

The influence of rhythm on short-term memory for serial order

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ABSTRACT

In the field of verbal short-term memory (STM), numerous theoretical models have been proposed to explain how serial order information is processed and represented. Evidence suggests that serial order is represented through associations between items and a varying contextual signal coding the position of each item in a sequence, but the nature of this contextual signal is still a matter of debate (i.e., event-based vs. time-based varying signal). According to event-based models of serial order, the contextual signal coding serial order is not sensitive to temporal manipulations, as it is the case in irregularly timed sequences. Up to now, the study of the temporal factors influencing serial order STM has been limited to temporal grouping and temporal isolation effects. The goal of the present study is to specify in more detail the role played by temporal factors in serial order STM tasks. To accomplish this, we compared recall performance and error patterns for sequences presenting items at a regular or an irregular and unpredictable timing in three experiments. The results showed that irregular timing does not affect serial recall nor the pattern of errors. These data clearly favor the view that serial order in verbal STM is represented with event- rather than time-based codes.

KEYWORDS

Serial recall; Timing; Temporal regularity; Working memory

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1. Introduction

The *problem of serial order* that characterizes a series of human behaviors and cognitive activities has since a long time fascinated the scientific community (see Lashley, 1951). For instance, consider a professional musician for whom it is critical to retrieve, plan and produce rapidly, series of movements in their correct serial order to perform a musical piece. Even though such activity requires a set of high-level skills and a lot of training, the same problem of serial order applies to everyday life situations, such

as following a cooking recipe or remembering a phone number. Even an activity as simple as remembering a list of digits or letters requires a set of complex cognitive mechanisms (see Hurlstone, Hitch, & Baddeley, 2014; Lewandowsky & Farrell, 2008).

Remembering a phone number is a particularly informative case regarding the problem of serial order. In the field of short-term memory (STM), a great deal of research has been conducted concerning how participants remember the serial order of verbal items such as digits presented in a list. Tasks requiring to recall serial order information from STM are characterized by a set of well-reproduced benchmark phenomena serving as a basis for the development of computational accounts of the different ordering processes involved in STM (for a review, see Hurlstone et al., 2014; Lewandowsky & Farrell, 2008; Oberauer et al., 2018).

One constraining effect for models of serial order is the temporal grouping effect. This effect involves the presentation of additional temporal pauses between some items during sequence presentation to create subgroups of items (e.g., in a list of nine items, introducing an additional pause between the third and fourth items, and between the sixth and seventh items, in order to create three groups of three items temporally distinct). In addition to the recall superiority of grouped sequences, one of the main features of temporal grouping is the increase of between-group transpositions of items keeping their initial within-group position, known as interposition errors (Henson, 1996). Another characteristic of temporal grouping is the multiply-bowed appearance of the serial position curve where each group is characterized by mini primacy and recency effects (Frankish, 1985, 1989; Hartley, Hurlstone, & Hitch, 2016; Hitch, Burgess, Towse, & Culpin, 1996; Ryan, 1969a, 1969b).

Currently, the best account of temporal grouping effects is provided by context-based models of STM relying on positional codes to represent serial order (see, e.g., Brown, Preece, & Hulme, 2000; Burgess & Hitch, 1999, 2006; Hartley et al., 2016; Henson, 1998; Lewandowsky & Farrell, 2008). These models propose that order information in a sequence is represented through the association between the items and the different states of a contextual signal, which varies as a function of item presentation and/or time. They also suggest the existence of multiple contextual signals to encode serial order at different hierarchical levels. The presence of several contextual signals enables tracking the occurrence of items at different time scales, allowing the representation of item position at the group level as well as group or item position at the whole-list level.

However, there is no consensus concerning the nature of the contextual signal coding positional information. In other words, what drives the signal to change during the presentation of a sequence is still a matter of debate. According to event-based models, serial order is represented through associations between items and a signal progressively changing as a new item is presented in the sequence (Henson, 1998; Lewandowsky & Farrell, 2008). In time-based models, the same principle applies except that the contextual signal represented by oscillators changes as a function of time, and serial order is represented by associations between the items and the current state of the oscillators at the time of presentation (Brown et al., 2000; Burgess & Hitch, 1999; Hartley et al., 2016; Henson & Burgess, 1997).

While both classes are able to account for the effects of temporal grouping, one issue is that they did not implement a mechanism allowing to extract the temporal structure of a sequence of memoranda. Models thus need prior information regarding the temporal structure of the sequence input—that is, the experimenter has to set the temporal structure by hand—to simulate temporal grouping effects. Henson and Burgess (1997) partly addressed the problem of the unknown temporal structure.

They proposed a connectionist model based on neurally-inspired oscillators running at different rates, one set of oscillators coding the relative temporal position of items within groups and a second set coding the relative temporal position of groups within the sequence. In addition to explaining the classical effects of temporal grouping, the model can account for the effects observed when to-be-remembered sequences present temporal groups of unequal size, such as the presence of relative interposition errors at recall (Henson, 1999b). However, the model relies on prior rhythmic parsing, making it difficult to deal with unpredictable rhythmic structure.

In an extension of that model, Hartley et al. (2016) proposed a realistic bottom-up mechanism that would allow deriving the temporal context of a sequence directly from the physical properties of items as they unfold in the environment. This mechanism is thought of as a set of neuronal oscillators tuned to run at different time scales and responding to local changes in the envelope of the auditory signal. In addition to simulating the classical effects of regular temporal grouping, the model of Hartley et al. (2016) was able to simulate the pattern of data observed when participants are presented with sequences composed of groups of irregular sizes (Ryan, 1969a). The model also supports that the coding of positional information is more likely to result from a bottom-up mechanism sensitive to the presentation timing of the input rather than from top-down expectations or knowledge about the temporal structure of the sequence (Farrell & Lelièvre, 2009). To sum up, even though there are conflicting evidences concerning the temporal nature of positional information in STM (Henson, 1999a; Ng & Maybery, 2002, 2005), the mechanisms proposed so far to address the problem of the unknown input temporal structure strongly rely on temporal components (see Hartley et al., 2016; Henson & Burgess, 1997). Thus, this highlights the importance of time-related information in coding serial order in STM (for a similar claim, see Farrell, 2008).

The importance of temporal aspects in STM for serial order information is also supported by other sources of evidence. There is evidence in the literature that temporal grouping of different sizes lead to different serial position curves and different patterns of transpositions (Hartley et al., 2016; Ryan, 1969a). It is also known that the maintenance of serially ordered verbal memoranda is sensitive to interfering tasks requiring the processing of rhythmic information irregularly organized (see, e.g., Gorin, Kowaliewski, & Majerus, 2016; Henson, Hartley, Burgess, Hitch, & Flude, 2003), while, conversely, STM for rhythm is disrupted by a concurrent task requiring articulatory activity (Saito & Ishio, 1998). At the same time, recent evidence suggests that presenting an isochronous rhythm during the retention phase of a serial order STM task improves serial recall performance (see Fanuel, Portrat, Tillmann, & Plancher, 2018; Plancher, Lévêque, Fanuel, Piquandet, & Tillmann, 2018). Taken together, these results strengthen the view according to which an important link exists between STM for rhythm, verbal STM for serial order, and timing processing (Saito, 2001), as well as a bidirectional association between timing and representation of serial order in STM (De Belder, van Dijck, Cappelletti, & Fias, 2017).

At the same time, in a series of studies looking at interposition patterns for temporally grouped sequences presenting items with different timings between the groups, Ng and Maybery (2002, 2005) reported evidence in favor of event-based models. They compared predictions from time-based and event-based models, according to which interposition errors should preserve, respectively, their temporal or ordinal within-group position. They showed that when the timing of item presentation differed between temporal groups, interposition errors preserved more frequently their within-group ordinal, rather than temporal position. Another challenge for time-based models is the

numerous evidence against a temporal isolation effect in STM tasks (for a review, see Lewandowsky, Wright, & Brown, 2007). Indeed, some time-based models (e.g., Brown, Neath, & Chater, 2007; Brown et al., 2000) assume that items temporally isolated from their neighbours during presentation benefit from better encoding and should result in better recall. Thus, the numerous evidence for an absence of a temporal isolation effect is challenging for time based-models of serial order.

2. The present study

The present project aims at further exploring the role that temporal factors play in serial order STM tasks. Thus far, the study of the influence of temporal components on serial order STM mostly involved regular or irregular patterns of temporal grouping (e.g., Hartley et al., 2016; Ryan, 1969a) or temporal isolation of items (e.g., Farrell, 2008; Lewandowsky et al., 2007). However, to the best of our knowledge, there are currently no studies dedicated to the manipulation of temporal factors in a context where groups are difficult to form, such as sequences of items played at a random pace (but see Farrell, 2008, for a study on temporal isolation in irregularly timed sequences). In a series of three experiments, we presented participants with sequences of digits presented either at a regular pace or at a pseudo-random pace. The latter had nonetheless some form of regularity. Nearly half the items followed a regular timing of presentation, alternated with items following an unpredictable random timing (see Figure 1 for an example). These experiments allowed to test an important prediction derived from event-based models of serial order STM (Burgess & Hitch, 1992; Henson, 1998; Lewandowsky & Farrell, 2008), according to which serial recall should not be sensitive to temporal manipulations as described in the present study. Indeed, as the pseudo-random rate of item presentation in irregular sequences should prevent the formation of clear temporal groups, and as event-based models are not equipped with a specific mechanism to track and extract the temporal structure of an input, this class of models does not predict an effect of irregular timing on serial recall.

Paradoxically, even though time-based models support that temporal factors play an important role in representing serial order information (Brown et al., 2007, 2000; Burgess & Hitch, 1999; Hartley et al., 2016; Henson & Burgess, 1997), it is not clear what predictions could be derived from these models when dealing with irregularly timed sequences. At the same time, considering together the data reported in the *Introduction* concerning the importance of temporal factors in serial order STM tasks, it is proposed that temporal regularity could influence the way serial order is represented in STM, with irregularly presented sequences being recalled worse than regular sequences. In addition, if rhythm influences the representation of serial order, the rhythmic pattern embedded in irregular sequences should be reflected in serial position curves and transposition gradients. Moreover, it is important to note that, even though it is not clear what predictions could be derived from time-based models, this class of models is, from a conceptual point of view, the most likely to predict an effect of temporal regularity in serial order STM tasks, and would be the best suited to accommodate such effects.

One has to note that the the present study differs from previous studies on the temporal isolation effect. In these studies, the focus is on the effect of isolating a specific item in the sequence on the recall of that item, that is, the influence of the duration of the pause preceding and following that item (see Lewandowsky et al., 2007). In the present study, the interest is to know whether serial recall is affected

by the whole temporal structure of the to-be-remembered sequence, without regard to temporal isolation. For instance, is serial recall influenced by item (dis)synchronization with the beat of a virtual isochronous rhythm during presentation (see Figure 1B)? Is serial recall performance different for items characterized by a regular versus irregular temporal interval with the preceding item during presentation (see Figure 1C)?

To conclude, it is believed that the present study has the potential to reveal currently unobserved timing-based phenomena in serial order STM tasks. Uncovering such effects would be of theoretical interest to further our understanding of the nature of serial order processes involved in STM tasks. The study of these phenomena would provide new and valuable data regarding the extent to which rhythmic aspects play a role in the representation of serial order. In addition, these data could be useful to test event-based models of serial order STM and to constrain future models. Finally, even though it is difficult, in the context of the present study, to derive predictions from time-based model, this class of models would be the best suited to accommodate the discovery of new timing-based serial order phenomena.

3. Experiment 1

3.1. Method

3.1.1. Sampling plan

There is a growing call in the field of psychological sciences to move towards a Bayesian framework in making inference and designing experiments (see, e.g., Wagenmakers, Marsman, et al., 2018). Bayesian statistical analyses have the advantage of not being sensitive to optional stopping rules, can be monitored during data collection, and are not influenced by the intention with which the data are collected (Berger & Berry, 1988; Dienes, 2016; Rouder, 2014). Moreover, in a Bayesian paradigm, the use of an optional stopping rule when a sufficient level of evidence is reached “guarantees the sensitivity of a study with a minimum of participants” (p. 82, Dienes, 2016). Taking into account all these considerations, we adopted a sequential Bayes factor sampling plan with a maximal number of subjects (see Schönbrodt & Wagenmakers, 2018; Schönbrodt, Wagenmakers, Zehetleitner, & Perugini, 2017).

We first recruited 20 adult participants and performed the planned analyses described in the *Analysis plan* section. For these analyses, we adopted a model comparison approach (see Rouder, Engelhardt, McCabe, & Morey, 2016), using the resulting Bayes factor (BF) obtained with the software JASP (version 0.9.2, JASP Team, 2019) as a relative measure of statistical evidence for the model being tested (Morey & Rouder, 2011). In other words, the BF can be interpreted as the relative predictive performance of two different hypothesis in explaining a given set of data. We stopped collecting data when for the two main analyses a defined level of statistical evidence has been reached (see the *Analysis plan* section for more details). If we did not meet the criterion to stop the experiment after the first 20 participants, we recruited more participants by groups of five while monitoring BF values, and we stopped the experiment once the criterion of statistical evidence has been reached for the two main analyses or, due to resource limitations, a maximum of 50 participants has been recruited. For more details about the analyses performed, see the *Analysis plan* section.

3.1.2. Participants

Participants were recruited on the campus of the University of Geneva and participated in the experiment in exchange of partial course credits. Participants took part to the experiment by groups of up to five people and all gave their written consent before starting the experiment. Finally, the experiment has been approved by the local ethics committee of the Faculty of Psychology and Sciences of Education of the University of Geneva. The same applies for Experiments 2 and 3.

For this experiment, a total of 53 participants have been recruited but three have been removed because they failed to meet the inclusion criteria. Thus, the final sample was composed of 50 participants (36 females; 46 right-handed; age: $M = 20.44$, $SD = 2.25$, range = 17–28; years of education: $M = 13.14$, $SD = 1.12$, range = 12–17; number of language spoken: $M = 1.74$, $SD = 0.72$, range = 1–3).

3.1.2.1. Inclusion and exclusion criteria. As the experiment involved the recall of digit lists presented auditorily in French, only French-speaking participants or participants with sufficient understanding of French have been recruited. Participants with any kind of neurological or speech disorders (e.g., dyslexia), or showing mean recall performance lower than two standard deviations from the group mean in the rhythmically regular condition, have been discarded from the experiment before performing the data analyses. In order to conform to the sampling plan exposed above, excluded participants have been systematically replaced by recruiting additional participants.

3.1.3. Stimuli

The stimuli used in this experiment consisted of 60 lists of nine digits ranging from 1 to 9. Digits were recorded by a French-speaking native male speaker with a 16-bit resolution and a sampling rate of 44,100 kHz. They were compressed to a duration of 350 milliseconds and saved as .wav audio files. As in Hartley et al. (2016), the lists were generated pseudo-randomly according to four different constraints: (1) no digit repetition within a list; (2) no numerically adjacent digits in adjacent positions (e.g., 1-2 or 7-8); (3) no more than two consecutive digits numerically ascending or descending (e.g., 7 \searrow 1 \nearrow 3 \nearrow 9 \searrow 5 was possible but not 7 \searrow 1 \nearrow 3 \nearrow 5 \nearrow 9); and (4) the same digit could not be presented at the same within-list position in consecutive trials. Finally, in order to avoid any unwanted effects stemming from the use of the same set of sequences for all the participants, a new set of 60 sequences has been created for each participant.

3.1.4. Experimental design

The experiment followed a repeated-measures design with a 2-level within-participant factor corresponding to the rhythmic structure of the to-be-remembered sequences (regular vs. irregular). The two types of sequences were presented in a pseudo-random order, that is, no more than three consecutive trials could have the same rhythmic structure. In regular sequences, digits were presented at a regular pace. In irregular sequences, digits occurring at odd-numbered serial positions were presented at the same time points as items at corresponding positions in regular sequences. The other items were presented at an unpredictable random pace. In other words, the inter-onset interval (IOI) between digits presented at odd-numbered serial positions was kept constant, while the IOI between digits occurring at even-numbered serial positions was unpredictable and randomly determined (see the *Procedure* section below for more

details). Note that for ease of reading, items at odd-numbered serial positions in irregular sequences, refer to as *rhythmically steady* items, while items at even-numbered serial positions refer to as *rhythmically unsteady* items.

3.1.5. Procedure

All the stimuli were played at a comfortable auditory level through headphones connected to the computer. Each trial started by hearing a 440-Hz pure tone lasting for one second generated directly by the program controlling the task. After a 500-millisecond silent period, the nine items were played at a pace following the rhythmic structure of the given trial (i.e., regular or irregular; see Figure 1). At the end of a trial, participants had to reconstruct the serial order of the digit sequence. For this, the digits 1 to 9 were horizontally displayed, from left to right, on the computer screen. Participants were reconstruct the order of the sequence, from the first to the last item, by clicking on each digit. When selected, the digit disappeared, and participants were left without the possibility to correct their response. The next trial started automatically after the selection of the last item. The experiment started with four training trials—each type of rhythmic structure presented twice—in order to ensure participants’ familiarization with the task requirements. Finally, to reduce cognitive fatigue and the decrease of motivation throughout the experiment, a short pause of a few minutes was proposed to participants after the 30th experimental trial.

For sequences composed of a regular rhythmic structure, all the items were played with an IOI of 800 milliseconds. For sequences composed of an irregular rhythmic structure, items at odd-numbered serial positions (i.e., rhythmically steady) had an IOI of 1600 milliseconds relative to the item at the preceding odd-numbered serial position, as if they occurred once every two beats of a regular rhythm presenting items at a rate of 800 milliseconds (see Figure 1A). For items occurring at even-numbered positions (i.e., rhythmically unsteady), the IOI relative to the preceding item in the sequence was randomly chosen in a range between 450 and 1150 milliseconds, excluding values in the range between 700 and 900 milliseconds to avoid values too close to the 800-millisecond regular pace. These values were chosen to ensure an inter-stimulus interval of at least 100 milliseconds between consecutive items in irregular sequences. Finally, the experiment has been implemented in and ran with the open source program Opensesame (version 3.2, Mathôt, Schreij, & Theeuwes, 2012).

3.2. Hypotheses

According to event-based models of serial order STM, the position of items in a sequence is represented through associations between the items and the state of a contextual signal changing as a function of item occurrences (Burgess & Hitch, 1992; Henson, 1998; Lewandowsky & Farrell, 2008). In that context, as change of the contextual signal is not driven by the timing of presentation, it is evident that event-based models would not predict an effect of irregular timing. Consequently, the absence of the expected benchmark features as described in the *Introduction* (i.e., superior recall for regular sequences, and altered pattern of errors and serial position curve for irregular sequences) would represent a strong argument in favor of event-based models of serial order STM. It is important to note that the sole presence of an effect of regularity on serial recall accuracy, but not on the pattern of transposition errors and the serial position curve, might still be considered as evidence for event-based models. Considering that temporal regularity can induce temporal preparation that helps

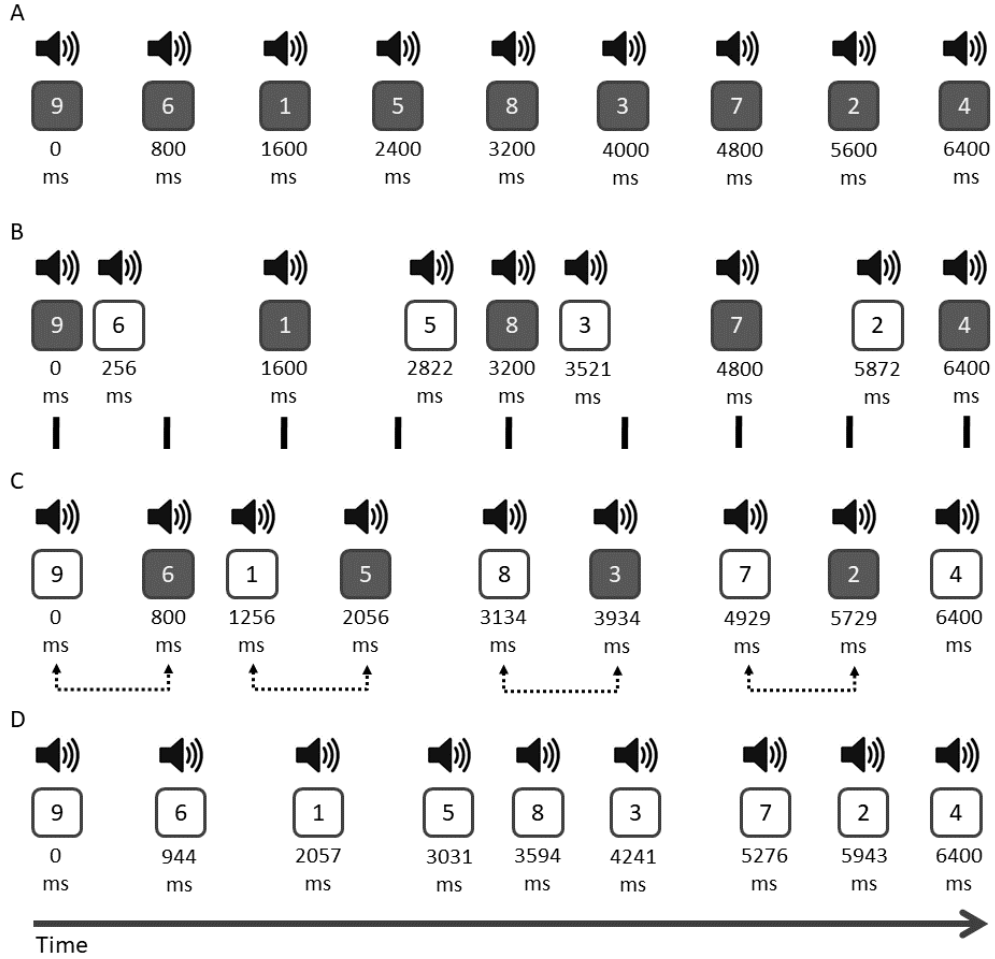


Figure 1. Example of a regular trial (A), an irregular trial in Experiment 1 (B), an irregular trial in Experiment 2 (C), and an irregular trial in Experiment 3 (D). Items depicted in grey are have a specific rhythmic status (i.e., items in regular trials and rhythmically steady items in irregular trials in Experiments 1 and 2). Grey items at odd-numbered serial positions in irregular trials in Experiment 1 (B) occur every 1600 milliseconds alternated with items following an irregular presentation rhythm (regular items occurred every two beats of a virtual 800-millisecond rhythm represented by the black vertical bars). In irregular trials in Experiment 2 (C), grey items at even-numbered serial positions always occur 800 milliseconds after the onset of the preceding items (the dashed arrows depict the regular IOI of 800 milliseconds). In irregular trials in Experiment 3 (D), items are white since timing is defined randomly for all items. Consequently, no items in Experiment 3 have a specific rhythmic status.

guiding attention to specific time points (Cutanda, Correa, & Sanabria, 2015; Jones, Moynihan, MacKenzie, & Puente, 2002), it is possible that regularity could guide attention and improve the encoding of items, resulting in only an effect of regularity on recall accuracy.

Alternatively, considering the evidence reported in the *Introduction* that regular and irregular timings impact serial order STM tasks, respectively in a positive and negative direction (e.g., Fanuel et al., 2018; Gorin et al., 2016; Henson et al., 2003; Plancher et al., 2018), one may predict to observe an effect of regularity in this experiment. Consequently, if rhythmic manipulations influence the way serial order is represented in STM tasks, we could expect that, compared to regular sequences, irregular sequences should be recalled less accurately, characterized by an altered pattern of serial order errors, and show a serial position curve reflecting the temporal manipulations implemented in the experiment.

3.2.1. *Serial position curve*

The serial position curve plots recall accuracy of items as a function of their position in the sequence. Usually, serial position curves take the form of a U-shape with recency and primacy effects (Cowan, Saults, Elliott, & Moreno, 2002; Oberauer, 2003). The primacy effect corresponds to a progressive decrease in recall accuracy from start to end of a sequence, while the recency effect is characterized by an upturn in recall accuracy for the last items.

As regards the serial position curve, we were first expecting a classical main effect of serial position characterized by a decrease of recall accuracy from the first to the last positions and an upturn of recall accuracy for the last items. We were also expecting a main effect of the type of sequence characterized by lower recall performance for irregular sequences. This effect should result from a higher number of errors in irregular sequences, due to the overall randomness of item timing that reduces the richness of serial order representation in irregular sequences. In addition to the two main effects, we were expecting an interaction between serial position and sequence type factors. As we hypothesized that rhythmically steady and unsteady items in irregular sequences could be characterized by different rhythmic temporal representation gained at encoding, we expected that this difference would have an impact on the shape of the serial position curve for irregular sequences. However, no specific predictions were made about the pattern of interaction, that is, in what way the shape of the serial position curve would change in the irregular condition compared the regular one.

3.2.2. *Transposition gradients*

In serial order STM, transposition gradients reflect the pattern of displacement distance of ordering errors. As reported in the *Introduction*, transposition errors are characterized by a locality constraint, that is, most of the errors involve a displacement to adjacent serial positions (Henson, 1996). The proportion of transposition errors also decreases as displacement distance increases.

Concerning the pattern of transposition gradients, we were first expecting a classical main effect of transposition distance, the proportion of transposition errors decreasing as a function the displacement distance increases. Regarding the effect of locality constraint (Henson, 1996), it is likely that the tendency to transpose items to adjacent positions could be affected by the hypothesized difference in terms of serial order representation between rhythmically steady and unsteady items in irregular sequences.

Consequently, as for the serial position curve analysis, we were expecting to observe an interaction between transposition distance and sequence type, with an altered pattern of transposition gradients for irregular sequences. Finally, we made no detailed predictions about the precise pattern of this interaction. It was plan to interpret the interaction, if any, in light of actual models of serial STM, in order to help choosing between actual models and potentially place new constraints on future models.

3.2.3. *Rhythmic transpositions*

In order to determine the influence of rhythmic structure on serial order recall in STM, our plan was to analyze participants' tendency to transpose items to serial positions that share the same rhythmic signature with their initial position (i.e., odd-to-odd or even-to-even serial order position transpositions). We hypothesized that in irregular sequences, rhythmically steady and unsteady items could be characterized by larger differences in their serial order representation compared to items at corresponding serial positions in regular sequences. Therefore, it could be expected that the proportion of rhythmic transpositions (i.e., odd-to-odd numbered serial positions) versus non-rhythmic transpositions (i.e., even-to-even numbered serial positions) would differ between regular and irregular sequence conditions. This would result in an interaction between the type of sequence and the type of transposition error, but we did not make precise predictions about the nature of this interaction.

3.3. *Analysis plan*

All the planned analyses reported below were performed using Bayesian repeated-measures analyses of variance (ANOVA) and Bayesian t -tests conducted with the open source software JASP with default settings for priors (version 0.9.2, JASP Team, 2019)¹. BF obtained through the analyses described below were interpreted according to the interpretation criteria suggested by Lee and Wagenmakers (2013): $BF < 3$ are considered as inconclusive evidence, and $BF > 3$ and $BF > 10$ are considered as moderate and strong evidence for the model being tested. For more details about how to perform and interpret Bayesian t -tests and Bayesian repeated-measures ANOVA with JASP, see Wagenmakers, Love, et al. (2018).

More precisely, we conducted Bayesian repeated-measures ANOVAs in which alternative models containing all combinations of effects as well as their interaction were compared to the null model including only the participant effect considered as a noise factor. Given that models that include an interaction without the corresponding main effects are considered implausible (see Rouder et al., 2016), only models including the constituent main effects of the corresponding interaction were considered (this is the default procedure in JASP). In the present study, we used the BF_{10} resulting from the comparison between each alternative model and the null model to select the best model (BF_{10} reflects the evidence in favor of the tested model relative to the null model, given the data). The model with the highest BF_{10} was considered as the model with the best predictive power. As a next step, the best model was compared to the second best model by dividing the BF_{10} of both models, producing a BF that can be interpreted as how much the data are likely to have been observed under the best model compared to the second best model. We monitored the relative BF between

¹The default prior distribution modeling the presence of an effect in Bayesian paired samples t -tests corresponds to a Cauchy distribution with an r scale of .707. In Bayesian ANOVA, fixed effects, random effects and covariates are by default represented by a Cauchy distribution with an r scale of 0.5, 1, and 0.354, respectively.

the best and the second best model in both main analyses (i.e., serial position curve and transposition gradients analyses, see below for more details) to determine whether enough evidence has been reached to stop the experiment. The chosen criterion specifies that the BF of the best model needs to be at least 10 times larger than the BF of the second best model. This would mean that the likelihood of observing the data is 10 times higher under the best model compared to the second best model, representing strong evidence in favor of the best model.

If after the first 20 participants the best model in both main analyses did not meet the stopping criterion, more participants were recruited, as described in the *Sampling plan* section. In case we did not reach the stopping criterion for both main analyses before reaching the maximum number of participants, we tested each effect separately with a Bayesian model averaging technique provided in JASP. This method determines the evidence supporting a given effect by averaging the evidence obtained for each model containing the effect of interest.

Finally, in Bayesian *t*-tests only two models are compared: a null model supporting an absence of effect and an alternative model supporting the presence of the effect. Consequently, only one BF_{10} is returned.

3.3.1. Serial position curve

It was plan to first analyze serial position curves by averaging for each participant, and separately for each type of sequence, recall accuracy as a function of item position across all the trials. This was done conducting a 2×9 Bayesian repeated-measures ANOVA, with a 2-level type of sequence factor (regular vs. irregular) and a 9-level serial position factor (from 1 to 9). In case the results favored an interaction between sequence type and serial position, it was planned to explore the extent to which recall accuracy differs between the two sequence conditions as a function of serial position by means of two-sided Bayesian paired samples *t*-tests.

3.3.2. Transposition gradients

We also planned to analyze transposition gradients by computing separately for each type of sequence, the proportion of serial order errors over all the errors produced as a function of their displacement distance; the displacement distance being computed in an absolute manner. This was done conducting a 2×8 Bayesian repeated-measures ANOVA, with a 2-level type of sequence factor (regular vs. irregular) and an 8-level displacement distance factor (from 1 to 8). If the interaction between sequence type and transposition distance was supported by the results, it was planned to explore the extent to which the transposition rate varies as a function of displacement differed between regular and irregular conditions via two-sided Bayesian paired samples *t*-tests.

3.3.3. Rhythmic transpositions

We finally planned to determine the proportion of rhythmic transposition errors (i.e., odd-to-odd numbered serial position transpositions) and non-rhythmic transposition errors (i.e., even-to-even numbered serial position transpositions) for each type of sequence separately. We intended to compare these proportions with a 2×2 Bayesian repeated-measures ANOVA, with a 2-level type of sequence factor (regular vs. irregular) and a 2-level displacement distance factor (rhythmic vs. non-rhythmic transpositions). In case the results provided support to the interaction between the two factors, it was planned to explore the nature of this interaction through two-sided Bayesian

Table 1. Results of the Bayesian repeated-measures analyses of variances for the serial position curves, transpositions gradients, and rhythmic transpositions analyses in Experiment 1.

Analysis	Models	P(M)	P(M data)	BF _M	BF ₁₀	Error %
Serial position curves	Null model (incl. subj.)	0.20	2.46e ⁻²²⁷	9.85e ⁻²²⁷	1.00	
	Sequence type	0.20	3.05e ⁻²²⁸	1.22e ⁻²²⁷	0.12	1.12
	Position	0.20	0.67	8.05	2.71e ²²⁶	0.39
	Sequence type + Position	0.20	0.33	1.95	1.33e ²²⁶	1.98
	Sequence type + Position + Sequence type × Position	0.20	4.70e ⁻³	0.02	1.91e ²²⁴	1.69
Transposition gradients	Null model (incl. subj.)	0.20	5.14e ⁻⁴²⁵	2.06e ⁻⁴²⁴	1.00	
	Sequence type	0.20	4.11e ⁻⁴²⁶	1.64e ⁻⁴²⁵	0.08	2.66
	Distance	0.20	0.93	51.84	1.81e ⁴²⁴	0.37
	Sequence type + Distance	0.20	0.07	0.31	1.39e ⁴²³	1.09
	Sequence type + Distance + Sequence type × Distance	0.20	1.62e ⁻⁴	6.47e ⁻⁴	3.14e ⁴²⁰	2.84
Rhythmic transpositions	Null model (incl. subj.)	0.20	0.69	8.84	1.00	
	Sequence type	0.20	0.11	0.51	0.17	3.65
	Transposition	0.20	0.17	0.79	0.24	1.72
	Sequence type + Transposition	0.20	0.03	0.11	0.04	3.75
	Sequence type + Transposition + Sequence type × Transposition	0.20	5.77e ⁻³	0.02	8.38e ⁻³	6.61

Note. All models include subject and for each analysis models are compared to the null model; Sequence type = rhythm effect; Position = serial position effect; Distance = absolute transposition distance effect; Transposition = type of transposition effect.

paired samples *t*-tests. Finally, it is important to note that this analysis did not depend on whether an interaction was revealed in the transposition gradients analysis, as one would expect. For instance, let us consider that the summed rates of rhythmic and non-rhythmic transpositions are equivalent in both conditions, but that the distribution of these error types is different between conditions. While such a pattern could be relevant for the purpose of our study, it could be invisible when looking at transposition gradients without the distinction between rhythmic and non-rhythmic transpositions.

3.4. Results

3.4.1. Planned analyses

Serial position curves, transpositions gradients and rhythmic transpositions observed in Experiment 1 are depicted in Figure 2. The results of the Bayesian repeated-measures ANOVA with sequence type (regular vs. irregular) and serial position (1 to 9) factors are shown in the top part of Table 1. The best model is the one containing only the effect of serial position, preferred over the second best model containing the two main effects of serial position and sequence type by a factor of 2.04. This means that the data are roughly two times more likely to have been obtained under the model with only the serial position effect rather than the same model complemented with the effect of sequence type.

As the experiment reached the maximum number of 50 participants without obtaining compelling evidence in favor of the best model (i.e., a BF larger than 10 when compared to the second best model), an analysis of effect has been performed, according to the initial plan. The results provided decisive evidence for the presence of an effect of serial position (BF_{Inclusion} = 6.00e¹⁵), but moderate (BF_{Exclusion} = 3) and strong (BF_{Exclusion} = 50) evidence against the presence of an effect of the type of

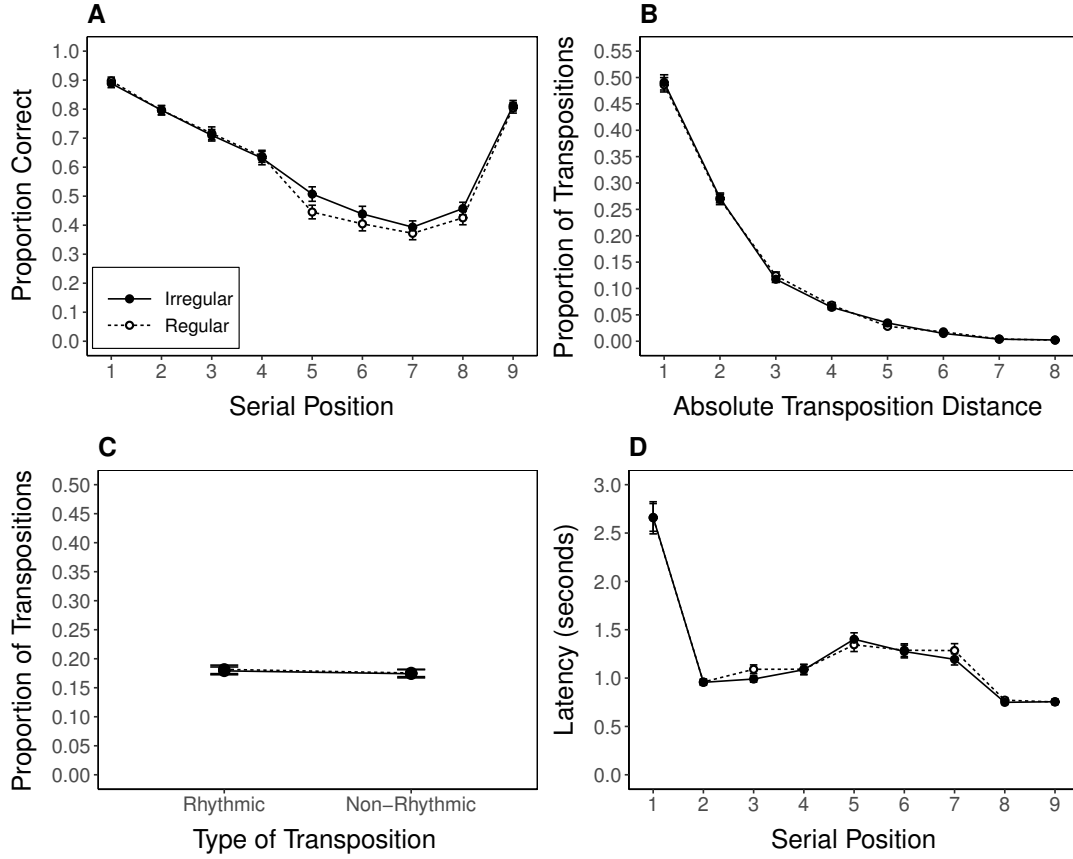


Figure 2. (A) Serial position curves from Experiment 1, averaged as a function of serial position and presentation rhythm. (B) Transpositions gradients from Experiment 1, averaged as a function of absolute displacement distance and presentation rhythm. (C) Rhythmic transpositions in Experiment 1, averaged across the type of transposition (rhythmic, non-rhythmic, other) and presentation rhythm. (D) Responses latencies of correct recall in Experiment 1, averaged as a function of absolute displacement distance and presentation rhythm. Error bars represent standard error of the mean.

sequence and an interaction between sequence type and serial position, respectively. Overall, the analysis of the serial position curves provided evidence for an absence of presentation rhythm on recall accuracy and on the shape of the serial position curve (see Figure 2A).

Concerning the analysis of transposition gradients, the results of the Bayesian repeated-measures ANOVA with type of sequence (regular vs. irregular) and absolute transposition distance (1 to 8) factors revealed that the best model is the model including only the effect of transposition distance (see middle part of Table 1). This model is preferred by a factor of 12.99 over the second best model containing the two main effects of sequence type and transposition distance. This indicates that the data are roughly 13 times more likely to have been observed under the best model rather than the second best model, representing strong support for the presence of only an effect of distance on the pattern of transpositions and for the absence of an effect of rhythm presentation (see Figure 2B).

The results of the Bayesian repeated-measures ANOVA with type of transposition (rhythmic vs. non-rhythmic) and type of sequence (regular vs. irregular) factors conducted on rhythmic transpositions is reported in the bottom part of Table 1. They

Table 2. Results of the Bayesian repeated-measures analyses of variances on response latencies as a function of serial position in Experiment 1.

Models	P(M)	P(M data)	BF _M	BF ₁₀	Error %
Null model (incl. subject)	0.20	7.73e ⁻¹⁷⁴	3.09e ⁻¹⁷³	1.00	
Sequence type	0.20	6.23e ⁻¹⁷⁵	2.49e ⁻¹⁷⁴	0.08	2.22
Position	0.20	0.92	44.19	1.19e ¹⁷³	0.74
Sequence type + Position	0.20	0.08	0.36	1.07e ¹⁷²	1.51
Sequence type + Position + Sequence type × Position	0.20	1.46e ⁻⁴	5.82e ⁻⁴	1.88e ¹⁶⁹	4.38

Note. All models include subject and are compared to the null model; Sequence type = rhythm effect; Position = serial position effect.

revealed that the best model is the null model, preferred over the second best model with only the type of transposition effect by a factor of 4.11. As shown in Figure 2C, this moderately supports the absence of an effect of rhythm presentation on the probability to transpose items with the same rhythmic signature (i.e., odd-to-odd or even-to-even serial position transpositions).

3.4.2. Exploratory analyses

The planned analyses support an absence of effect of rhythm on serial order STM performances, favouring strongly event-based theories. At the same time, it is a possibility that rhythm did not affect performances, while nonetheless impact the dynamic of recall. Past researches reported that the temporal structure of memoranda can be reflected in response latencies—that is, the temporal interval separating two outputted items (see, Farrell & Lewandowsky, 2004; Farrell, Wise, & Lelièvre, 2011; Maybery, Parmentier, & Jones, 2002). To explore the possibility that rhythm influenced the dynamic of recall, we analyzed response latency as a function of serial position. Response latency was scored as the time taken to recall an item relative to the item previously recalled, or relative to the last presented item for the first item recalled. The results of a Bayesian repeated-measures ANOVA conducted on response latency for correct items with sequence type (regular vs. irregular) and serial position (1 to 9) factors is shown in Table 2. The results revealed that the best model is the model with only the effect of serial position, being preferred over the second best model with the two main effects of type of sequence and serial position by a factor of 11.07. This represents strong evidence against an effect of rhythm on response latency curves (see Figure 2D).

Another phenomenon that was not considered in the initial plan is the influence of item temporal proximity on the rate of transposition errors. Such an analysis would be of interest to help to disentangle between time-based and event-based theories. The former class of models assumes that serial order of items is represented on a temporal continuum, leading to the fact that the closer in time the items are, the more they are likely to be confused (Brown et al., 2007, 2000; Henson & Burgess, 1997). Based on this assumption, when an item is surrounded by a short and a long temporal interval, one may expect to observe more transpositions to the temporally closer position than the more distant one. Conversely, event-based theories (Henson, 1998; Lewandowsky & Farrell, 2008) would predict that in the same context, transpositions should involve the closer position as frequently as the distant position. In the present experiment, temporal intervals between items in the irregular sequences can be labelled as short (between 450 and 700 milliseconds) or long (between 900 and 1150 milliseconds). We analysed in irregular trials all the items surrounded by a short and a long interval that

were erroneously recalled at an adjacent serial position. Then, we determined the proportion of items that were transposed to the closest serial position and compared this rate to what would be observed by chance—that is, 0.50 as predicted by event-based theories—via a Bayesian one sample t -test with an alternative hypothesis specifying a mean higher than chance—that is, the prediction of time-based theories. The rate of adjacent transpositions to the closest serial position was of 0.52 ($SD = 0.10$). The analysis revealed a BF_{10} of 1.08 representing similar support to both models and being considered as inconclusive.

3.5. Discussion

Based on evidences that rhythm can influence performances in STM tasks (positively or negatively, see Fanuel et al., 2018; Gorin et al., 2016; Henson et al., 2003; Plancher et al., 2018; Saito, 1994), it was hypothesized that presenting items with an irregular timing might negatively impact serial recall accuracy and affect error patterns as well. At the same time, if we assume that time plays no role in the representation of serial order as hypothesized in event-based models, one could have made the opposite prediction that timing should not affect serial recall performances.

The results of Experiment 1 support that presenting participants with temporally irregular sequences has no impact on recall accuracy, as well as on the shape of the serial position curve. It is noteworthy that even though one consider that the panel A of Figure 2 might suggest an effect of the type of sequence on serial recall accuracy, it is numerically speaking in the wrong direction relative to the initial prediction. The same evidence for the absence of an effect of timing presentation was observed when looking at the patterns of transpositions errors. Exploratory analyses also provided support in favor of event-based theories of serial order. The analysis of response latencies—known to reflect temporal input temporal structure (see Farrell, 2008; Maybery et al., 2002)—showed evidence for the absence of an effect of timing presentation on the recall dynamic. Additional analysis of adjacent transpositions as a function of temporal proximity did not provide evidence that transpositions involved more frequently the closest serial position when an item is surrounded by a short and a long interval. Even though the analysis of transposition as a function of temporal proximity provided equivocal results, the fact that interpositions involving the closest position is only 2% above the chance-level speaks against time-based accounts of serial order representation. This rather suggests that for items surrounded by a short and a long interval, adjacent transpositions towards the closer position were as frequent as to the distant position, in line with predictions from event-based theories of serial order.

Altogether, the results from this experiment strongly support event-based models of STM acknowledging no role of time in the representation of serial order (for similar conclusions, see Ng & Maybery, 2002, 2005). At the same time, it was hypothesized that in irregular sequences rhythmically steady items would have been characterized by serial order representations different than those characterizing unsteady items—what was expected to be observed through the shape of the serial position curve and error patterns. However, it is a possibility that the hypothesized time-based mechanisms involved in coding serial order are sensitive to temporal manipulations which are relative, but no absolute as it was the case in Experiment 1. This alternative was tested in the next experiment.

4. Experiment 2

4.1. Method

The method in Experiment 2 was the same as in Experiment 1, except that we changed the rhythmic pattern of the irregular sequences (see Figure 1C). In Experiment 1, we manipulate the regularity of item occurrences in an absolute way: each rhythmically steady item regularly occurs every two beats of a virtual 800-milliseconds rhythm relative to the start of the sequence. In Experiment 2, we manipulated the regularity of item occurrences in a relative manner. In other words, items that occurred at even-numbered serial positions always had a regular IOI of 800 milliseconds relative to the preceding item in the sequence (see grey digits in Figure 1C), while items that occurred at odd-numbered serial positions had a random IOI relative to the preceding item in the sequence (see white digits in Figure 1C). Consequently, items at even-numbered and odd-numbered serial positions in Experiment 2 correspond to rhythmically steady and rhythmically unsteady items, respectively. Finally, random IOIs were determined as described in Experiment 1 and their sum was always equal to 3200, that is, half of the sum of the IOIs in a sequence.

4.1.1. Participants

For this experiment, 43 participants have been recruited but three have been removed from the sample because they failed to meet the inclusion criteria. The sample used for the analysis was composed of 40 participants (30 females; 31 right-handed; age: $M = 21.92$, $SD = 4.35$, range = 18–39; years of education: $M = 13.30$, $SD = 1.38$, range = 12–19; number of language spoken: $M = 1.65$, $SD = 0.89$, range = 1–5).

4.2. Hypotheses

Hypotheses in Experiment 2 were exactly the same as in Experiment 1, except that rhythmically steady and unsteady items are now assumed to occur at even-numbered and odd-numbered serial positions, respectively (see Figure 1C).

4.2.1. Serial position curve

The same hypothesis as described in Experiment 1 applied here. We expected a main effect of the type of sequence in favor of regular sequences, a classical effect of serial position, and an interaction between the two factors, but without making specific predictions about the pattern of interaction that could be observed.

4.2.2. Transposition gradients

The hypothesis about transposition gradients developed in Experiment 1 also applied in Experiment 2. We were expecting to observe a main effect of transposition distance and an interaction between transposition distance and sequence type factors without precise prediction regarding the nature of the interaction.

4.2.3. Rhythmic transpositions

For rhythmic transpositions, the same hypothesis than developed in Experiment 1 applied to Experiment 2. It was expected to observe an interaction between the type

Table 3. Results of the Bayesian repeated-measures analyses of variances for the serial position curves, transpositions gradients, and rhythmic transpositions analyses in Experiment 2.

Anaylsis	Models	P(M)	P(M data)	BF _M	BF ₁₀	error %
Serial position curves	Null model (incl. subject)	0.20	6.80e ⁻¹⁷⁵	2.72e ⁻¹⁷⁴	1.00	
	Sequence type	0.20	5.88e ⁻¹⁷⁶	2.35e ⁻¹⁷⁵	0.09	1.17
	Position	0.20	0.91	40.69	1.34e ¹⁷⁴	0.86
	Sequence type + Position	0.20	0.09	0.39	1.31e ¹⁷³	1.08
	Sequence type + Position +	0.20	2.06e ⁻⁴	8.23e ⁻⁴	3.02e ¹⁷⁰	1.63
	Sequence type × Position					
Transposition gradients	Null model (incl. subject)	0.20	2.07e ⁻³²³	8.28e ⁻³²³	1.00	
	Sequence type	0.20	1.82e ⁻³²⁴	7.28e ⁻³²⁴	0.09	2.58
	Distance	0.20	0.92	43.61	4.43e ³²²	0.44
	Sequence type + Distance	0.20	0.08	0.37	4.05e ³²¹	3.41
	Sequence type + Distance +	0.20	1.83e ⁻⁴	7.33e ⁻⁴	8.85e ³¹⁸	1.20
	Sequence type × Distance					
Rhythmic transpositions	Null model (incl. subject)	0.20	0.18	0.89	1.00	
	Sequence type	0.20	0.03	0.13	0.17	0.95
	Transposition	0.20	0.65	7.39	3.58	1.22
	Sequence type + Transposition	0.20	0.12	0.52	0.63	4.40
	Sequence type + Transposition +	0.20	0.02	0.10	0.13	1.96
	Sequence type × Transposition					

Note. All models include subject and for each analysis models are compared to the null model; Sequence type = rhythm effect; Position = serial position effect; Distance = absolute transposition distance effect; Transposition = type of transposition effect.

of transposition (rhythmic: even-to-even serial position transpositions; non-rhythmic: odd-to-odd serial position transpositions) and the type of sequence, but no predictions were made concerning the nature of the interaction.

4.3. Analysis plan

The analysis plan was be the same as in Experiment 1.

4.4. Results

4.4.1. Planned analyses

Serial position curves, transposition gradients and rhythmic transpositions from Experiment 2 are displayed in Figure 3. The results of the Bayesian repeated-measures ANOVA on recall accuracy as a function of the type of sequence (regular vs. irregular) and serial position (1 to 9), revealed that the best model is the model containing only the effect of serial position. This model was preferred over the second best model containing the two main effects of serial position and sequence type by a factor of 10.20 (see the top part of page 17). This suggest that the data are 10 times more likely to have been observed under the best model with only the effect of serial position than under the model with the two main effects and represent strong evidence for the best model (see Figure 3A).

The analysis of the pattern of transposition errors was performed via a Bayesian repeated-measures ANOVA with type of sequence (regular vs. irregular) and absolute transposition distance (1 to 8) factors. The results revealed that the best model is the model with only the effect of distance favoured over the second best model with the two main effects of distance and sequence type by a factor of 10.93 (see the middle part of Table 3). This represents strong evidence in favour of only an effect of distance on

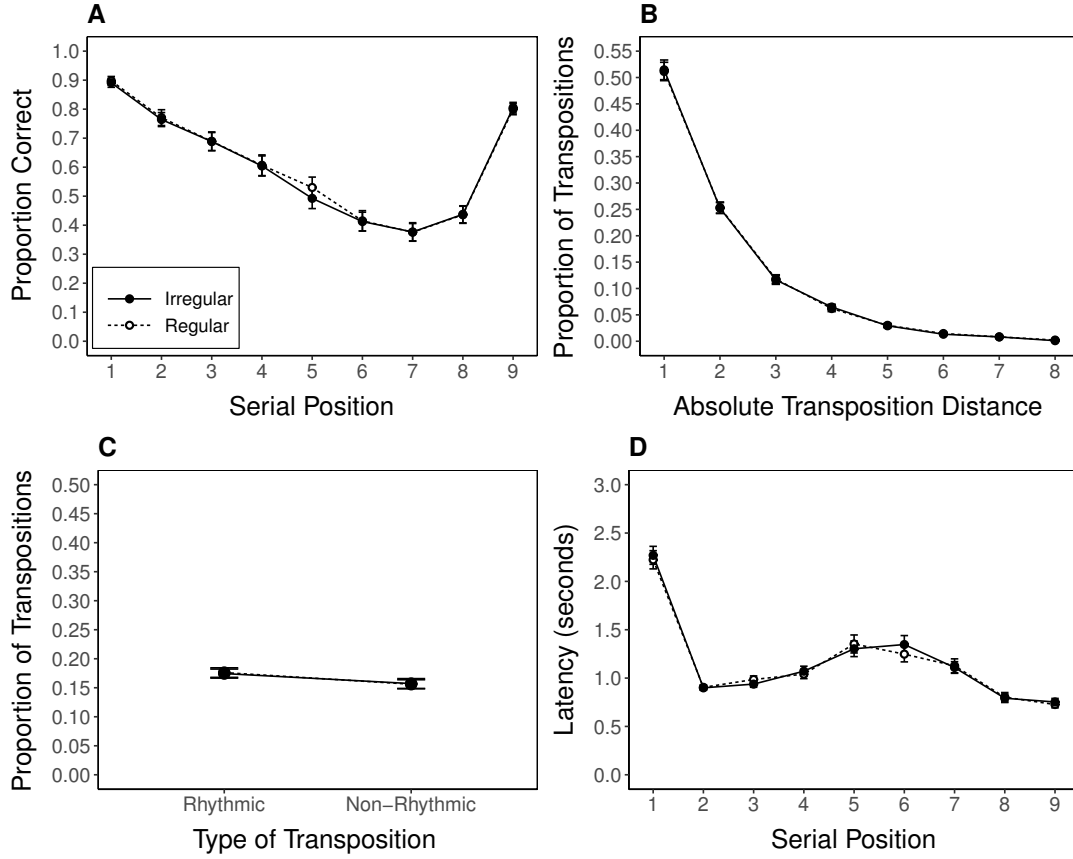


Figure 3. (A) Serial position curves from Experiment 2, averaged as a function of serial position and presentation rhythm. (B) Transpositions gradients from Experiment 2, averaged as a function of absolute displacement distance and presentation rhythm. (C) Rhythmic transpositions in Experiment 2, averaged across the type of transposition (rhythmic, non-rhythmic, other) and presentation rhythm. (D) Responses latencies of correct recall in Experiment 2, averaged as a function of absolute displacement distance and presentation rhythm. Error bars represent standard error of the mean.

the pattern of transposition errors with no effect of presentation rhythm (see Figure 3B).

Rhythmic transpositions errors were analyzed via a Bayesian repeated-measures ANOVA with type of transposition (rhythmic vs. non-rhythmic) and type of sequence (regular vs. irregular) factors. The results showed in the lower part of Table 3 support the model with only an effect of the type of transposition, being favor over the null model by a factor of 3.58. As the best model is supported only by moderate evidence, analysis of effects has been performed (see Supplementary Material). We observed a $BF_{\text{Exclusion}}$ of 7.14 and 10 for the main effect of type of sequence and the interaction between the two main effects, respectively. However, inconclusive evidence characterized by a $BF_{\text{Inclusion}}$ of 2.48 has been observed for the effect of the type of transposition. Thus, the main observation is that the type of of sequence did not influence the pattern of rhythmic transpositions (see Figure 3C).

4.4.2. Exploratory analyses

As in Experiment 1, the pattern of response latencies has been explored to determine whether relative regularities embedded in irregular sequences influenced partici-

Table 4. Results of the Bayesian repeated-measures analyses of variances on response latencies as a function of serial position in Experiment 2.

Models	P(M)	P(M data)	BF _M	BF ₁₀	Error %
Null model (incl. subject)	0.20	5.52e ⁻¹⁴³	2.21e ⁻¹⁴²	1.00	
Sequence type	0.20	4.66e ⁻¹⁴⁴	1.86e ⁻¹⁴³	0.08	1.37
Position	0.20	0.92	47.32	1.67e ¹⁴²	0.41
Sequence type + Position	0.20	0.08	0.33	1.40e ¹⁴¹	0.87
Sequence type + Position + Sequence type × Position	0.20	7.79e ⁻⁴	3.12e ⁻³	1.41e ¹³⁹	62.59

Note. All models include subject and are compared to the null model; Sequence type = rhythm effect; Position = serial position effect.

pants’ response latency. The analysis has been performed, as in Experiment 1, using a Bayesian repeated-measures ANOVA with sequence type (regular vs. irregular) and serial position (1 to 9) factors. The results revealed that the best model is the model with only an effect of serial position, preferred over the second best model with the two main effects of sequence type and serial position by a factor of 11.95 (Table 4). This means that data are roughly 12 times more likely to have been observed under the best than the second model, representing strong evidence in favour of an effect of serial position, and the absence of an effect of presentation rhythm on response latencies (see Figure 3D).

In addition, an analysis of the proportion of adjacent transpositions as a function of temporal proximity was performed as in Experiment 1. In Experiment 2, patterns of IOIs consisted of alternation between randomly defined intervals (short or long) and regular interval lasting for 800ms. Thus, each item at positions 2 to 8 was surrounded by an interval of 800ms and either a short or a long interval. We performed the same analysis as in Experiment 1, considering the regular interval of 800ms as short when the other interval was long, and vice versa. The results of a Bayesian one sample *t*-test with an alternative specifying a mean greater than the 0.50 chance-level, performed on the rate of adjacent transpositions involving the closest serial position, provided moderate evidence in favor of the null model (BF₀₁ = 6.66). This represents moderate support to the view that adjacent transpositions involved the closest serial position (mean = 0.50, SD = 0.08) as frequently as the more distant one.

4.5. Discussion

This second experiment tested the effect of timing irregularity of the presented items on serial order STM recall performance. The results obtained were perfectly in line with those from Experiment 1, providing evidence for the absence of an effect of timing presentation, and of the (relative) rhythmic structure embedded in irregular sequences, on serial recall performances. This was observed through planned analyses of serial recall accuracy and position, and transposition patterns. As in Experiment 1, exploratory analyses of response latencies and adjacent transpositions as a function of temporal proximity provided additional support in favour of the absence of an effect of rhythm on serial recall performance.

Considered together with the results reported in Experiment 1, the data observed in the present experiment strongly support event-based theories considering that the representation of serial order changes as a function of item occurrences, assuming no role of time. According to this theory, presenting participants with a regular timing, an irregular timing but with an embedded rhythmic structure, or an irregular timing

totally random, should lead to the same pattern of data. Experiment 3 was thus designed to compare serial recall for regular sequences and irregular sequences without any hidden rhythmic structure, representing a final test of the predictions derived from event-based theories².

5. Experiment 3

5.1. Method

The method in Experiment 3 was be the same as in Experiments 1 and 2, except that in irregular trials all the items were played according to a randomly defined timing, and were fully unpredictable. Timing was defined as described in the method of Experiment 1, ensuring that IOIs sum to 6400 milliseconds, and that individual IOI values range between 450 and 1150 milliseconds, excluding values within the 700-900 milliseconds range.

5.1.1. Participants

For this experiment, 54 participants have been recruited but four have been removed from the sample because they did not meet the inclusion criteria. The final sample on which the analyses have been performed was composed of 50 participants (38 females; 46 right-handed; age: $M = 21.34$, $SD = 3.43$, range = 18–36; years of education: $M = 13.12$, $SD = 0.98$, range = 12–17; number of language spoken: $M = 1.74$, $SD = 0.75$, range = 1–3).

5.2. Hypothesis

The aim of Experiments 1 and 2 was to confront the prediction derived from event-based theories predicting no effect of irregular rhythm on serial recall, to another hypothesis proposing that rhythm might influence the way serial order is represented in STM. In line with the second position, it has been hypothesized that, in Experiments 1 and 2, recall accuracy should be better for regular sequences compared to irregular sequences. Moreover, it was suggested that the rhythmic pattern embedded in irregular sequences in the two experiments might be reflected in serial position curves and transpositions gradients.

In Experiment 3, the timing of item presentation in irregular sequences was, on average, the same as in Experiments 1 and 2³. However, Experiment 3 has been designed in a way that no rhythmic structure was embedded in irregular sequences. Thus, Experiment 3 served as a control experiment and was interpreted in light of the data obtained in Experiments 1 and 2.

It was expected that, in case the results from the two first experiments were in line with the predictions from event-based models, the results of Experiment 3 would be similar to those in Experiments 1 and 2. On the contrary, if the overall results in Experiments 1 and 2 would have supported the hypothesis that rhythmic aspects

²I am imdebted to Steve Majerus for suggesting this last experiment.

³For Experiment 1, IOIs in irregular sequences, averaged across the 50 participants, correspond to 801, 799, 804, 796, 790, 810, 806, and 794 milliseconds. For Experiment 2, IOIs in irregular sequences, averaged across the 40 participants, correspond to 800, 807, 800, 801, 800, 797, 800, and 795 milliseconds. For Experiment 3, IOIs in irregular sequences, averaged across the 50 participants, correspond 799, 800, 805, 806, 790, 804, 798, and 798 milliseconds.

Table 5. Results of the Bayesian repeated-measures analyses of variances for the serial position curves, transpositions gradients, and rhythmic transpositions analyses in Experiment 3.

Anaylsis	Models	P(M)	P(M data)	BF _M	BF ₁₀	error %
Serial position curves	Null model (incl. subject)	0.20	5.09e ⁻²¹⁵	2.04e ⁻²¹⁴	1.00	
	Sequence type	0.20	5.25e ⁻²¹⁶	2.10e ⁻²¹⁵	0.10	1.83
	Position	0.20	0.82	17.87	1.61e ²¹⁴	0.36
	Sequence type + Position	0.20	0.18	0.89	3.59e ²¹³	4.12
	Sequence type + Position + Sequence type × Position	0.20	3.17e ⁻⁴	1.27e ⁻³	6.23e ²¹⁰	3.20
Transposition gradients	Null model (incl. subject)	0.20	1.85e ⁻³⁶⁰	7.39e ⁻³⁶⁰	1.00	
	Sequence type	0.20	1.41e ⁻³⁶¹	5.64e ⁻³⁶¹	0.08	0.77
	Distance	0.20	0.93	52.59	5.03e ³⁵⁹	0.48
	Sequence type + Distance	0.20	0.07	0.30	3.77e ³⁵⁸	1.00
	Sequence type + Distance + Sequence type × Distance	0.20	9.56e ⁻⁴	3.83e ⁻³	5.18e ³⁵⁶	1.80

Note. All models include subject and for each analysis models are compared to the null model; Sequence type = rhythm effect; Position = serial position effect; Distance = absolute transposition distance effect; Transposition = type of transposition effect.

influence the way serial order is represented in STM, Experiment 3 was plan to represent a critical test for that hypothesis. Since the timing of item presentation is, on average, closely matched across the three experiments but that Experiment 3 did not present a rhythmic structure in the irregular sequences, it was hypothesized that the rhythm regularity factor should not affect the shape of the serial position curve nor transposition gradients; only the recall advantage for regular sequences should remain.

5.3. Analysis plan

The same guidelines as described in Experiments 1 and 2 were used to analyze data collected. One difference is the absence of rhythmic transpositions analysis, due to the fact that no rhythmic structure was embedded in the irregular sequences in Experiment 3.

5.4. Results

5.4.1. Planned analyses

Serial position curves, transpositions gradients and rhythmic transpositions from Experiment 3 are depicted in Figure 4. The results of the Bayesian repeated-measures analysis performed on recall accuracy as a function of serial position (1 to 9) and sequence type (regular vs. irregular) showed that the best model is the model containing only an effect of serial position. This model is preferred over the second best model with the two main effects of serial position and type of sequence by a factor of 4.47, representing moderate evidence in favor of the best model (see the top part of Table 5).

As we reached the maximum sample size of 50 participants without meeting the defined level to stop data collection, we ran an analysis of effects. The results provided strong evidence for the presence of an effect of serial position on recall accuracy ($BF_{\text{Inclusion}} = 6.00e^{15}$), but moderate ($BF_{\text{Exclusion}} = 6.67$) and strong ($BF_{\text{Exclusion}} = 787$) evidence against the presence of an effect of sequence type and an interaction between the two effects. The results overall support that recall accuracy varied only as a function of serial position with no effect of presentation timing (see Figure 4A).

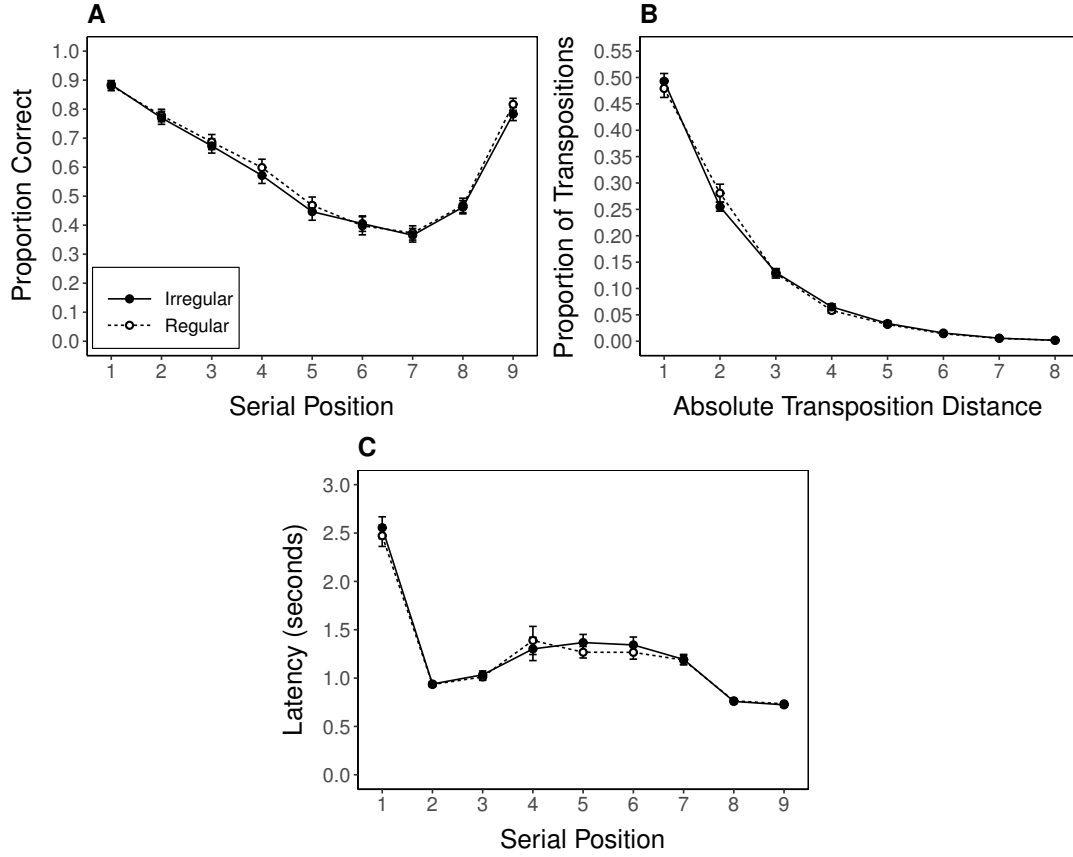


Figure 4. (A) Serial position curves from Experiment 3, averaged as a function of serial position and presentation rhythm. (B) Transpositions gradients from Experiment 3, averaged as a function of absolute displacement distance and presentation rhythm. (C) Responses latencies of correct recall in Experiment 3, averaged as a function of absolute displacement distance and presentation rhythm. Error bars represent standard error of the mean.

Transposition gradients were analyzed via a Bayesian repeated-measures ANOVA with type of sequence (regular vs. irregular) and absolute transposition distance (1 to 8) factors. The analysis revealed that the best model is the model with only an effect of distance and the model is favored over the second best model with the two main effects of distance and sequence type by a factor of 13.33 (see the middle part of Table 5). This suggests that the data are roughly 13 times more likely to be observed under the best model than under the second best model, representing strong support to the presence of an effect of distance on transposition errors (see Figure 4B).

5.4.2. Exploratory analyses

As in Experiments 1 and 2, the response latencies associated to correctly recalled items were analyzed in order to determine whether irregularity of item presentation at input would influence output timing. Thus, response latencies were analyzed via a Bayesian repeated-measures ANOVA with type of sequence (regular vs. irregular) and serial position (1 to 9) factors. The results revealed that the best model is the model with only the effect of serial position, preferred over the second best model with the two main effects of serial position and type of sequence by a factor of 10.86 (see Table 6). This indicates that the data are roughly 11 times more likely to be obtained under

Table 6. Results of the Bayesian repeated-measures analyses of variances on response latencies as a function of serial position in Experiment 3.

Models	P(M)	P(M data)	BF _M	BF ₁₀	Error %
Null model (incl. subject)	0.20	3.20e ⁻¹⁴²	1.28e ⁻¹⁴¹	1.00	
Sequence type	0.20	2.59e ⁻¹⁴³	1.04e ⁻¹⁴²	0.08	1.10
Position	0.20	0.92	43.33	2.86e ¹⁴¹	0.36
Sequence type + Position	0.20	0.08	0.37	2.63e ¹⁴⁰	1.07
Sequence type + Position + Sequence type × Position	0.20	1.73e ⁻⁴	6.93e ⁻⁴	5.41e ¹³⁷	2.12

Note. All models include subject and are compared to the null model; Sequence type = rhythm effect; Position = serial position effect.

the best rather than the second best model, thus representing strong evidence in favor of only an effect of serial position on response latencies, and more critical support the absence of an effect of timing presentation (see Figure 4C).

We also reproduced the same analysis of adjacent transpositions as a function of temporal proximity following the same procedure as described in Experiment 1. The results of the Bayesian one sample *t*-test with an alternative hypothesis specifying a mean greater than the 0.50 chance-level did not provide evidence that adjacent transpositions involved more frequently close serial position (mean = 0.52, SD = .13) than the more distant one. The evidence was anecdotally supporting the null hypothesis relative to the alternative (BF₀₁ = 2.43).

5.5. Discussion

As in Experiments 1 and 2, the manipulation of presentation timing had no effect on recall performance. We observed the same serial position curve for regular and irregular sequences, as well as the same pattern of errors. Exploratory analyses of response latencies and adjacent transpositions errors also provided evidence against an effect of irregular rhythm. This pattern of results is in line with the predictions from event-based models of serial order STM, according to which time plays no role in representing serial order.

6. General Discussion

The present study was conducted with the aim of better understanding the role of time in the representation of serial order information in STM. To reach this goal, we tested the claim of event-based theories according to which serial order is represented through time-independent codes (Henson, 1998; Lewandowsky & Farrell, 2008). In line with this view, it was predicted that item presentation timing should not influence serial recall performances. This prediction was contrasted with another one assuming that, if time plays a role in the representation of serial order in STM, recall performances should be affected by the manipulation of presentation timing. This second prediction was inspired by theories supporting the existence of time-based representation of serial order in STM (Brown et al., 2007, 2000; Burgess & Hitch, 1999; Hartley et al., 2016), as well as by evidence that temporal manipulations can influence—positively and negatively—performances in serial order STM tasks (see Fanuel et al., 2018; Gorin et al., 2016; Henson et al., 2003; Plancher et al., 2018). In three experiments, we asked participants to reconstruct the serial order of 9-digit lists presented either with a reg-

ular or an irregular timing. Through the analysis of serial recall components known to be sensitive to temporal manipulations—that is, response accuracy, the shape of the serial position curve, and transposition errors (see, e.g., Hartley et al., 2016)—we found, consistently across the three experiments and for each component, evidence against an effect of presentation timing. In addition, exploratory analyses of responses latencies—described in previous studies as reflecting input temporal structure (Farrell, 2008; Maybery et al., 2002)—showed that participants’ recall dynamic is immune to the manipulation of presentation timing. Finally, other exploratory analyses of transpositions as a function of temporal proximity did not provide support to the view that adjacent transposition errors are influenced by temporal proximity. Considered together, these results provide strong evidence in favor of event-based theories assuming that serial order is represented through time-independent codes (Henson, 1998; Lewandowsky & Farrell, 2008).

At the same time, one could argue that the initial presentation timing was neutralized by participants’ rehearsal, leading to the regularization of the temporal structure of irregular sequences. However, previous studies showed that the effects characterizing temporal manipulations in serial recall tasks do not depend on rehearsal. First, there is evidence that the temporal grouping effects observed with auditory material resist articulatory suppression (Hartley et al., 2016; Hitch et al., 1996). Second, the boosting effect observed in serial recall tasks when the maintenance phase is filled with an isochronous rhythm is also present when participants perform a concurrent articulatory suppression task (Plancher et al., 2018). Finally, Ng and Maybery (2002, 2005) observed that interposition errors in grouped sequences are driven by positional rather than temporal cues, supporting event-based theories of serial order. Interestingly, the authors replicated their observation with articulatory suppression, ruling out an interpretation based on regularization through rehearsal. Consequently, despite the absence of articulatory suppression in the present study, it seems unlikely that the null effect of timing was due to the regularization through the rehearsal of the temporal structure of irregular sequences.

A second alternative to explain the absence of an effect of timing would be that the temporal manipulations used in this study involuntarily induced the perception of group structures for a subset of irregular trials. In that case, an effect of presentation timing for such subset may have been washed out in the planned analyses where performance was averaged across all the irregular trials. If so, the dispersion characterizing recall accuracy data should be larger for irregular than regular sequences, reflecting the presence of two subsets in irregular trials. To explore this possibility, the standard deviation associated with recall accuracy collapsed across serial positions has been compared between regular and irregular conditions. The comparison was performed with directed Bayesian paired samples t -tests characterized by an alternative model predicting a larger standard deviation for irregular trials. The results provided moderate (Experiment 1: $BF_{01} = 4.39$; Experiment 2: $BF_{01} = 6.34$) and inconclusive (Experiment 3: $BF_{01} = 0.79$) evidence in favor of the null model predicting no difference between regular and irregular sequences in terms of data dispersion. In order to have a better picture of the results, a meta-analytic Bayesian t -test was performed, with the alternative model predicting again a larger standard deviation for irregular trials. The results confirmed the absence of a difference between the two types of trials in terms of data dispersion, providing strong support for the null hypothesis ($BF_{01} = 22.88$)⁴. Thus, the analysis of data dispersion suggests that the alternative

⁴The meta-analytic t -test was performed with the *BayesFactor* package (Morey & Rouder, 2015) ran in *R* (R

explanation—that is, a subset of irregular trials were perceived as grouped—is not a likely interpretation.

Another alternative to explain the null effect of timing would be to consider that serial order information was represented along both temporal and positional dimensions (see Brown et al., 2007), but that participants relied weakly on the temporal dimension. Previous research showed that information about timing and position can be dissociated in serial order STM (Farrell, 2008; Farrell & McLaughlin, 2007), and that participants can also allocate different weights to the temporal and positional dimensions to retrieve the serial order of items (Lewandowsky, Nimmo, & Brown, 2008). It is thus a possibility that information about timing was readily available in STM but, considering that this information does not provide an additional layer of information to structure the sequences, participants allocated their attention only to the positional dimension of serial order during retrieval.

6.1. Theoretical implications for models of serial order short-term memory

The results reported in this study corroborate previous findings supporting that time-based manipulations, at the exception of temporal grouping, has no or only negligible influence on serial order STM task performances (see, e.g., Brown & Lewandowsky, 2005; Farrell & McLaughlin, 2007; Lewandowsky, Duncan, & Brown, 2004; Ng & Maybery, 2002, 2005). Thus, these results strongly suggest that serial order is represented with absolute positional codes and support event-based theories of serial order (Henson, 1998; Lewandowsky & Farrell, 2008).

Event-based theories support that serial order is represented through the binding of the items and the different states of a contextual signal representing positions, the signal state changing as items occurred in a sequence but without influence of the passage of time (Lewandowsky et al., 2004; Ng & Maybery, 2002, 2005). This way of representing serial order allows this class of models to account for the null effect of temporal manipulations observed in the present study, as well as the absence of a temporal isolation effect and time-independent interpositions observed in previous studies (Lewandowsky et al., 2004; Ng & Maybery, 2002, 2005). However, event-based models made no specific assumption regarding the mechanism underlying the recruitment of the additional contextual signal in grouped sequences. In other words, it is not clear how group boundaries are detected. Consequently, even though event-based theories can account for the null effect of timing in the present study, it is not clear how temporal variations in grouped sequences would lead to the recruitment of an additional contextual signal, but not in irregularly timed sequences used here.

In the Start-End model (Henson, 1998), it is suggested that group boundaries provide the condition to insert additional contextual markers, but the details regarding how a group boundaries are detected are missing. In that model, positional information is coded relative to both the start and the end of a sequence. As it is difficult to conceive how the items are coded relative to the end of a sequence that has not yet occurred, Henson (1998) proposed that the end marker represents the degree of expectation regarding when the last item may occur. The fact that temporal grouping leads to recruiting an additional contextual signal could be explained by considering that in an experiment where the grouped sequences are characterized by a regular grouping

Core Team, 2014), following the method proposed by Morey and Rouder (2011). The alternative was modeled as a Cauchy distribution with an r scale of 0.707.

structure, participants can rely on their expectation about the grouping structure to engage an additional contextual marker. To the opposite, in the case of irregular sequences as in the present study, the absence of predictability regarding the temporal structure of the sequences would impede the use of top-down temporal representations. However, even though top-down expectations play a role in temporal grouping (Farrell, 2008; Farrell & Lelièvre, 2009), there is evidence that the effects associated with temporal grouping do not depend on the degree of expectation regarding the temporal structure of the input (Hartley et al., 2016). Consequently, an explanation of the fact that grouped sequences recruit an additional contextual signal but not the irregular ones, based on top-down expectations, seems difficult to uphold.

In an alternative version of the Star-End model, Henson and Burgess (1997) described a parsing mechanism allowing the detection of temporal groups. According to these mechanisms, a group is detected once an item fails to occur during the temporal interval defined by the last two items. Given the variability of successive inter-item intervals in the irregular sequences used in the present study, a parsing mechanism as described in Henson and Burgess (1997) should have led to the detection of temporal groups in such sequences. For instance, the trial in Figure 1C should be parsed in a 3-1-2-3 grouping structure. However, as previously reported, there is no evidence in the results supporting the presence of grouping in irregular sequences—even for a subset of them. One could nonetheless argue that the irregular timings used in this study were characterized by some degree of variability in terms of the number of groups that could have been induced, as well as regarding the size of these groups, reducing thus the effectiveness of grouping. In order to test this possibility, we took advantage of the fact that the product of group sizes is a strong predictor of recall accuracy. We then parsed the irregular sequences according to the mechanism described in Henson and Burgess (1997) and we correlated for each participant the product of the group sizes of irregular trials with the recall accuracy for the corresponding trials. While in a previous study the correlation between the product of group sizes and recall accuracy has been reported around .75 (see Hartley et al., 2016), no sign of such association was found when averaging the correlation across participants (Experiment 1: mean = .04, SD = .14, range = -.23-.28; Experiment 2: mean = .05, SD = .20, range = -.42-.48; Experiment 3: mean = .03, SD = .20, range = -.31-.47). Thus, the absence of any sign of grouping in irregular sequences in the present study speaks against a mechanism detecting group boundaries based on inter-item interval duration.

While the results of this study can be easily accounted for by event-based theories, the extent to which these results are challenging for time-based models is not clear. A shared characteristic of models relying on time-based codes is that serial order is represented through binding between the items and a temporal correlate (Brown et al., 2007, 2000; Henson & Burgess, 1997). A natural consequence of such representation is that temporal closeness between items increases their confusability. Based on this assumption, one may expect that, from trial to trial, changing the temporal distribution of the items while the sequence duration is kept constant—as in the present study—should influence the probability to correctly recall each item individually, but not, or only minimally, the recall accuracy of the entire sequence. In other words, when two items were presented closer from each other compared to the regular interval of 800 ms, this mechanically increased the distance between two other items in the sequence. For instance, let consider the following example with the regular sequence {1...2...3...4...5}, and the irregular sequence {1....2..3....4..5}, with dots corresponding to arbitrary temporal units. When comparing the temporal distribution of the items in these sequences, one can see in the irregular sequence that Item 5 is less discriminable

from Item 4, but it is compensated by a higher discriminability of Item 1 relative to Item 2. Similarly, the confusability between Item 2 and Item 3 is higher in the irregular sequence but it is also compensated by higher discriminability between Item 3 and Item 4. From a time-based perspective, our results could be accounted for by assuming that, from trial to trial, the irregular timings influenced the recall probability of individual items within a sequence, but through a compensation principle, not the mean recall probability of a sequence. However, another implication of representing serial order along a temporal dimension is that transposition errors should be driven by temporal proximity. The exploratory analysis of error movements as a function of temporal proximity showed that adjacent transpositions did not involve the temporally closer serial position than the more distant one, a result difficult to reconcile with time-based theories representing serial order on a single temporal dimension.

Other models suggest that serial order is represented by the activity of temporal oscillators entrained by item presentation, representing a hybrid category incorporating both event-based and time-based representations (Burgess & Hitch, 1999; Hartley et al., 2016). Since Burgess and Hitch (1999) provided no description of the way the temporal oscillators are entrained, we will focus on the bottom-up multi-scale population oscillator model (BUMP, Hartley et al., 2016). In the BUMP model, serial order is represented through associations between items and the different states of a set of oscillator pairs tuned to respond to local amplitude variations at different time-scales. The tuning range of the oscillators is thought to respond to different temporal scales corresponding roughly to the presentation rate of item, group, and entire sequence. For regularly timed sequences, rapid oscillators respond strongly to the individual items. However, as they go through an entire cycle per item, they contribute only poorly to serial order representation. On the other hand, the slowest oscillators, which are sensitive to variations at the level of the entire sequence, provide positional representation which are more distinctive. In case of grouping, intermediate oscillators responding strongly to temporal variations corresponding to groups duration are recruited, providing more distinctiveness to the items compared to regular sequences but increasing the similarity between item sharing similar within-group positions. Given the absence of a clear temporal structure in the irregular sequences used in this study, it seems reasonable to expect that, from the population of oscillators described in the BUMP model, rapid and intermediate oscillators would not strongly phase with the items, while the slowest oscillators should respond strongly. Thus, the distinctiveness of the items would be mostly determined by their association with the phase of slowest oscillators, as in regular sequences. In that case, serial order would be represented as the temporal position of the items relative to the entire sequence duration, making the nature of the representation, as well as predictions regarding the effect of irregularity, close to those described in time-based models discussed in the preceding paragraph.

To sum up, STM models relying on event-based serial order representations (Henson, 1998; Lewandowsky & Farrell, 2008) can easily explain the null effect of irregular timing observed in the present study. However, they lack a mechanism to explain how, in sequences with timing variations, an additional contextual signal is recruited only in the presence of clear temporal groups but not when the timing is irregular and impedes the formation of such groups. On the other hand, it appears that models relying on time-based representations (Brown et al., 2007, 2000; Hartley et al., 2016) could also accommodate the main effect that is the absence of irregularity effect. However, the observation that adjacent transpositions involved as frequently the temporally closest position than the more distant one is at odds with the prediction of time-based models that temporally closer items should be confused more. It is noteworthy that the ability

of time-based models to account for the null effect of irregular timing, as well as the predictions regarding adjacent transpositions, is based on a general interpretation such class of models. Consequently, detailed simulations will be required to confirm the predictions regarding their behaviour when dealing with irregularly timed sequences as used in this study.

6.2. Can timing manipulations only boost the representation of serial order?

The main prediction formulated for the study was that sequences presented with an isochronous presentation rate would be better recalled than irregularly timed sequences. The results strongly support the absence of a negative effect of irregularity on recall accuracy and error patterns. At the same time, it is known that when the memoranda are presented with a hierarchically organized rhythmic structure—as it is the case for temporal grouping—recall accuracy dramatically increases (Frankish, 1985; Hartley et al., 2016; Hitch et al., 1996; Ryan, 1969b). Based on these results, one could argue that the presentation timing of the to-be-recalled material can impact recall performances only positively, as it is the case when the material is hierarchically structured in temporal groups.

At the same time, there is evidence that some temporal manipulations affect serial recall performances negatively. For instance, serial order STM tasks performed concurrently to a rhythm tapping task showed poorer performance compared to a control condition (Gorin et al., 2016; Henson et al., 2003). However, it is important to take into consideration that the negative effect of rhythm is observed with *production* tasks. Disruption of serial order STM by the concurrent production of rhythm has been interpreted as resulting from the interference induced by the recruitment of shared mechanisms to produce rhythm and to represent serial order (Gorin et al., 2016; Henson et al., 2003). However, it is not clear whether the interference results from the rhythmic nature of the task or its motor component. In a series of works, it was shown that the phonological similarity effect for visually presented material disappeared under interference tasks involving a strong motor component, such as verbal articulatory suppression, finger tapping, or whistling (Saito, 1994, 1998). Moreover, disruption of serial order STM has also been found with chewing (Kozlov, Hughes, & Jones, 2012), a task that can be viewed as a silent articulatory task without the production of any verbal content. A more parsimonious account of the negative effect of rhythm tapping on serial order STM would be to consider that the motor component disrupts the execution plan of the recall action, rather than the rhythmic nature of the task. Since the deleterious effect of rhythm on serial recall is observed in experiments involving a rhythm production task, it can be argued that the evidence that rhythm *per se* causes serial order STM impediment is inconclusive.

The picture is, however, different when we look at the effect of rhythm when the temporal manipulation does not require a motor production. For instance, the presentation of an isochronous rhythm during the maintenance of a verbal list increases the recall accuracy of the list, while presenting an irregular rhythm leads to similar performance compared to a silent condition (Plancher et al., 2018). These results support a boosting effect of regularity but a null effect of irregularity. The absence of effect of irregularity is also supported by a series of experiments demonstrating that the effect of irrelevant speech on serial recall accuracy is not greater when the irrelevant material is played at an irregular rate compared to conditions with a regular irrelevant speech

(Parmentier & Beaman, 2015). There is also evidence that the Hebb learning effect—that is, higher accuracy for repeated sequences—is boosted when repeated sequences are temporally grouped, but the learning remains, though to a lesser extent when the grouping structure change at each presentation of the repeated sequence (Hitch, Flude, & Burgess, 2009, but see Bower & Winzenz, 1969). Considered together, these results cast doubt on the fact that rhythmic irregularity has a negative impact on serial recall.

This phenomenon could be accounted for by neuronal oscillators as described in some serial order STM models (see, e.g., Brown et al., 2000; Burgess & Hitch, 1999; Hartley et al., 2016; Henson & Burgess, 1997). More particularly, Hartley et al. (2016) described oscillators sensitive to local amplitude variations of the speech envelope. As mentioned in the preceding section, in the case of irregular sequences as in the present study, rapid and intermediary oscillators should respond only weakly to the items because of the non-isochronous presentation rate and the absence of specific grouping structure. Only slow oscillators, which are insensitive to rapid fluctuations of speech envelope, should respond to the occurrence of the items and would then be useful to discriminate between the items. The absence of effect of irregularity could thus be explained by the fact that regular and irregular sequences recruit the same slow oscillators while grouped sequences recruit additional intermediary oscillators that provide more discriminability and consequently recall accuracy.

6.3. Conclusion

The study showed that the immediate recall of rhythmically irregular and unpredictable sequences of verbal material leads to similar recall and error patterns as in regular sequences. These results are consistent with the view proposed by event-based class of STM models, proposing that serial order is represented along an ordinal dimension where time plays no role. While these results seem partially problematic for the time-based class of models, modeling work is required to determine the extent to which such models could accommodate the observations reported here. Finally, the absence of an effect of timing places new constraints on theories of serial order.

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Data availability statement

All relevant data, namely raw data, data processing scripts, and statistical analyses output files are openly accessible via the Open Science Framework (<https://osf.io/dkaw9/>). The experimental material used to perform the study is openly accessible via the pre-registered version of the study stored on the Open Science Framework

(<https://osf.io/s3tvh>). The code used to process the data and generate the figures can be reproduced in a capsule available on Code Ocean (<https://doi.org/10.24433/CO.6002203.v1>)

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The author declare that the research was conducted in the absence of any competing interest that could be construed as a potential conflict of interest.

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