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Temporal regularities allow saving time for maintenance in working memory

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Recent evidence suggests that working memory (WM) performance can be enhanced in the presence of an isochronous rhythm during the retention interval because it improves refreshing. Considering the cognitive load (CL) effect as an indicator of refreshing, the present study investigated whether an isochronous rhythm might benefit memory performance under varying cognitive load. For that goal, the presence of a regular rhythm and the cognitive load of the concurrent task (i.e., reading of digits that were either same or different within a trial) were systematically varied. Recall performance was decreased by high cognitive load compared with low cognitive load but was improved in the regular rhythm condition compared with the silent condition. No interaction between cognitive load and rhythm was observed. The present results suggest that temporal regularities might speed up the reading of the digits rather than improve the efficiency of refreshing, resulting in more time available for refreshing and, consequently, improved memory performance. These findings are interpreted in the framework of the dynamic attending theory and in the scope of recent models of working memory, which are also considering the temporal components of working memory and the importance of the temporal structure of working memory tasks.

Keywords: refreshing; working memory; temporal regularities; attentional resources

Introduction

Previous working memory (WM) research has investigated the features of a concurrent task that cause forgetting of information relevant for the main task. In contrast, the potential features that might improve WM performance have received little attention. Music cognition research highlights the benefit of temporal regularities for various cognitive processes, including perception,¹ language processing,^{2,3} and learning.⁴⁻⁶ In relation to WM, improved memory performance has recently been reported in the presence of a regular sound during the interval of maintenance in comparison with a silent condition (a benefit that was not observed for an irregular sound condition).⁷ Two mechanisms have been proposed to allow for the maintenance of verbal information in WM:⁸ (1) the phonological loop via subvocal rehearsal^{9,10} and (2) attentional

refreshing (also referred as *refreshing*), an attention-based mechanism, which consists of briefly thinking about information that is no longer perceptually present.¹¹ When subvocal rehearsal was impeded by an articulatory suppression task, the benefit of temporal regularities persisted. Consequently, temporal regularities were suggested to enhance not only verbal maintenance but also refreshing.⁷ In the present study, we further investigated whether temporal regularities indeed boost attentional refreshing by using the cognitive load (CL) effect as an indicator of the occurrence of refreshing.

Attention plays a central role in recent models of WM.^{12,13} One particular attention-based model of WM, the time-based resource-sharing model,¹⁴ proposes that, owing to the competition between two proposed functions of WM (i.e., maintenance and processing) for limited and domain-general

attentional resources, memory traces decline when concurrent processing activities require attention.⁸ Refreshing allows for the maintenance of memory trace and thus prevents forgetting by placing the memory trace in the focus of attention.^{8,11,15}

One way to investigate refreshing is to manipulate the level of CL of a secondary task.¹⁴ CL is typically manipulated in complex span tasks (i.e., tasks involving one primary task for which some items have to be memorized and one secondary task in which other items have to be processed). To-be-processed items are presented in alternation with to-be-memorized ones. CL manipulation can be done, for example, by increasing the number of to-be processed items presented in an unchanging amount of time or by increasing the complexity of the task (e.g., location judgment versus simple reaction time tasks).¹⁶ CL is conceived as the proportion of time during which attention is captured by processing the items of the concurrent task regarding the total amount of time available for the processing. By manipulating the CL, this proportion is altered. If processing the items consumes more time, then less time is available for refreshing. Consequently, memory traces decay more strongly, and memory performance is impaired. This CL effect is considered as evidence for refreshing as a maintenance mechanism, and its manipulation is often used to improve the understanding of this mechanism.^{16–20}

If maintenance in WM relies on attention, then temporal regularities should improve its efficiency, as they are known to influence temporal attention and event processing.¹ On the basis of music cognition research, the dynamic attending theory (DAT)^{21–23} provides a theoretical framework to formulate hypotheses about how to improve attentional focusing and thus efficiency of refreshing. The DAT postulates that attentional resources are not distributed continuously and equally over time but develop cyclically over time. Temporal regularities could entrain internal oscillators and thus guide attention over time. Although the distribution of attentional resources spontaneously follows an endogenous rhythm, these rhythms can synchronize with an external and regular rhythm. Consequently, perceivers can develop predictions about the temporal occurrence of a future event and allocate more attentional resources at the expected temporal moment, resulting in enhanced cognitive processing of an event occurring at this moment.

For example, among other empirical findings, if tone sequences are isochronously presented, providing a temporally regular structure, the perceiver can predict the occurrence of the last tone. If this last tone is presented at an expected moment, then its pitch judgment will be more accurate, highlighting an enhancement of its processing.²⁴

Based on the DAT and related empirical findings, a recent study has shown that the temporal regularity of a series of items benefits maintenance in WM.⁷ Here, a series of six to-be-memorized letters was visually displayed and had to be serially recalled after a 6-s retention interval. The retention interval was either silent or filled with six tones. When the tones were isochronously presented (Exp. 1a), recall performance was better than during the silent retention interval. In contrast, when the tones were randomly presented (Exp. 1b), recall performance did not differ from the silent condition. Rather than the mere presence of tones, the maintenance in memory was enhanced by their temporally regular structure. This benefit persisted under concurrent articulation (Exp. 2), highlighting that refreshing, and not only articulatory rehearsal, benefited from temporal regularities.

The present study aimed to further investigate the benefit of temporal regularities on refreshing. In agreement with the DAT,^{22,23} we predicted that temporal regularities boost refreshing and used the CL effect as a tool to investigate refreshing. If the efficiency of refreshing is modulated by temporal regularities, then the CL effect should interact with these regularities. Consequently, if more time is available, then more refreshing can take place and it should be boosted by the temporal regularities. Alternatively, temporal regularities can also improve and speed up the processing of the digits, resulting in more time available for refreshing the CL of the concurrent task.

To test these assumptions, a Brown–Peterson–like paradigm was used as in Plancher *et al.*⁷ The primary task consisted of memorizing sequences of letters, while the secondary task was a digit-reading task that filled the retention interval. The CL of the digit-reading task was manipulated: digits were either the same or different within a trial, two conditions corresponding to low CL and high CL, respectively.²⁵ As processing different items requires more time than processing repeated items (Ref. 26–29), the proportion of time available for refreshing was

varied. Manipulating the similarity between digits allowed us to keep constant the rhythm of the task, which is fundamental in studies investigating the role of temporal regularities. To test the potential benefit of temporal regularities on refreshing, a brief tonal marker of an isochronous auditory rhythm appeared between each to-be-processed digit, that is, when maintenance is supposed to occur, and contrasted with a silent condition. If temporal regularities benefit maintenance in WM, recall performance should be improved in the presence of the isochronous rhythm in comparison to silence. Moreover, if temporal regularities specifically benefit refreshing, then this improvement should be stronger in the low (versus high) CL condition. No interaction between CL and rhythm would, however, suggest that regularities benefit the processing of the digits. Recall performance would thus be increased because of more available time for refreshing rather than an improvement of refreshing efficiency per se.

Method

Participants

Twenty undergraduate students (18 to 28-year-old, mean age = 23.34, SD = 3.44) from the university of Lyon participated in the experiment after having given their informed consent. Participants were all French native speakers and had received no ($n = 17$) or only 2 years of musical training ($n = 3$).

Materials

A Brown–Peterson task^{30,31} was created based on the material used in Plancher *et al.*⁷ Twenty-four sequences of six letters were created (e.g., LDKJSZ). Letters were all monosyllabic consonants, that is, all consonants of the Latin alphabet except *W*, which is a trisyllabic consonant in French. Repetitions of a letter within a sequence were avoided, as well as acronyms and alphabetically ordered strings. Throughout the experiment, each letter was used approximately equally often (six or seven times) and occurred equally often in each of the six positions. Two blocks were created from these 24 sequences, with 12 sequences in each block. Each block was assigned to one of the experimental conditions (rhythm or silent), and this assignment as well as the order of the presentation of the blocks was counterbalanced across participants following a Latin square. Each sequence was presented in each experi-

mental condition, and half of the participants began with the silent condition whereas the other half began with the rhythm condition.

For the concurrent processing task (i.e., the digit-reading task), series of six digits were created. The CL of this task varied among trials within a given block: for the low-CL condition, the six digits were always the same (i.e., 2), and for the high-CL condition, series were created with different digits and without repetition of a digit within a series (e.g., 285631). The CL was randomized across trials. Letters and digits were presented in black color in the middle of a white screen in 36-point Courier New font. For the rhythm condition, the used sound was played with a woodblock timbre and had a duration of 113 milliseconds.

Procedure

At the beginning of each trial, a black asterisk was displayed for 500 ms in the center of the white screen and followed by a white screen for 100 ms. Then, each sequence of six letters was sequentially presented. Each letter was presented 800 ms and followed by a white screen of 200 ms. Participants were instructed to read each letter aloud and to memorize them. After the letters' presentation, a series of six digits was sequentially displayed in the center of the screen. Each digit remained on the screen for 200 ms and was followed by a white screen for 800 ms. Participants were instructed to read digits aloud, as fast and accurately as possible, while keeping letters in mind. In the rhythm condition, a short sound was isochronously presented six times with a sound-onset asynchrony (SOA) of 1000 ms. The sound was presented 150 ms before the appearance of a digit, that is, during the period typically dedicated to maintenance. In the silent condition, no sound was presented.

After the digit-reading task, a question mark appeared on the screen for a duration of 3000 ms. Participants were instructed to recall the letters aloud in their order of appearance (see Fig. 1 for a schematic representation of the experimental design). If less than six letters were recalled, participants had to specify the serial position of the recalled letters. At the beginning of the experiment, participants were instructed to recall the letters in such a way that the experimenter could report the order of recall, saying "I don't know" if they did not know the position of the missing letter. For

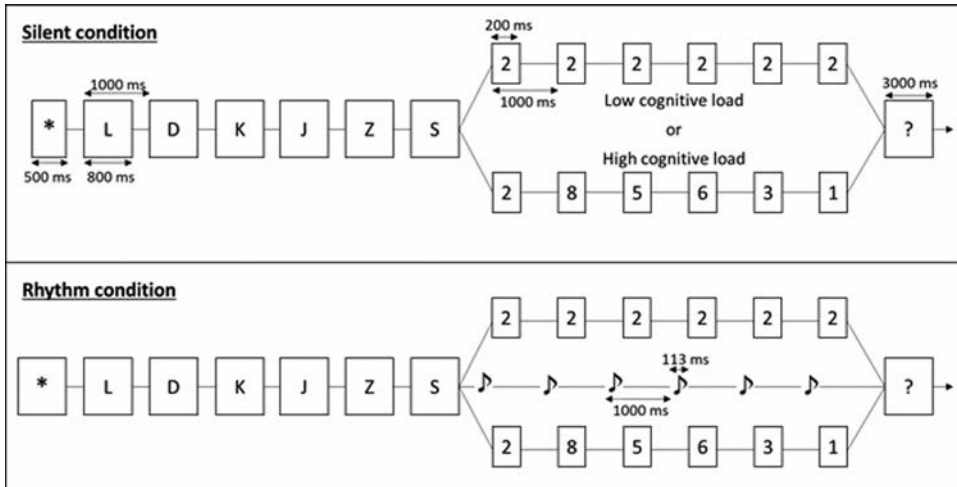


Figure 1. Schematic representation of the experimental design. Participants had to read and memorize the six letters and then to read six digits aloud. Digits were either always identical (low CL) or different (high CL) within a trial. In half of the trials, an isochronous rhythm was presented (rhythm condition), whereas in the other half no sound was presented (silent condition).

example, if the letter “D” was forgotten in the sequence “LDKJSZ,” the participant had to say “L, I don’t know, K, J, S, Z.” One point was attributed to each letter recalled at the accurate serial position, leading to a maximum of six points.

Each block (i.e., rhythm and silent) began with two training trials that were identical to the test trials explained above.

Results

A 2×2 ANOVA with CL (low, high) and rhythm conditions (rhythm, silent) as within-subject factors was performed on the mean number of letters correctly recalled. Bayesian factor (BF) analyses were also computed using JASP 0.8.1.2 with the default settings.³² The BF is the resulting statistic of a model comparison and is considered a relative measure of statistical evidence.³³ Following the guidelines provided by Lee and Wagenmakers,³⁴ we considered that a Bayes factor gives anecdotal evidence of an effect when lower than three, positive evidence when between 3 and 10, strong evidence between 10 and 30, very strong evidence between 30 and 100, and decisive evidence when higher than 100.

The main effect of CL was significant ($F(1,19) = 8.39, P < 0.01, \eta^2p = 0.31$). Recall performance was better with the low CL ($M = 3.40, SD = 1.11$) than with the high CL ($M = 2.74, SD = 1.31$) (Fig. 2). The BF associated with this effect was 23, giving strong evidence in favor of the CL effect.

The effect of rhythm conditions was also significant ($F(1,19) = 11.10, P < 0.01, \eta^2p = 0.37$). Recall performance was better in the rhythm condition ($M = 3.28, SD = 1.21$) than in the silent condition ($M = 2.86, SD = 1.26$). The BF associated with this effect was 6, providing positive evidence in favor of the effect of rhythm conditions. The interaction between CL and rhythm conditions was not significant ($F < 1$). Evidence in favor of the interaction was only anecdotal (BF = 1).

Overall, the BF associated with the model that included both rhythm conditions and CL main effects was 123, indicating decisive evidence in favor of these effects combination and pointing out that this model was the best fitted to the observed data. It is also worth pointing out that the BF associated with the full model was 37. While it was not the best-fitted model, it still indicates very strong evidence in favor of the model comprising both main effects and the interaction, with a slightly stronger increase in memory performance in the low-CL condition than the high-CL condition (rhythm-silent = 0.424 for the low CL, BF = 9, and 0.412 for the high CL, BF < 1).

To check for potential order effects of the blocked presentation of the two conditions, we performed a 2 (condition: rhythm versus silence; within-subject) $\times 2$ (CL: low versus high) $\times 2$ (order: rhythm-silence versus silence-rhythm) ANOVA. The main effects of rhythm conditions and CL were

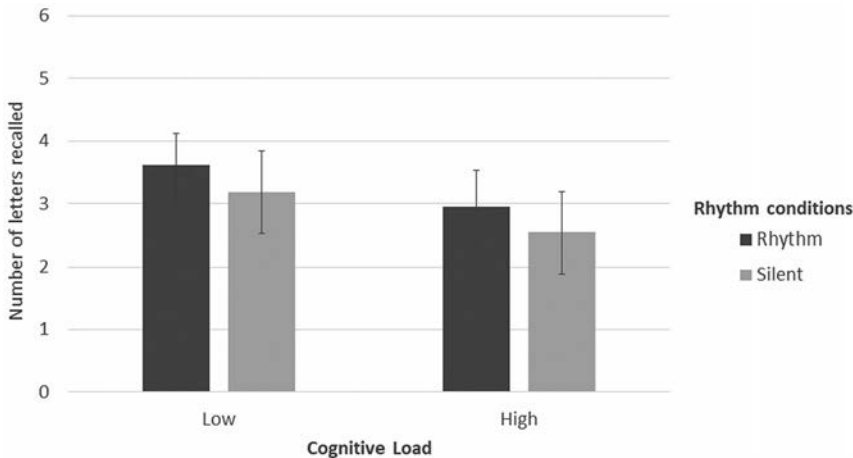


Figure 2. Recall performance (with a maximum of six letters) according to CL (low, high) and rhythm condition (rhythm, silent). Vertical bars represent standard errors.

confirmed ($P < 0.01$ and $BF = 4$ for rhythm conditions; $P < 0.05$ and $BF = 24$ for CL). No main effect of order ($F < 1$, $BF < 1$) or interactions with this factor were revealed ($BF = 2$ for interaction with CL, $BF < 1$ for interactions with rhythm conditions and for the three-way interaction).

Discussion

The present study aimed to investigate whether temporal regularities improve maintenance in WM, with the hypothesis that refreshing should be enhanced due to the presence of an isochronous rhythm. We compared recall performance in the presence of an isochronous rhythm during the retention interval with a silent retention interval while manipulating the CL of a digit-reading task that competes with maintenance.

We replicated the expected CL effect on recall performance, with a decrease in memory performance in the high-CL condition compared to the low-CL condition.³⁵ Based on the assumption that reading different digits requires more time than always reading the same digits,²⁵ (see also Refs. 26–29 for related results with words), we assumed that more processing time was necessary to accurately perform the concurrent task with nonrepeated digits and thus led to less time available for attentional maintenance—that is, refreshing—in order to prevent the decay of memory traces. The CL effect had been extensively studied using complex span tasks (e.g., Refs. 14,16,20, and 36) but, to our knowledge, no study had investigated the effect of CL with a

single extended period of processing, as in a Brown–Peterson paradigm. The CL effect is considered an indicator for the occurrence of refreshing.³⁷ The present study thus provided evidence that refreshing takes place when memory items are encoded before the processing phase such as in a Brown–Peterson paradigm, and not only in complex span tasks in which memorization and processing are alternated.

We also replicated the previously reported enhancement of recall performance in the presence of an isochronous rhythm during the retention interval in comparison to the classical, silent retention interval.⁷ Temporal regularities thus seemed to improve the memory performance also in this WM task. We did not observe an interaction between CL and rhythm, highlighting that the boosting effect of temporal regularities on recall performance did not differ with the amount of time available for refreshing. This interaction would have been evidence of improved refreshing with temporal regularities. We are thus not able to affirm that temporal regularities specifically (or solely) benefited refreshing.

Another possibility is that the positive effect of temporal regularities on memory performance benefits the concurrent processing task and in consequence the time available for maintenance. This is consistent with predictions of the DAT. In the presence of regular external events, internal oscillations synchronize and follow the temporal structure provided by the external events. Because of this synchronization, temporal expectations about the potential occurrence of future events

are possible. Processing an event occurring at the expected moment is thus suggested to be facilitated. Several studies have provided evidence for the benefit of temporally regular structures in various cognitive processes, such as perception, learning, and speech perception and production,^{4,24,38–40} in comparison with an irregular temporal structure, a violation of temporal expectations, or no externally regular structure at all. For example, in a pitch-comparison task, series of tones were presented. The pitch of the last tone had to be compared to the pitch of the first tone and could be either higher, lower, or the same. Between the to-be-compared tones, eight tones—referred to as distractors—were presented and subjects were told to ignore them. The temporal structure of the distractor presentation was either regular (i.e., the distractors were presented in an isochronous rhythm), irregular (i.e., the distractors were presented in a nonisochronous rhythm), or missing (i.e., no distractors were presented). When distractors were regularly presented, they provided a temporally regular structure that allowed for developing temporal expectations about the moment of occurrence of the subsequent tones. The time interval preceding the last tone was also varied to allow for the manipulation of the congruency between the occurrence of this last tone (i.e., the tone that must be compared with the first one) and the temporal structure provided by the previous tones. When a temporal structure was provided, pitch comparison performance was better when the last tone presentation was congruent with the temporal expectation rather than if the last tone occurred sooner or later relative to this expected moment. When distractors did not provide a temporal structure, then the timing of the to-be-compared tone did not affect comparison performance.²⁴ Performance in pitch comparison then benefited from the presence of a temporally regular structure. Consistent with this previous study and other related empirical findings, our study provided evidence that a temporally regular structure presented during retention benefits memory performance.

During the retention interval, two processes were supposed to occur: the reading of currently occurring digits and the maintenance of previously presented letters. The DAT cannot predict which mechanism is enhanced, as both can benefit from the presence of temporal regularities. As mentioned previously, it is unlikely that temporal regu-

larities specifically boosted refreshing, because the improvement was not greater when more time was available for maintenance (i.e., in the low-CL condition). The presence of the rhythm might have instead benefitted memory performance by speeding up digit reading. When a sound precedes a digit, the reading of the digit might be facilitated. Such an enhancement might be rather due to the temporal expectations based on the information provided by the sound regarding the upcoming occurrence of the visual item (see, for example, Ref. 41). Because of this processing facilitation, the time required to read the digit was reduced and, consequently, more time was available during the retention interval. This additional free time could then be used to attentionally refresh the items and, consequently, memory performance increased in comparison to the silent condition.

Alternative interpretations to our findings can be considered by oscillator-based conceptions of serial recall in WM.^{42–45} These models emphasize the role of temporal context at encoding on the retention of the serial information. More specifically, the rhythm and timing of the item presentation is crucial for memory of spoken sequences as highlighted by the enhancement of recall performance when spoken sequences of digits are regularly grouped compared to an irregular grouping.⁴³ Previously observed improvement of the learning of verbal or musical material presented regularly rather than irregularly can also strengthen the proposal of a central role of temporal structures during encoding.^{4–6} Focusing on how the to-be-learned material is presented in time, the bottom-up multiscale population oscillators (BUMP)⁴³ proposed a bottom-up mechanism to account for the role of the temporal context at encoding of items. At encoding, the items are associated with a context signal that is restated at recall and thus reactivates the item in memory. Depending on similarity between the rate of the stimulus presentation and the period of the associated oscillator, the strength of the amplitude of the context signal influences the item availability at recall, resulting in a better recall of the regularly presented stimuli than of the irregular ones. Although the BUMP model only accounts for the benefit of temporally regular structures at encoding and at retrieval on serial recall, one might wonder whether the BUMP model can be applied to our data. Our study showed that a regular external rhythm

presented only during maintenance enhanced serial recall performance. This benefit can be due to the restatement of the context signal associated with the to-be-memorized items thanks to the regular rhythm that would help the context signal to keep its amplitude at a sufficiently high activation level to prevent the suppression of the items and then its forgetting. Indeed, if the rhythm benefits maintenance because of the restatement of context signal associated with the item at encoding, then the memory benefit must disappear when the temporal patterns at encoding and during maintenance are different. In our study, the temporal patterns during encoding and maintenance were more similar in the silent condition, where both letters and digits were presented with an SOA of 1000 ms, than in the rhythm condition where the presence of the tones changed the temporal context. Following the BUMP proposals, this difference of temporal patterns in the rhythm condition should have disrupted the reactivation of the temporal context and then the restatement of the items. The present findings thus seem better accounted by the DAT than by oscillator-based models of serial recall in WM.

Other WM models can account for the CL effect, but not the rhythm effect. Interference-based models, such as the serial-order in a box (SOB)^{46,47} model, proposed that forgetting in WM is due to the competition between the to-be-remembered information and the subsequently presented information—the information presented between encoding and recall.⁴⁸ The SOB model assumes that the interference caused by new items depends on their novelty: the more novel an item is, the more it will interfere with the to-be-remembered items and lead to their forgetting. This assumption was tested using a Brown–Peterson paradigm where letters had to be remembered and the distractors (i.e., to-be-read words) were either the same or different within a trial.⁴⁸ Recall performance was greater when distractors were always the same within a trial than when they were always different. This decrease in memory performance when distractors were always different was assumed to be due to the interference between the to-be-read words and the memoranda, and was interpreted following the SOB model.^{46,47} The SOB model proposed that new information is continuously superimposed onto previously presented items with an encoding

strength that depends on the novelty of the newly presented item in comparison with the previous items. Regarding the novelty of the items of a secondary task that concurs with the memorization, a newly presented item that is different from the previous one (i.e., a novel item) will interfere with the memoranda and thus impair memory performance in contrast to an item that is very similar to the previous one. To counteract the interference caused by distractors, the SOB model proposed a mechanism, referred to as *removal*, that suppresses information no longer relevant for the ongoing task.^{47,49,50} This removal hypothesis might account for the CL effect, as more removal could have occurred in conditions where more time was available (i.e., in the low-CL condition), leading to better memory performance. As predicted by SOB, we observed better memory performance when to-be-read items were always the same within a trial in contrast to always-different distractors within a trial. However, memory performance was increased in the presence of the tones during the retention interval. The interference-based interpretation would have predicted either a slightly detrimental effect or no effect of the sound on memory performance, as the sounds were always the same throughout the experiment. One might then wonder whether the presence of temporal regularities would have benefited removal efficiency. The removal efficiency depends on (1) the encoding strength—and thus on the novelty of the items—with a higher efficiency for more weakly encoded items and (2) the available time that can be used for removal, with a higher efficiency when more time can be devoted to it. In the present study, encoding strength of items differed between the two CL conditions as distractors were either always different digits (high CL) or always the same digit (low CL), while the amount of available time differed between the two conditions. If the presence of temporal regularities improved the efficiency of the removal, one would have expected that the benefit of temporal regularities would have been higher in the low CL than in the high CL, which was not the case.

Another interference-based investigation of WM reviewed more specifically the effect of the presence of an irrelevant sound to the ongoing task on WM performance and highlighted that serial recall was impaired in the presence of an irrelevant auditory stream (i.e., the irrelevant sound effect (ISE)).⁵¹ With a repeated, unchanged sound, memory

performance would yet not be impaired. Regarding ISE, no effect of an additional sensory stimulation during maintenance (i.e., no detrimental effect of the tones) was expected. However, we observed an improvement of memory performance in the presence of this additional sensory stimulation.

Our study was, along with Plancher *et al.*,⁷ the first attempt to investigate whether an internal process—such as refreshing—can benefit from temporal regularities presented during the maintenance period. Previous studies have instead focused on the effect of temporal regularities on improvement of the processing of an external event.^{4–6,21–24} Our findings showed that the presence of temporal regularities during maintenance enhances memory performance. We expected the benefit to be greater with a low- rather than high-CL concurrent task, which would have testified of a specific enhancement of efficiency of refreshing. In light of our findings, this specific enhancement of refreshing cannot be secured, and it might be that the observed benefit of temporal regularities over recall performance was due to a reduction of the time needed to process the concurrent task (i.e., the processing of an external stimulation). This amount of time thus became available for maintenance and benefited memory performance. The two explanations (i.e., a specific enhancement of refreshing and a reduced processing time in the presence of temporal regularities) are not mutually exclusive. Our results cannot constitute an argument to refute the hypothesis under which temporal regularities benefit specifically refreshing.⁷ If we make the hypothesis that both mechanisms—refreshing and processing—can benefit from temporal regularities, but only one process can benefit from temporal regularities at a time, the processing of external stimuli might thus benefit more from temporal regularities than does an internal process, such as refreshing. Moreover, Bayesian analyses were not clearly in favor of an absence of interaction. The probability of the model including the interaction was very strong, with a slightly higher benefit of rhythm on memory performance when more time was available for refreshing, in the low-CL condition compared with the high-CL condition. The specific improvement of refreshing thus might be hidden by beneficial effects of temporal regularities on digit processing.

To conclude, our study highlights a benefit of temporal regularities during the retention inter-

val. Closer examination to disentangle whether this effect was due to the mere presence of the isochronous rhythm or to the informational content of the sound regarding the onset of the subsequent digit seems necessary. Because the present study suggested that temporal structure is important for WM, further studies investigating the impact of a concurrent task on memory performance should consider the temporal structure provided by the items presented as the secondary task. A temporally regular structure of items presented during the retention interval might facilitate the processing of the concurrent task and then increase the amount of time available for maintenance. Even if the items are not relevant to the ongoing task, the temporal structure of their presentation might influence memory performance.

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Competing interests

The authors declare no competing interests.

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