



HAL
open science

Boosting maintenance in working memory with temporal regularities.

Gaën Plancher, Yohana Lévêque, Lison Fanuel, Gaëlle Piquandet, Barbara Tillmann

► **To cite this version:**

Gaën Plancher, Yohana Lévêque, Lison Fanuel, Gaëlle Piquandet, Barbara Tillmann. Boosting maintenance in working memory with temporal regularities.. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 2018, 44 (5), pp.812-818. 10.1037/xlm0000481 . hal-02378160

HAL Id: hal-02378160

<https://hal.science/hal-02378160>

Submitted on 21 Jul 2022

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1

2

3 **Boosting maintenance in working memory with temporal regularities**

4

5 Gaën PLANCHER¹, Yohana LÉVÊQUE^{2,3}, Lison FANUEL^{1,2,3}, Gaëlle PIQUANDET^{1,2,3}, Barbara
6 TILLMANN^{2,3}

7

8 ¹ Cognitive Mechanisms Research Laboratory, Lyon 2 University, F-69676, Bron (France)

9 ² CNRS, UMR5292; INSERM, U1028; Lyon Neuroscience Research Center, Auditory
10 Cognition and Psychoacoustics team, Lyon (France)

11 ³ University Lyon 1, Lyon (France)

12 **Correspondence** should be addressed to **Gaën Plancher**, Laboratoire d'études des
13 mécanismes cognitifs, Université Lumière Lyon 2, 5 Avenue Pierre Mendès-France, 69676
14 Bron Cedex, France. gaen.plancher@univ-lyon2.fr +33 (0) 4 78 77 43 49.

15

16 **Acknowledgement:** This research was supported by the LABEX ANR-11-LABX-0042 of
17 Université de Lyon, within the program "Investissements d'Avenir" (ANR-11-IDEX-0007)
18 operated by the French National Research Agency (ANR) and was conducted in the
19 framework of the LabEx CeLyA ("Centre Lyonnais d'Acoustique", ANR- 10-LABX-0060).
20 Funding for this project was also provided by a grant from la Région Rhône-Alpes.

21 **Word count:** 4940

22

23 **Abstract**

24

25 Music cognition research has provided evidence for the benefit of temporally regular
26 structures guiding attention over time. The present study investigated whether maintenance in
27 working memory can benefit from an isochronous rhythm. Participants were asked to
28 remember series of six letters for serial recall. In the rhythm condition of Experiment 1a, a
29 wood block sound was presented six times with a regular stimulus-onset-asynchrony during
30 the delay between encoding and recall. In the silent condition, no sound was presented. The
31 presence of the regular rhythm resulted in improved memory performance (Experiment 1a.),
32 an effect also observed under articulatory suppression (Experiment 2), suggesting that
33 temporal regularities can enhance maintenance in working memory including attentional
34 refreshing. Experiment 1b confirmed this interpretation by showing that the presentation of a
35 non-isochronous rhythm did not result in improved memory performance in comparison to a
36 silent condition. The findings are discussed in relation to current working memory models and
37 the theoretical framework of dynamic attending.

38

39 **Keywords:** working memory, rhythm, temporal expectations, temporal attention, attentional
40 refreshing

41

42

43 **Introduction**

44 Everyday-life activities require maintaining information active in working memory (WM) to
45 avoid forgetting (e.g., repeating a phone number until dialing). While repeating the information,
46 we may intuitively feel that this rehearsal involves some temporal regularity, such as a rhythmic
47 pattern. Over the last decades, an increasing number of studies has provided evidence for the
48 influence of temporal structures and regularities on cognition, but their potential influence on
49 memory during the delay period (i.e., maintenance) has not been investigated yet. Our study
50 examined the potential benefit of a regular rhythm on the maintenance of serial order
51 information in WM.

52 The role of temporally regular structures for guiding attention over time has been developed
53 in the dynamic attending theory (DAT) (Jones & Boltz, 1989; Large & Jones, 1999). The DAT
54 proposes that attention is not equally and continuously distributed over time, but develops via
55 attentional cycles. External stimulus regularities can entrain internal oscillators that guide
56 attention over time and induce temporal expectations about future events, thus facilitating
57 sequencing and event processing. Supporting evidence has been provided by numerous studies
58 showing processing benefits of temporally regular structures over irregular structures and for
59 events respecting temporal expectations over events violating these expectations (i.e., events
60 occurring too early or too late) (e.g., Jones et al., 2002). Cutanda, Correa and Sanabria (2015)
61 observed a beneficial effect of regular rhythmic sequences on temporal preparation: participants
62 detected faster an auditory target after a regular rather than an irregular auditory sequence, even
63 while performing a concurrent and costly auditory working memory task. The benefit of
64 temporal regularities has been also shown for speech processing (Quené & Port, 2005; Schmidt-
65 Kassow & Kotz, 2009), learning (Hoch, Tyler, & Tillmann, 2013; Selchenkova et al., 2014;
66 Selchenkova, Jones, & Tillmann, 2014), and, to some extent, for memory. A memory advantage
67 has been shown for regular rhythmic event sequences over irregular ones (e.g., Povel & Essens,

68 1985; Silverman, 2012) and for texts spoken with a rhythmic pattern over naturally spoken texts
69 (Purnell-Webb & Speelman, 2008; Tillmann & Dowling, 2007).

70 In these memory studies, temporal regularities have been implemented into the to-be-learned
71 material. However, temporal regularities do not need to be implemented into the material to
72 benefit cognition. The regular temporal structure of a stimulus presented *before* the to-be-
73 processed, task-relevant material can exert an indirect influence on task performance, such as
74 intensity or pitch discrimination (Geiser, Notter, & Gabrieli, 2012; Jones et al., 2002), syllable
75 detection and syntactic processing (Cason & Schön, 2012; Przybylski et al., 2013).

76 To our knowledge, no study has yet investigated whether temporal regularities presented
77 during the retention interval (i.e., after the presentation of the to-be-memorized stimuli), can
78 boost maintenance of the to-be-recalled items in WM. Studying the influence of regular
79 structures and temporal attention in WM is relevant as recent models have underlined the central
80 role of attention in WM (Cowan, 2005; Barrouillet, Portrat, & Camos, 2011). WM functions of
81 storage and processing compete for attention, which is a limited resource. When attention is
82 necessary for processing activities, memory traces decline (Barrouillet et al., 2011). To prevent
83 memory decay, a mechanism of maintenance (referred to as attentional refreshing) aims to
84 restore the activation level of the decayed memory traces by focusing attention on the to-be
85 memorized items (Cowan, 2005; Raye, Johnson, Mitchell, Greene, & Johnson, 2007; Barrouillet,
86 et al., 2011). Importantly, this mechanism has been distinguished from verbal rehearsal. Even
87 though both mechanisms can maintain verbal information in WM, they are considered to be
88 independent, in particular because of some specific effects of each mechanism on recall and of
89 distinct underlying brain networks (Camos, 2015). We hypothesize that if memory benefits from
90 attentional refreshing, a factor like temporal regularity that enables to guide attention, should
91 improve refreshing and boost memory performance.

92 Our aim was to study whether temporal regularity guiding attention can facilitate maintenance
93 of verbal information in WM. Participants were presented with series of visual letters for
94 subsequent recall. The to-be-remembered letter series were followed by either a sequence of
95 sounds presented with an isochronous rhythm or a silent retention delay¹. The DAT predicts a
96 benefit of the regular sound sequence on memory performance (Boltz & Jones, 1986): in the
97 presence of the temporal regularities, participants synchronize their attentional cycles on these
98 regularities, and this might increase the benefit of attentional refreshing during maintenance.

99

100 **Experiment 1a.**

101 **Method**

102 *Participants*

103 Twenty undergraduates (15 females, mean age = 24.55) from Lyon University gave their
104 informed consent to participate in the experiment. They had received no (N=14) or short
105 musical training (N=6; average = 2.33 years (\pm SD=1,03), range 1 to 3).

106

107 *Materials*

108 A simple verbal span task was created based on Plancher and Barrouillet (2013). Twenty-four
109 series of 6 different letters had to be remembered (ex: LDKJSZ). Letters included only
110 consonants, but excluded W (a trisyllabic word in French). Each series was created to avoid
111 repetitions, acronyms and alphabetically ordered strings. Each letter was used approximately
112 equally often (7 or 8 times) and appeared approximately equally often in each of the six
113 positions. Two blocks of twelve different series of letters were presented, and each block was
114 assigned to one experimental conditions (rhythm or silent). These assignments were
115 counterbalanced across participants following a Latin square so that each series was studied in
116 each experimental condition across participants. Letters were presented in the center of a

117 white screen in black colour using a 36-point Courier New font. For the rhythm condition, a
118 sound played with a woodblock timbre and a duration of 58 ms (including resonance) was
119 used.

120

121 *Procedure*

122 Trials began with a black asterisk in the center of the screen, displayed for 500 ms, followed
123 by a 100 ms delay and then six letters were successively displayed with a stimulus-onset-
124 asynchrony (SOA) of 1000 ms per item (i.e., letters remained on the screen for 800 ms)
125 (Figure 1). Participants were instructed to read out loud and memorize the letters when they
126 appeared on the screen. After the last letter, the white screen remained for 6000 ms. During
127 this delay, in the rhythm condition, the wood block sound was presented six times with a SOA
128 of 1000 ms. In the silent condition, no sound was presented. After the delay, a question mark
129 appeared on the screen for 3000 ms, and participants had to recall the letters out loud in their
130 order of appearance. When fewer than six letters were recalled, participants were asked to
131 specify the serial position of the recalled letters.

132 Before the 12 experimental trials of each condition, participants performed two
133 practice trials. The order of the two blocks (rhythm, silence) was counterbalanced across
134 participants.

135 *Data analyses*

136 For each condition, recall performance was scored by calculating the mean number of letters
137 recalled in the correct position, which were analysed with a one-way ANOVA with condition
138 (rhythm, silent) as within-subject factor. In addition, we computed Bayes factors (BF), the
139 resulting statistic of a model comparison and considered as a relative measure of statistical
140 evidence (Morey & Rouder, 2011). Following recommendations of Lee and Wagenmakers

141 (2013), BF is considered as anecdotal evidence when inferior to three, as positive evidence
142 when comprised between three and 10, as strong evidence between 10 and 30, as very strong
143 evidence between 30 and 100 and as decisive evidence when superior to 100. To check for
144 potential order effects, we performed a 2x2 ANOVA with condition as within-subject factor
145 and order of conditions (Silent-Rhythm vs. Rhythm-Silent) as between-subjects factor.

146 -----
147 Insert Figure 1 about here
148 -----

149 **Results and Discussion**

150 The main ANOVA revealed that the effect of condition was significant, $F(1, 19) = 49.69$,
151 $p < .0001$; $\eta^2_p = .72$. Verbal recall performance was higher for the rhythm condition (4.96/6)
152 than the silent condition (4.05/6). The BF was 15297 constituting decisive evidence in favor
153 of this effect. The ANOVA including order confirmed the main effect of condition, $p < .0001$,
154 but no effect of order nor interaction were observed, $F < 1$ (Figure 2A).²

155

156 -----
157 Insert Figure 2 about here
158 -----

159 Experiment 1a revealed improved memory performance in the presence of a regular
160 rhythm during the delay (in comparison to a silent delay), suggesting that temporal
161 regularities enhance maintenance in WM. To investigate whether the effect of condition was
162 indeed due to the regularity of the rhythm and not due to the presence of a sound sequence,
163 Experiment 1b compared an irregular sound condition to a silent condition. If regularity is key,
164 then the benefit of sound against silence should not be observed with a sound presented in a
165 non-isochronous way. If however, some other mechanisms, such as arousal, were in play, then
166 performance should be better in the presence of an irregular rhythm than in silence.

167 **Experiment 1b.**

168 **Method**

169 *Participants*

170 Twenty other undergraduates (19 females, mean age = 20.85) from Lyon university gave their
171 informed consent to participate. Participants had received no (N=13) or short musical training
172 (N=7; average = 2.57 years (\pm SD=1,13), range 1 to 4).

173

174 *Materials, Procedure, Data analyses*

175 Material and procedure were identical to Experiment 1a, except that in the non-isochronous
176 rhythm condition the wood block sound was presented six times with different SOAs. Twelve
177 different sequences of six sounds were created using random SOAs (see Table 1). The
178 sequences were presented in random order for each participant. Data analyses were as in
179 Experiment 1a except that the condition factor was defined by the levels “non-isochronous
180 rhythm vs. silent”.

181

182

183

184

Insert Table 1 about here

185 **Results and Discussion**

186 The main ANOVA revealed that the effect of condition was not significant, $F < 1$. Verbal
187 recall performance did not differ between non-isochronous rhythm (3.60/6) and silent (3.63/6)
188 conditions. The BF was only of 0.33 in favor of the effect, and of 3 in favor of a null effect,
189 representing moderate evidence in favor of the null hypothesis. The ANOVA including order
190 confirmed the non-significant condition effect, and revealed no effect of order, $F < 1$; but an
191 interaction between condition and order, $F(1,19) = 28.79, p < .001; \eta^2_p = .62$. This interaction

192 indicates a learning effect, with better performance in the block performed second; i.e., Silent
193 > Rhythm in Order 1 ($p < .01$) and Rhythm > Silent in Order 2 ($p < .001$) (Figure 2B).

194

195 **Comparison between Experiment 1a and Experiment 1b**

196 To investigate whether the isochronous rhythm (Experiment 1a.) led to better performance
197 than a non-isochronous rhythm (Experiment 1b.), we performed a 2x2 ANOVA with
198 condition (rhythm; silent) as within-subject factor and experiment (1; 2) as between-
199 participants factor. The main effects of experiment and rhythm, $F(1, 38) = 8.92, p < .01; \eta^2_p$
200 $= .19$ and $F(1, 38) = 22.54, p < .0001; \eta^2_p = .37$, respectively, as well as their interaction were
201 significant, $F(1, 38) = 26.47, p < .0001; \eta^2_p = .41$: performance was significantly better for
202 isochronous (4.96/6) than non-isochronous rhythm (3.60/6) ($p < .001$), while performance did
203 not differ between the two silent conditions ($p = .22$). This analysis confirmed the hypothesis
204 that memory performance was enhanced by the temporal regularities of the presented sounds
205 and not by the simple presence of sounds. Because temporal regularities are hypothesized to
206 modulate attention, Experiment 2 investigated whether temporal regularities were beneficial
207 for attentional refreshing. To prevent maintenance through verbal rehearsal and allow for
208 measuring the effect on attentional refreshing, participants were required to repeat out loud a
209 syllable sequence during the delay (isochronous rhythm or silence, as in Experiment 1a).

210

211 **Experiment 2**

212 **Method**

213 *Participants*

214 Twenty other undergraduates (17 female, mean age = 21.95) from the Lyon University gave
215 informed consent to participate. Participants had received no (N=15) or short musical training
216 (N=5, average = 1.6) for one or two years.

217 *Materials, Procedure, Data analyses*

218 Materials, procedure (including the implementations of rhythm and silent conditions) and data
219 analyses were identical to Experiment 1a, except that immediately after the last letter,
220 “babebibobu” appeared in blue on the screen for 500 ms, requiring participants to rapidly and
221 continuously articulate out loud these syllables until the question mark.

222

223 **Results and Discussion**

224 The main ANOVA revealed that the effect of condition was significant, $F(1,19) = 6.32, p < .05,$
225 $\eta^2 p = .25$. Recall performance was better in the rhythm (2.55/6) than the silent condition
226 (2.22/6). The BF was of 3, thus representing moderate evidence in favor of this effect. The
227 ANOVA including order confirmed the significant condition effect, $p < .05$, and revealed that
228 the main effect of order and its interaction with condition were not significant, $F < 1$. These
229 results confirmed that an isochronous rhythm can improve maintenance in WM and showed
230 more specifically its effect on attentional refreshing (Figure 2C).³

231

232 **Comparison between Experiment 1a and Experiment 2**

233 An ANOVA with condition (rhythm, silent) as within-subject and experiment (1a, 2) as
234 between-subjects factors was performed. The main effects of condition and experiment were
235 significant, $F(1,38) = 45.44, p < .0001, \eta^2 p = .54$, and $F(1,38) = 130.24, p < .0001, \eta^2 p = .77$,
236 respectively. Recall performance was better in the rhythm (3.76/6) than the silent condition
237 (3.14/6) and better in Experiment 1a (4.51/6), when both mechanisms of maintenance were
238 available, than in Experiment 2 (2.39/6) when verbal rehearsal was blocked. Moreover, the
239 interaction was significant, $F(1,38) = 10.00, p < .01, \eta^2 p = .21$, revealing that the condition effect,
240 albeit significant in both experiments, was larger in Experiment 1a ($p < .0001$) than in

241 Experiment 2 ($p < .05$). This analysis suggests that both mechanisms of maintenance (rehearsal
242 and attentional refreshing) can benefit from temporal regularities.

243

244 **Discussion**

245 Building on two research domains (WM and dynamic attending), our study investigated how
246 WM can benefit from temporal regularities guiding attention over time. The aim was to
247 investigate the impact of an isochronous rhythm on maintenance in WM. While previous
248 research has provided evidence for a beneficial effect of temporal structures on various
249 aspects of cognition, we have demonstrated for the first time the benefit of temporal structures
250 on maintenance in WM. In particular, we observed better recall performance of letter series
251 after a delay filled with a repeated, isochronously presented sound compared to a silent delay
252 (Experiment 1a), and this effect was also observed under articulatory suppression
253 (Experiment 2). Importantly, the sole presence of a sound cannot account for this result, as the
254 benefit was not observed with non-isochronous sound sequence (Experiment 1b.). These
255 results are in agreement with the DAT predicting a benefit of temporal regularities on
256 cognitive processing (Jones & Boltz, 1989; Large & Jones, 1999). In the presence of external
257 stimulus regularities, participants synchronize their attentional cycles to these beats, leading
258 to more attentional resources available at certain time points, which then increase the
259 efficiency of maintenance processes during the retention period.

260 In the research domain of WM, there is growing consensus that the maintenance of
261 information relies on attention (e.g., Barrouillet et al., 2011; Cowan, 2005). Attentional
262 refreshing refers to a process by which the level of activation of memory traces (decaying
263 because of time) is restored by focusing attention on these memory traces (Barrouillet et al.,
264 2011). Even though the nature of this mechanism is still poorly understood, it has been

265 demonstrated that refreshing relies on domain-general attention (e.g. verbal, visual, spatial;
266 Vergauwe, Barrouillet, & Camos, 2010). Beyond attentional refreshing, verbal rehearsal had
267 been previously identified as a mechanism for maintaining verbal information (see Baddeley,
268 2012; Camos, 2015 for reviews; but see Lewandowsky & Oberauer, 2015 for a debate on
269 verbal rehearsal). Because the effect of the isochronous rhythm was greater in Experiment 1
270 (where both mechanisms were available) than in Experiment 2 (where verbal rehearsal was
271 blocked), our findings suggest that both maintenance types benefit from temporal regularities.
272 The DAT can account for an increase of efficiency not only of attentional refreshing, but also
273 of verbal rehearsal. First, the initiation of verbal rehearsal has been shown to require attention
274 (e.g., Naveh-Benjamin & Jonides, 1984). Second, during verbal rehearsal, memory items are
275 subvocally rehearsed through processes shared by language production (Baddeley, 2007) and
276 it has been shown that language production can benefit from temporal regularities (e.g., Cason,
277 Hidalgo, Roman, Isoard, & Schön, 2015).

278 Combining WM accounts, which give a central role to attention (Barrouillet et al., 2011;
279 Cowan, 2005), with the DAT, suggests that an external regular sound leads participants to
280 time-lock maintenance with the beat, providing more attentional resources when maintenance
281 is done, thus making refreshing more powerful and leading to better memory performance.
282 The refreshing rate for verbal information has been estimated around 43 ms (Vergauwe,
283 Camos, & Barrouillet, 2014). Under the hypothesis that participants refreshed the entire list (6
284 letters) when the sound was presented, refreshing should take around 258 ms. Interestingly, it
285 has been demonstrated that attention is more efficient, not only when external regularities
286 were presented, but also at subdivisions of these regularities (i.e. 500 or 250 ms) (Jones, 2008;
287 Large & Jones, 1999). Overall, this suggests that beyond available time (i.e. free time for
288 refreshing or rehearsing of a memory trace), temporal regularities during that available time
289 assure more efficient maintenance.

290 At first sight, the current beneficial effect of the isochronous sound sequence on
291 memory contradicts the irrelevant sound effect (ISE), which showed that immediate serial
292 recall is disrupted by an interfering sound, whether speech or music (e.g., Colle & Welsh,
293 1976; Neath, 2000). However, some studies did not observe the ISE for a single repeated item
294 (e.g. Larsen & Baddeley, 2003; Jones, Madden, & Miles, 1992; Bell, Röer, Dentale, &
295 Buchner, 2012). In addition, irrelevant speech decreased memory performance only when it
296 involved multiple tokens or a single token presented in a syncopated time series, but not when
297 it involved a single token presented isochronously with equal time intervals (Larsen &
298 Baddeley, 2003). In contrast to these findings, we did not observe a performance *decrease*
299 when the same tone was presented with an irregular rhythm (in comparison to silence,
300 Experiment 1b), but we observed a performance *increase* when the same tone was presented
301 in a regular (isochronous) sequence. For our Experiments 1a and 2, the beneficial effect of a
302 regular sound during maintenance period was thus predicted neither by previous ISE results
303 nor by current theories of WM, but is in agreement with the DAT predicting a benefit of
304 temporal regularities on cognitive processing.

305 In the past decade, numerous computational or mathematical models of serial order in
306 short-term memory have been proposed to account for memory performance. For example,
307 the oscillator models (Brown, Preece, & Hulme, 2000; Henson and Burgess, 1997; Hartley,
308 Hurlstone, & Hitch, 2016; Burgess & Hitch, 1999) assume that serial order information is
309 encoded using time-based codes. Serial order would be retained via associations between the
310 to-be-memorized items and a context signal that changes progressively during the
311 presentation of a sequence. At recall, successive states of the temporal context signal are
312 replayed, and the learned associations reactivate the items. The model of Hartley et al. (2016)
313 proposes that serial order is encoded by a population of oscillators that are driven in a bottom-
314 up way by the structure of auditory-verbal input and are sensitive to local variations in its

315 temporal structure. This model can explain the recall benefit of a regular sequence over
316 irregular or unpredictably grouped sequences (Ryan, 1969). Applying the oscillator models to
317 our study requires extending the role of the oscillators and of the regularity from the to-be-
318 encoded sequence to the maintenance period. In Experiment 1a, when an isochronous rhythm
319 was presented during the delay period, the oscillators models could hypothesize that the
320 letters are reactivated / refreshed in parallel to the sounds, according to the similarity between
321 the current state of the timing signal and the state to which each item was associated, i.e. one
322 letter or sound approximately every second. The recall performance is thus better with an
323 isochronous rhythm presented during the delay period compared to a silent condition or a
324 non-isochronous condition. However, the results of Experiment 2 are more difficult to
325 accommodate with the oscillator models. According to these models, no performance
326 enhancement would be expected when the background sequence has a temporal rhythm that is
327 different from the to-be-recalled sequence, in particular because the background sequence
328 entrains oscillators other than those used to represent the to-be-recalled sequence. In
329 Experiment 2, participants were required to rapidly and continuously articulate the syllables
330 “babebibobu” during the delay. Uttering this verbal sequence gives a different temporal
331 context (several syllables per second) than the one presented at encoding (one letter per
332 second), it should thus disrupt the reactivation of the temporal context and the letters
333 associated with that context. However, even under articulatory suppression, in Experiment 2
334 we observed the benefit of the regular sound, thus favoring an explanation in terms of the
335 DAT and attentional refreshing.

336 In conclusion, we demonstrated the benefit of temporal structures on WM, suggesting
337 an increase of maintenance efficiency due to the presentation of an isochronous rhythm
338 during retention. We expect the present results to generalize not only to stimuli other than
339 tones played with a wood block timbre, but also to different to-be-remembered items, such as

340 words and nonwords and to different modality presentations of the to-be-remembered items,
341 such as an auditory presentation. Future studies should further test whether the observed
342 effect is strong enough to build up on a single trial basis or whether there is a benefit to
343 remain in the same temporal context (e.g., regular vs. irregular) during an experimental block.
344 Our findings also motivate future research investigating, for example, its extension when
345 encoding and maintenance differ in temporal structure (i.e. different SOAs for memoranda
346 and sounds) or implement more complex rhythmic structures, enhancing metric binding. As
347 WM is a cognitive construct connected with several higher-order cognitive functions (e.g.
348 language comprehension, mathematics, reasoning, spatial model construction), it is
349 sometimes considered as the heart of cognition. In a clinical approach, WM is known to be
350 highly vulnerable to aging, disease, trauma or stroke, and developing measures to improve
351 WM function could have a considerable impact on the well-being of these populations. The
352 improvement of WM with temporal regularities strengthens the hypothesis to use music or
353 music-like materials to boost cognitive functions, leading to new perspectives for
354 rehabilitation and brain stimulation (see Bigand et al., 2015 for a review in domains other
355 than WM).

356

357 **References**

358

359 Baddeley, A. D. (2007). *Working Memory, Thought and Action*. Oxford: Oxford University Press.

360

361 Baddeley, A. D. (2012). Working Memory: Theories, models, and controversies. *Annual Review of*

362

Psychology, 63, 1–29.

363

364 Barrouillet, P., Portrat, S., & Camos, V. (2011). On the law relating processing to storage in working
365 memory. *Psychological Review*, 118, 175-192.

366

367 Bell, R., Röer, J. P., Dentale, S., & Buchner, A. (2012). Habituation of the irrelevant sound effect:
368 Evidence for an attentional theory of short-term memory disruption. *Journal of experimental*
psychology: Learning, memory, and cognition, 38, 1542-1557.

- 369 Bigand, E., Tillmann, B., Peretz, I., Zatorre, R. J., Lopez, L., & Majno, M. (2015). The neurosciences
370 and music V: cognitive stimulation and rehabilitation. *Annals of the New York Academy of*
371 *Sciences*, 1337.
372
- 373 Boltz, M., & Jones, M. R. (1986). Does Rule Recursion Make Melodies Easier to Reproduce ? If Not
374 What Does ? *Cognitive Psychology*, 18, 389–431.
- 375 Brown, G. D., Preece, T., & Hulme, C. (2000). Oscillator-based memory for serial order.
376 *Psychological Review*, 107, 127–181.
- 377 Burgess, N., & Hitch, G. J. (1999). Memory for serial order: A network model of the phonological
378 loop and its timing. *Psychological Review*, 106, 551–581.
- 379 Camos, V. (2015). Storing Verbal Information in Working Memory. *Current Directions in*
380 *Psychological Science*, 24, 440–445.
- 381 Cason, N., Hidalgo, C., Roman, S., Isoard, F., & Schön, D. (2015). Rhythmic priming enhances
382 speech production abilities: Evidence from prelingually deaf children, *Neuropsychology*, 29, 102-
383 7.
384
- 385 Cason, N., & Schön, D. (2012). Rhythmic priming enhances the phonological processing of speech.
386 *Neuropsychologia*, 50, 2652-2658.
387
- 388 Colle, H. A., & Welsh, A. (1976). Acoustic masking in primary memory. *Journal of Verbal Learning*
389 *and Verbal Behavior*, 15, 17-31.
390
- 391 Cowan, N. (2005). Working memory capacity. Hove, East Sussex, UK: Psychology Press.
392
- 393 Cutanda, D., Correa, Á., & Sanabria, D. (2015). Auditory temporal preparation induced by rhythmic
394 cues during concurrent auditory working memory tasks. *Journal of Experimental Psychology:*
395 *Human Perception and Performance*, 41, 790-797.
396
397
- 398 Geiser, E., Notter, M., & Gabrieli, J. D. (2012). A corticostriatal neural system enhances auditory
399 perception through temporal context processing. *The Journal of Neuroscience*, 32, 6177-6182.
400
- 401 Hartley, T., Hurlstone, M. J., & Hitch, G. J. (2016). Effects of rhythm on memory for spoken
402 sequences: A model and tests of its stimulus-driven mechanism. *Cognitive Psychology*, 87, 135–
403 178.
404
- 405 Henson, R. N. A., & Burgess, N. (1997). Representations of serial order. In J. A. Bullinaria, D. W.
406 Glasspool, & G. Houghton (Eds.), *4th Neural Computation and Psychology Workshop* (pp. 283–
407 300). London: Springer.
408
- 409 Hoch, L., Tyler, M. D., & Tillmann, B. (2013). Regularity of unit length boosts statistical learning in
410 verbal and nonverbal artificial languages. *Psychonomic bulletin & review*, 20, 142-147.
411
- 412 Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological review*, 96,
413 459-491.
414
- 415 Jones, M. R., Moynihan, H., MacKenzie, N., & Puente, J. (2002). Temporal aspects of stimulus-driven
416 attending in dynamic arrays. *Psychological science*, 13, 313-319.
417

- 418 Jones, M. R. (2008). Musical time. In S. Hallam, I. Cross, & M. Thaut (Eds.), *The Oxford handbook of*
419 *music psychology* (pp. 81–92). Oxford, England: Oxford Psychology Press.
- 420
- 421 Jones, D., Madden, C., & Miles, C. (1992). Privileged access by irrelevant speech to short-term
422 memory: The role of changing state. *Quarterly Journal of Experimental Psychology: Human*
423 *Experimental Psychology*, *44A*, 645–669.
- 424
- 425 Large, E. W., & Jones, M. R. (1999). The dynamics of attending: how people track time-varying
426 events. *Psychological review*, *106*, 119-159.
- 427
- 428 Larsen, J. D., & Baddeley, A. D. (2003). Disruption of verbal STM by irrelevant speech, articulatory
429 suppression, and manual tapping: do they have a common source? *Quarterly Journal of*
430 *Experimental Psychology*, *56*, 1249–1268.
- 431
- 432 Lee, M. D., & Wagenmakers, E. J. (2013). *Bayesian cognitive modeling*. Cambridge: Cambridge
433 University Press.
- 434
- 435 Lewandowsky, S. & Oberauer, K. (2015). Rehearsal in serial recall: An unworkable solution to the
436 nonexistent problem of decay. *Psychological Review*, *122*, 674-679.
- 437
- 438 Morey, R. D., & Rouder, J. N. (2011). Bayes factor approaches for testing interval null hypotheses.
Psychological methods, *16*, 406-419.
- 439
- 440 Naveh-Benjamin, M., & Jonides, J. (1984). Maintenance rehearsal: A two-component analysis.
441 *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*, 369–385.
- 442
- 443 Neath, I. (2000). Modeling the effects of irrelevant speech on memory. *Psychonomic Bulletin &*
444 *Review*, *7*, 403-423.
- 445
- 446 Plancher, G., & Barrouillet, P. (2013). Forgetting from working memory: Does novelty encoding
447 matter? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *39*, 110-125.
- 448
- 449 Portrat, S., Barrouillet, P., & Camos, V. (2008). Time-related decay or interference-based forgetting in
450 working memory? *Journal of experimental psychology: Learning, memory, and cognition*, *34*,
451 1561-1564.
- 452
- 453 Povel, D. J., & Essens, P. (1985). Perception of temporal patterns. *Music perception*, *2*, 411-440.
- 454
- 455 Purnell-Webb, P., & Speelman, C. P. (2008). Effects of music on memory for text. *Perceptual and*
456 *motor skills*, *106*, 927-957.
- 457
- 458 Przybylski, L., Bedoin, N., Krifi-Papoz, S., Herbillon, V., Roch, D., Léculier, L., Kotz, S.A., &
459 Tillmann, B. (2013). Rhythmic auditory stimulation influences syntactic processing in children
460 with developmental language disorders. *Neuropsychology*, *27*, 121-131.
- 461
- 462 Quené, H., & Port, R. (2005). Effects of timing regularity and metrical expectancy on spoken-word
463 perception. *Phonetica*, *62*, 1-13.
- 464
- 465 Raye, C. L., Johnson, M.K., Mitchell, K. J., Greene, E. J., & Johnson, M. R. (2007). Refreshing: A
466 minimal executive function. *Cortex*, *43*, 135–145.
- 467
- 468 Ryan, J. (1969). Grouping and short-term memory: Different means and pattern of grouping.
469 *Quarterly Journal of Experimental Psychology*, *21*, 137–147.

- 470 Schmidt-Kassow, M., & Kotz, S. A. (2009). Event-related brain potentials suggest a late interaction of
471 meter and syntax in the P600. *Journal of Cognitive Neuroscience*, *21*, 1693-1708.
472
- 473 Selchenkova, T., François, C., Schön, D., Corneyllie, A., Perrin, F., & Tillmann, B. (2014). Metrical
474 presentation boosts implicit learning of artificial grammar. *Plos one*, *9*:e112233.
475
- 476 Selchenkova, T., Jones, M. R., & Tillmann, B. (2014). The influence of temporal regularities on the
477 implicit learning of pitch structures. *The Quarterly Journal of Experimental Psychology*, *67*,
478 2360-2380.
479
- 480 Silverman, M. J. (2012). Effects of melodic complexity and rhythm on working memory as measured
481 by digit recall performance. *Music and Medicine*, *4*, 22-27.
482
- 483 Tillmann, B., & Dowling, W. J. (2007). Memory decreases for prose, but not for poetry. *Memory &*
484 *Cognition*, *35*, 628-639.
485
- 486 Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general
487 resource? *Psychological Science*, *21*, 384-390.
488
- 489 Vergauwe, E., Camos, V., & Barrouillet, P. (2014). The impact of storage on processing: How is
490 information maintained in working memory? *Journal of Experimental Psychology. Learning,*
491 *Memory, and Cognition*, *40*, 1072-95.
492

Footnotes

493
494
495
496

¹The task used here is an immediate serial recall task, which can be referred to as a measure of short-term memory. However, as we investigated the maintenance mechanisms described in the framework of working memory models, we referred to it in terms of working memory.

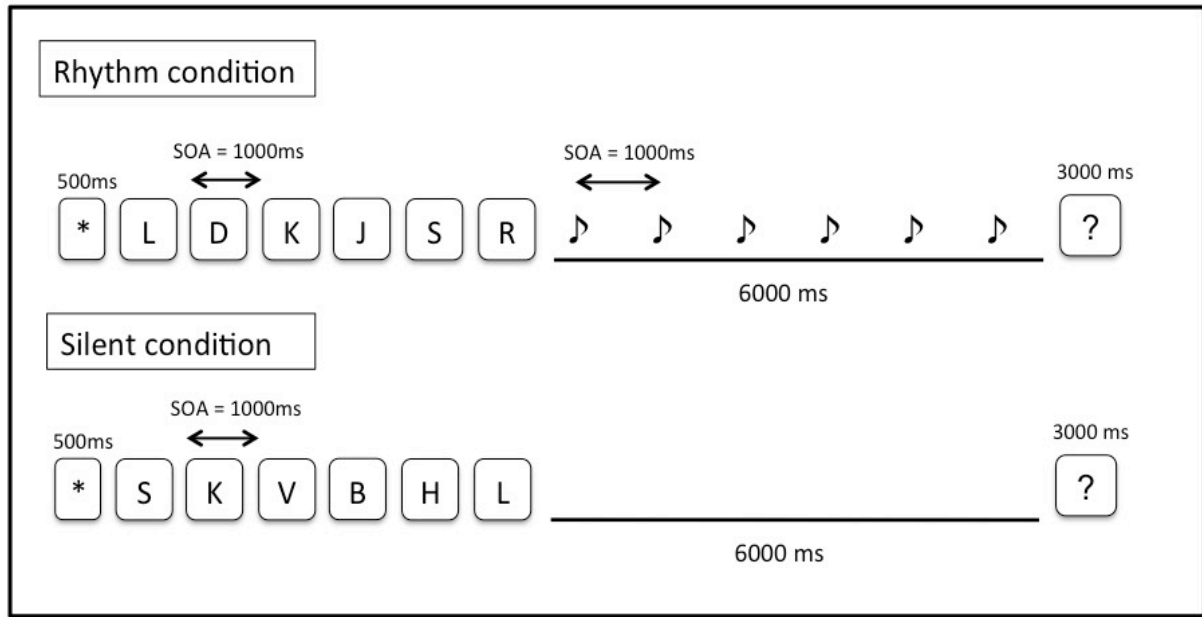
500
501
502
503
504
505
506
507

²We performed one-way ANOVAs (with condition as within-subject factor) on each potential error type: a significant effect of condition was observed on forgetting (omission of letters), $F(1, 19) = 7.07, p < .05$; Cohen's $d = 0.34$, intrusion (recall of non-presented letters), $F(1, 19) = 13.29, p < .01$; $d = 0.94$, and transposition (exchanged letter positions), $F(1, 19) = 19.64, p < .0001$; $d = 1.17$, which showed the strongest decrease in the rhythm condition. Even though transposition errors were also more frequent than forgetting or intrusion errors, this result suggests that temporal regularities are particularly useful for maintaining order information.

508
509
510
511
512

³We performed one-way ANOVAs (with condition as within-subject factor) on each potential error type, but the effect of condition was not significant. This finding suggested that the effect of temporal regularities on the maintenance of order information was reduced by the articulatory suppression (in comparison to Experiment 1a.).

513



514

515 **Figure 1.** Schematic presentation of the experimental design. Participants were presented
 516 with the to-be-remembered letters, each letter being followed by a retention delay containing
 517 or not a rhythm. The figure illustrates the two experimental conditions. SOA=Stimulus-Onset-
 518 Asynchrony.

519

520

521

522

523

524

525

526

527

528

529

530

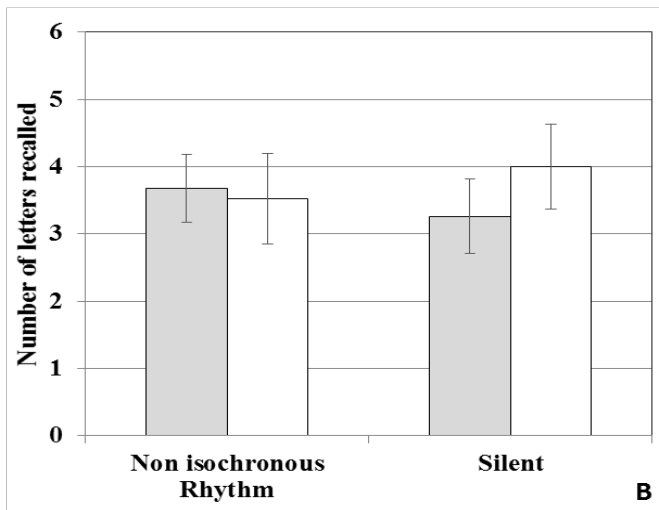
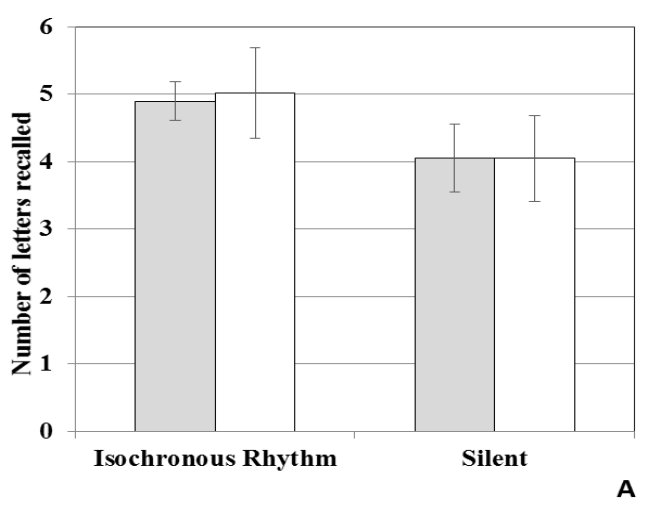
531

532

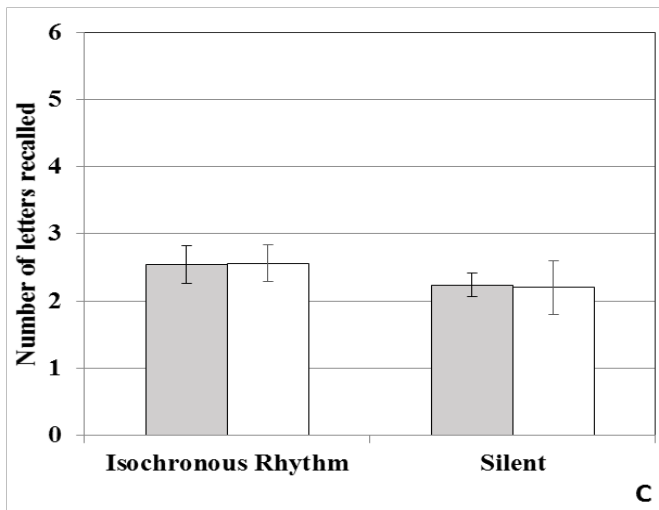
533

534

535
 536
 537
 538
 539
 540
 541
 542
 543
 544
 545
 546
 547
 548
 549
 550
 551
 552
 553
 554
 555
 556
 557



■ Order 1 S-R
 □ Order 2 R-S



558 **Figure 2.** Recall performance (with a maximum of 6 letters) for Experiments 1a (A), 1b (B)
559 and 2 (C) according to the experimental condition (rhythm, silent) and the order of the
560 condition (means and standard errors). S-R = Silent-Rhythm; R-S = Rhythm-Silent.

561

562 **Table 1.** Detailed description of the SOAs (in ms) separating the sounds of the 12 sequences
 563 used in Experiment 1b.

564

	0 – Sound 1	Sounds 1-2	Sounds 2-3	Sounds 3-4	Sounds 4-5	Sounds 5- 6	Sound 6-6000	Sum	Standard deviation	Mean
Sequence 1	324	434	1325	588	1604	1012	713	6000	475.60	857.14
Sequence 2	60	943	558	1167	1480	1214	578	6000	486.75	857.14
Sequence 3	89	1159	943	879	667	1611	652	6000	471.80	857.14
Sequence 4	437	958	947	508	1055	645	1450	6000	354.09	857.14
Sequence 5	103	492	1557	465	1362	1284	737	6000	547.29	857.14
Sequence 6	245	370	657	1369	1337	167	1855	6000	660.35	857.14
Sequence 7	141	496	908	1419	1030	239	1767	6000	605.72	857.14
Sequence 8	327	337	204	1259	1247	1810	816	6000	605.71	857.14
Sequence 9	189	334	1560	588	1479	1137	713	6000	543.50	857.14
Sequence 10	94	606	1525	799	1170	1239	567	6000	486.95	857.14
Sequence 11	51	1019	751	1487	520	1525	647	6000	530.39	857.14
Sequence 12	299	263	1737	996	492	1484	729	6000	577.45	857.14

565

566

567