that are known to be stored in the phonological loop (Baddeley & Hitch, 2019). Two issues were of special interest:

(i) whether the effects of the presentation mode (static vs. dynamic) and the duration of the delay, which we identified during the reproduction of visual-spatial stimuli (trajectories), are reproduced in the case of verbal sequences (consisting of alphanumeric characters); and

(ii) whether these effects depend on the type of verbal stimuli (letters vs. digits).

To clarify these issues, we used the delayed serial recall task, which makes it possible to analyze how changes in reproducing serial information depend on the domain of the initial information (simultaneous [static] or sequential [dynamic]) and the length of time the information is retained in WM. Such a task does not in itself require a special transformation of information, whereby the differences in responses that can be detected can be interpreted as evidence of differences in the original encoding and/or information transformations during the delay period.

Methods

Subjects

A total of 24 right-handed (according to their self-report) adult subjects (13 women and 11 men) aged 21 to 55 years (32.2 ± 7.9 years) participated in the study. All participants gave informed consent to participate in the study. The study received ethical approval from the Ethics Committee of the Institute of Developmental Physiology.

Stimuli

Two kinds of verbal sequences were used in the study. The first kind of stimuli were sequences of consonant Cyrillic letters 3 to 5 characters long (no repetitions). Examples of such stimuli are: "ТЛМ", "ГТДН", and "РЗБДП". Several examples of sequences of that kind are also shown in Figure 1A (on the left). The second kind of stimuli were sequences of digits from 0 to 9, also 3 to 5 characters long (no repetitions). Examples of such stimuli are: "249", "7304", and "19358". Several examples of sequences of that kind are also shown in Figure 1A (on the right). Two presentation modes were used: the static mode and the dynamic mode. In the static mode, the entire sequence was shown as a string for a fixed time (T = 2000 ms). In the dynamic mode, the characters were presented one at a time (each character was shown for 500 ms). A short beep was used as an auditory imperative signal to prompt the subjects to recall the sequence.

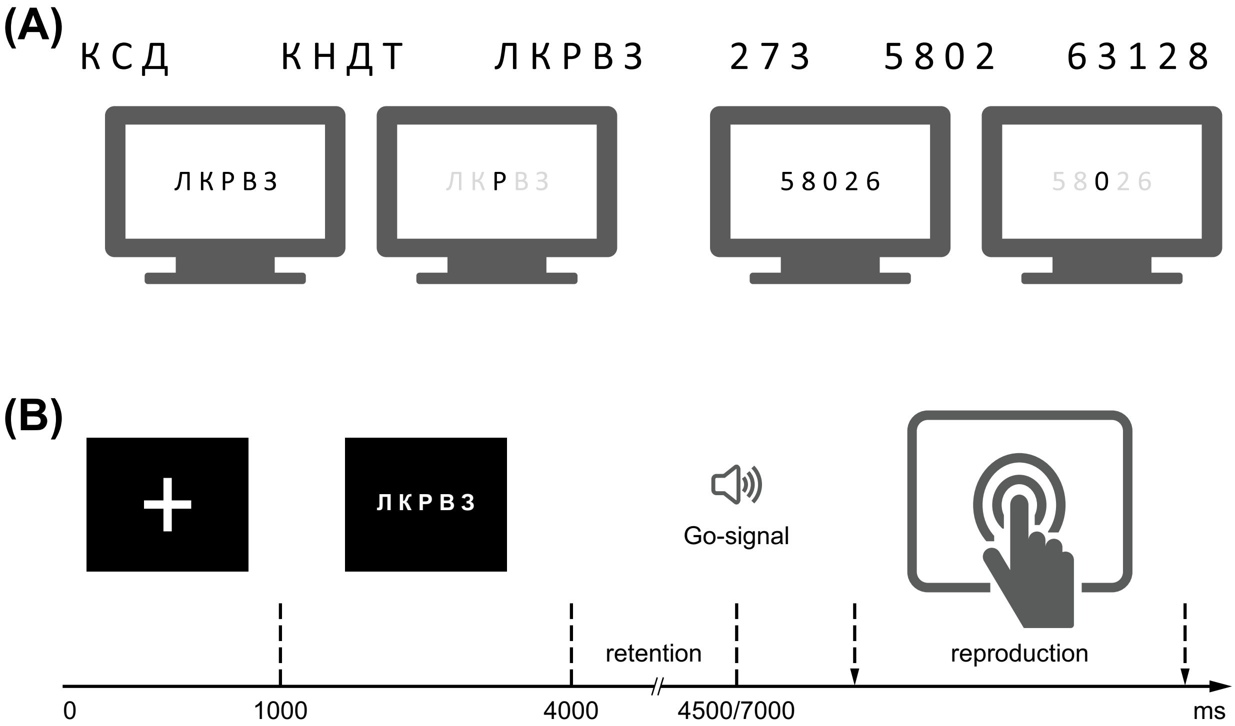

Figure 1. Verbal stimuli used in the experiment (A); the schedule of events within a single trial (B).

The Subjects' Task and the Structure of the Experiment

Subjects performed a version of the serial recall task: they were asked to memorize a sequence of characters (letters or digits) and, after a variable delay, to recall the order in which the characters were shown. The event timing within a trial is shown in Figure 1. At the beginning of a trial, the subject was asked to position and keep the index finger inside the small rectangle (home position) at the bottom of the touch-screen. Then, a fixation cross appeared on the screen and, after a 1-second delay, it was replaced by a target sequence. Next, after a variable delay (500 or 3000 ms), the auditory imperative signal (a short beep) was sounded and a randomly permuted version of the target sequence appeared. The probes with the short and long delays were presented in a pseudorandom order with equal probability. The subject's task was to report as quickly and accurately as possible the order of characters in the target sequence by touching with the index finger the characters of the permuted sequence shown on the touch screen.

The experiment consisted of 4 blocks of 48 trials each to separately present two kinds of sequences (letters, digits), each in two different modes (static, dynamic). Sequences varied in length from 3 to 5 elements, with an equal number of 16 trials showing the sequences of each length in a pseudorandom order. Each block was preceded by a short training block of 4 trials.

The experimental procedure was implemented in Octave ver. 5.2.0 using Psychtoolbox ver. 3 under the Linux operating system (Kubuntu distribution). The control script was executed on a Lenovo Yoga computer with a touchscreen (14" diagonal, 1920 × 1080 resolution). This script controlled the presentation of stimuli (visual and auditory) and recorded the touches and movements of the subject's finger across the screen. During the experiment, the subject sat in an armchair in a darkened room and looked at a screen located at such a distance from the subject that it was convenient for him or her to touch the screen with his or her finger and choose the stimuli on it (50–60 cm). The behavioral part of the experiment was accompanied by the recording of the subject's electroencephalogram (not analyzed in the present paper).

Data Processing

The primary data analysis was carried out using a script created in the Octave environment. Two indices were computed for further analysis: (1) the proportion of correct responses; and (2) reaction time — the time (in seconds) that elapsed from the beginning of the imperative signal until the moment when the subject's index finger left the home position. We exclude from the following analysis any ultra-short reactions (less than 100 ms).

To assess the influence of experimental factors on the proportion of correct responses (accuracy) and reaction time (RT), an analysis of variance with repeated measures (rmANOVA) was carried out with the following four within subject factors: stimulus type, STIM (letters, digits); presentation mode, MODE (static, dynamic); delay time, DELAY (500 ms, 3000 ms); and sequence length, LENGTH (3, 4 or 5 elements). The distribution of RT departed from the normal one, but ANOVA is known to be robust to a violation of normality (Harwell, Rubinstein, Hayes & Olds, 1992).

Results

The results of the analysis of variance are presented in Table 1.

As can be seen from the Table 1, the following effects turned out to be significant for accuracy:

(1) the STIM effect (Figure 2A), showing that digital sequences are reproduced more accurately;

Table 1. rmANOVA Results

Effect	Accuracy (Proportion of Correct Responses)				Reaction Time			
	dfs	*F*	*p*-value	η_p^2	*dfs*	*F*	*p*-value	η_p^2
STIM	**1, 23**	**59.744**	**< .001**	**.722**	1, 23	0.015	.905	.001
MODE	**1, 23**	**17.314**	**< .001**	**.429**	1, 23	1.568	.223	.064
DELAY	1, 23	0.743	.398	.031	1, 23	0.081	.778	.004
LENGTH	**2, 46**	**41.650**	**< .001**	**.644**	**2, 46**	**18.404**	**< .001**	**.444**
STIM × MODE	**1, 23**	**26.195**	**< .001**	**.532**	1, 23	0.931	.345	.039
STIM × DELAY	1, 23	0.232	.635	.010	1, 23	0.227	.639	.010
MODE × DELAY	1, 23	0.613	.442	.026	**1, 23**	**5.578**	**.027**	**.195**
STIM × LENGTH	**2, 46**	**33.505**	**< .001**	**.593**	2, 46	0.250	.780	.011
MODE × LENGTH	**2, 46**	**6.806**	**.003**	**.228**	2, 46	2.272	.115	.090
DELAY × LENGTH	2, 46	0.290	.750	.012	2, 46	0.165	.849	.007
STIM × MODE × DELAY	1, 23	0.771	.389	.032	1, 23	0.909	.350	.038
STIM × MODE × LENGTH	**2, 46**	**4.011**	**.025**	**.149**	2, 46	0.143	.867	.006
STIM × DELAY × LENGTH	2, 46	0.198	.821	.009	2, 46	1.693	.195	.069
MODE × DELAY × LENGTH	2, 46	1.732	.188	.070	2, 46	2.302	.111	.091
STIM × MODE × DELAY × LENGTH	2, 46	0.653	.525	.028	2, 46	1.236	.300	.051

Note: *dfs* — degrees of freedom; significant ($p < .05$) effects are shown in bold.

(2) the MODE effect (Figure 2B), suggesting a higher accuracy in the STAT mode;

(3) the LENGTH effect (Figure 2D), showing that, with increasing sequence length, the accuracy of performance decreases. A pairwise comparison showed a significant difference at $p < .035$ between all three levels of the factor (hereinafter, Tukey's HSD test was used for pairwise comparisons);

(4) the STIM × MODE interaction (Figure 3A), showing that, for the letter sequences, the performance accuracy in the dynamic mode is noticeably lower than in the static one ($p < .001$), while in the case of digit sequences, the accuracy scores in the two modes are practically the same ($p = .939$);

(5) the STIM × LENGTH interaction (Figure 3B), suggesting that the accuracy decreases with an increasing length of letter sequences more ($p < .001$ when comparing sequences of three or four elements with those of five elements) than it does in the case of digit sequences ($p > .1$);

(6) the MODE × LENGTH interaction (Figure 3C), showing that, in the dynamic mode, the accuracy decreases with an increasing of its length ($p < .01$ for a pairwise comparison of sequences of 3, 4 and 5 elements) than it does in the static mode; ($p = .977$ for a pairwise comparison of sequences of 3 and 4 elements, $p = .007$ for a comparison of sequences of 3 and 5 elements, and $p = .003$ for a comparison of sequences of 4 and 5 elements); and finally,

(7) the STIM × MODE × LENGTH interaction (Figure 4), suggesting that, when showing digits, there is no interaction between length and mode, while in the case of letters, the effect of length turns out to be stronger in the dynamic mode than in the static one.

An assessment of the impact of the experimental factors on RT showed the following significant effects:

(1) the effect of LENGTH (Figure 5D), showing that RT grows with increasing sequence length. Tukey-adjusted pairwise comparisons showed significant differences at the $p < .001$ level between sequences of 3 and 4 elements and those of 3 and 5 elements; and

(2) the MODE × DELAY interaction (Figure 6), suggesting that, in the static mode, RT tends to increases slightly with an increasing delay ($p = .440$), while in the dynamic mode, RT shows an opposite tendency — it slightly decreases with a growing delay ($p = .339$). Pairwise comparisons showed the only significant difference: the difference between RT in the static and dynamic modes at a 500 ms delay ($p = .035$).

Discussion

We found that the statically presented sequences of letters were recalled more accurately than those presented dynamically. This may be due to the fact that, compared to the dynamic mode, the static mode allows for a longer

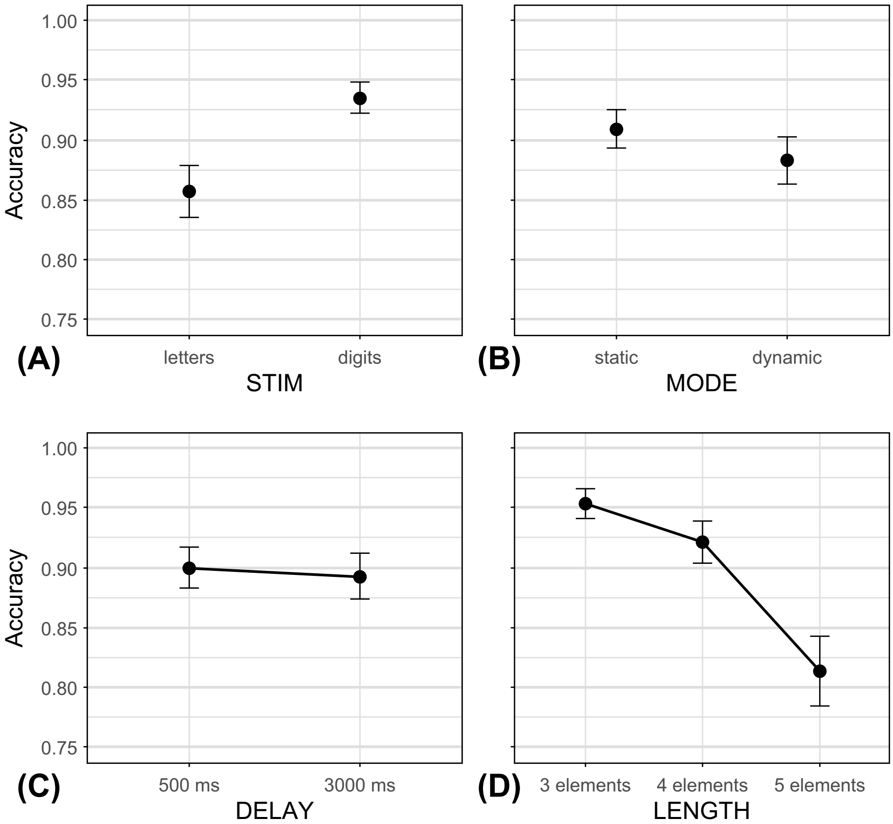

Figure 2. Average performance accuracy versus (A) stimulus type, (B) presentation mode, (C) delay time, and (D) sequence length. Error bars correspond to 95 % confidence intervals.

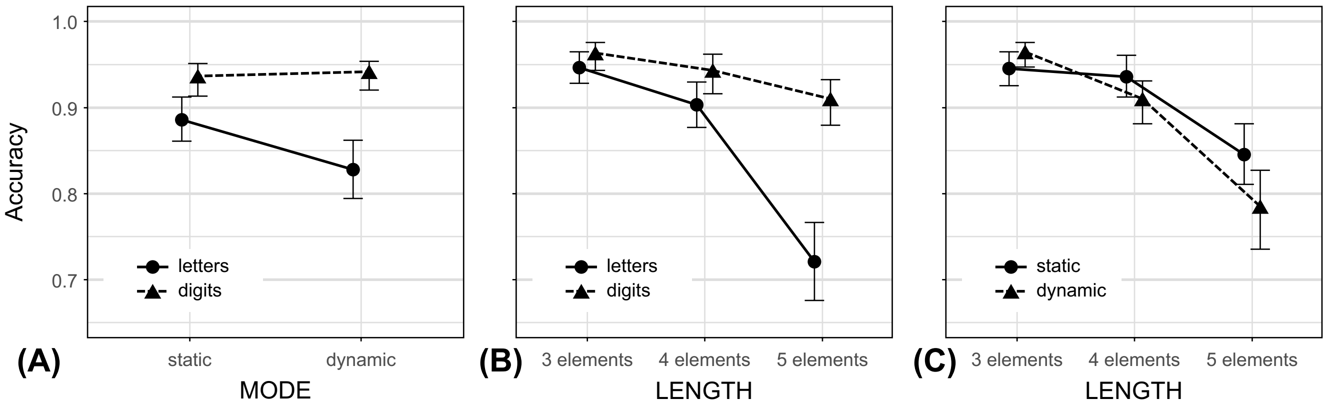

Figure 3. Average performance accuracy versus (A) the type of stimuli in the static and dynamic presentations, (B) the length of sequences for letters and digits, (C) the length of a sequence in the static mode and the dynamic mode.

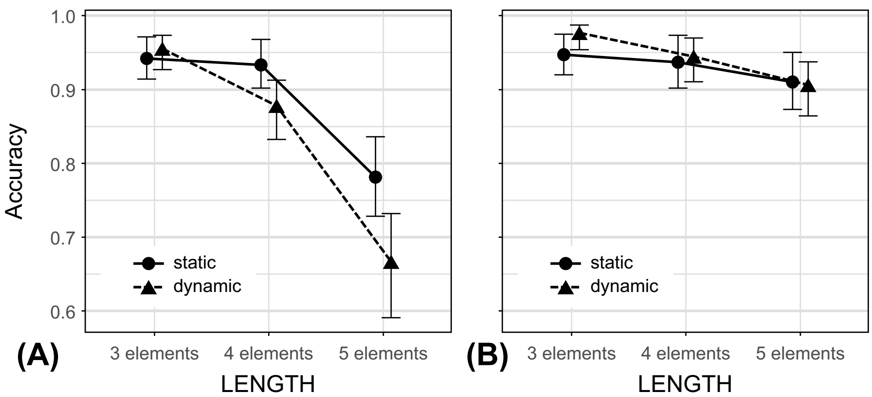

Figure 4. Average performance accuracy versus the length of the sequence and the presentation mode for letters (A) and digits (B). Error bars correspond to 95 % confidence intervals.

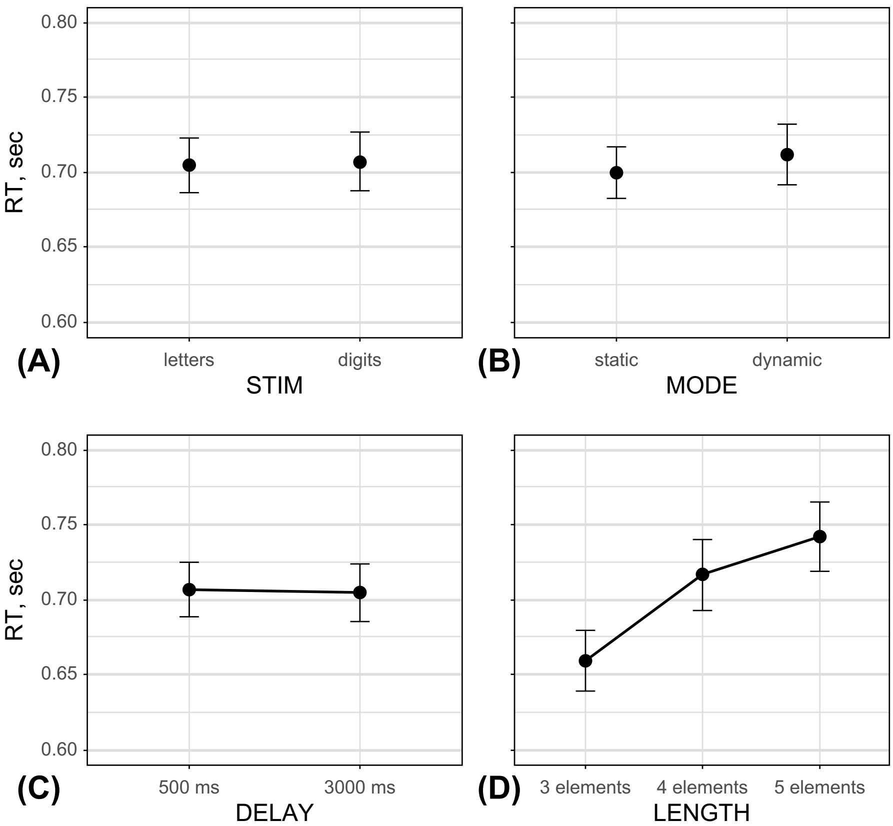

Figure 5. Average RT versus (A) stimulus type, (B) presentation mode, (C) delay time, and (D) sequence length. Error bars correspond to 95 % confidence intervals.

encoding time and does not require the subject to hold already seen items in WM as the presentation goes on, which reduces the overall memory load and results in forming a more complete and reliable representation of the sequence. Note that a similar effect was observed when producing non-verbal sequences of linear strokes (Korneev & Kurganskii, 2014a).

Surprisingly, this effect was not observed, and the above reasons did not apply to the sequences of digits that were recalled with more accuracy than sequences of letters and equally accurately in both static and dynamic modes. What might be the difference between the two types of sequences? The sequences of consonants used in this work did not make up any meaningful words, not even syllables. On the contrary, almost any sequence of digits constitutes a number (an exception is a sequence with leading zeros) thus making it possible to retain it as a single object or a shorter sequence (i. e. chunking, see for example Fendrich & Arengo, 2004) and also use not just phonological but also a semantic representation (Shivde & Thompson-Schill, 2004). For example, '4325' 4-element sequence could be stored as the "forty-three" — "twenty-five" 2-element sequence). This view on the digit sequences is corroborated by the weakly expressed length effect for this kind of sequences, well known from the literature (Barton, Hanif, Björnström, & Hills, 2014).

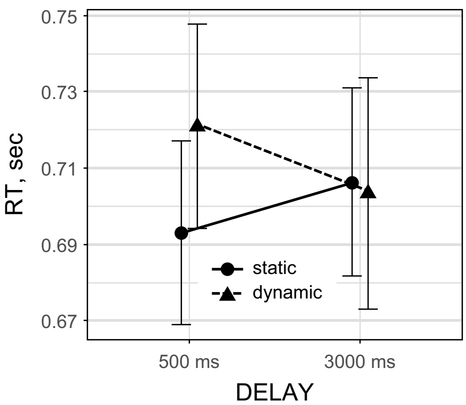

Figure 6. Average RT versus delay time (DELAY) for the static and dynamic presentation modes. Error bars correspond to 95 % confidence intervals.

Unlike accuracy, reaction times increased with the length of the sequence for both letters and digits. This discrepancy between accuracy and RT scores may be due to the fact that accuracy scores are affected primarily by perceptual processes while RT values are related more to the sequence of responses that participants have to prepare to report the retained sequence. In the latter case, the observed RT increase may merely reflect Hick's law (Hick, 1952; see also the review by Proctor & Schneider, 2018), according to which the response time grows as the number of alternatives increases.

When averaged over both kinds of verbal sequences (letters and digits), the RT did not change with an increase in the imperative signal delay, in contrast to the results obtained on non-verbal sequences (Korneev & Kurganskii, 2014a). However, the presence of a DELAY × STIM interaction suggests that digit and letter sequences are differently affected by the DELAY factor. When reporting the memorized letter sequences, the RT decreased, but when reporting the memorized digit sequences, the RT tended to increase. If we consider the systematic change in the RT during retention in WM to be an indicator of the transformation of the representation of a sequence in working memory (Korneev et al., 2017), then in the present case of verbal sequences, we have to suggest that the putative transformation (if any) is either quantitatively (less pronounced) or qualitatively (of different nature) different. Indeed, when reporting a broken line retained in WM, the subjects must literally reproduce a figure seen seconds before. Such a copying process requires a complex motor response whose preparation is based on the transformation of a visual image into a sequence of motor commands. However, neither a copying of the visual image nor a complex motor response is necessary when reporting memorized letter or digit sequences. The differences in the retention-related dynamics of RT for letter and digit sequences can be attributed to the difference we already discussed above: digit sequences can be memorized as numbers, while letter sequences are perceived and memorized as a series of elements. Based on this view, one may suggest that a sequence of letters is "closer" to a series of linear strokes constituting a broken line than a sequence of digits, and that is why the RT dynamics over the retention period is closer to that observed when the sequence of strokes is produced.

Limitation and Further Directions

In the present study, we considered the reaction time, which allows us to judge the amount of preliminary preparation for a motor response and reflects the peculiarities of a representation of serial information. However, it may also be important to consider temporal indicators of series performance such as the duration of pauses between performing individual elements of a sequence. We plan to use this parameter in a further analysis of the obtained results in our upcoming publications.

Conclusions

The results reported in the present work suggest that the memorization of verbal sequences depends on the way they are presented, with the static presentation mode resulting in a more complete and stable representation of the sequence. A comparison between the data obtained for sequences of letters and those obtained for sequences of digits shows that these two types of verbal sequences are memorized in different ways. It seems that, in the case of digits, a sequence of elements may be chunked, i. e. combined into a smaller number of larger entities instead of being stored in WM as a sequence of original elements. When the delay is varied in the case of verbal sequences, the RT changes only slightly, which means that the putative transformations (if any) of the representation in this case are less pronounced than in the case of the motor reproduction of broken lines.

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экспериментальные сообщения

Рабочая память в задачах воспроизведения вербальных последовательностей: влияние типа стимула и режима предъявления

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Аннотация. Предшествующие исследования показывают, что использование статического или динамического способа предъявления серий невербальных стимулов (последовательности штрихов, составляющих ломаную линию), а также варьирование времени удержания этой информации в рабочей памяти могут влиять на точность и временные характеристики воспроизведения последовательностей. Целью настоящей работы является исследование особенностей запоминания и воспроизведения последовательностей вербальных стимулов в зависимости от способа их предъявления и времени удержания их в рабочей памяти. Для этого взрослым испытуемым предлагалось запоминать и воспроизводить последовательности букв и цифр, которые предъявлялись либо единовременно (статически), либо последовательно (динамически). Варьировались время задержки ответа (500 или 3000 мс) и длина последовательностей (от 3 до 5 элементов). Оценивалась точность воспроизведения стимулов, а также время реакции испытуемых. Оказалось, что запоминание вербальных последовательностей зависит от способа их предъявления, причем при статическом предъявлении, по-видимому, возникает более полная репрезентация запоминаемой информации. Показано, что последовательности букв и цифр запоминаются по-разному. Предполагается, что, в отличие от последовательностей букв, последовательности цифр хранятся в рабочей памяти не как последовательность отдельных элементов, а как более короткие последовательности более крупных групп или как целое. В отличие от задачи на воспроизведение ломаной линии, в случае воспроизведения вербальных последовательностей не выявлено значимого изменения времени реакции при варьировании времени удержания информации в рабочей памяти.

Ключевые слова: рабочая память, вербальные последовательности, цифры, буквы, время реакции, внутренняя репрезентация

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