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IN PRESS/ Memory & Cognition**Sequential versus simultaneous presentation of memoranda in verbal working memory:****(How) does it matter?**Laura Ordonez Magro^{1,2}, Jonathan Mirault¹, Jonathan Grainger^{1,2}, & Steve Majerus^{3,4}¹Aix-Marseille Université, Marseille, France²Centre national de la recherche scientifique, France³University of Liège, Liège, Belgium⁴Fund for Scientific Research –F.R.S.-FNRS, Belgium**Corresponding author:**

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32 Abstract

33 To-be-memorized information in verbal working memory (WM) can be presented
34 sequentially, like in oral language, and simultaneously, like in written language. Few studies
35 have addressed the importance and implications for verbal WM processing of these two
36 presentation modes. While sequential presentation may favor discrete, temporal encoding
37 processes, simultaneous presentation may favor spatial encoding processes. We compared
38 immediate serial recall tasks for sequential versus simultaneous word list presentation with a
39 specific focus on serial position curves of recall performance, transposition gradients, and the
40 nature of serial order errors. First, we observed higher recall performance in the simultaneous
41 compared to the sequential conditions, with a particularly large effect at end-of-list items.
42 Moreover, results showed more transposition errors between non-adjacent items for the
43 sequential condition, as well as more omission errors especially for start-of-list items. This
44 observation can be explained in terms of differences in refreshing opportunities for start-of-list
45 items during encoding between conditions. This study shows that the presentation mode of
46 sequential material can have a significant impact on verbal WM performance, with an
47 advantage for simultaneous encoding of sequence information.

48 1. Introduction

49 To date, the mechanisms underlying encoding in working memory (WM) have been
50 widely investigated but several questions remain unanswered, and the way memoranda is
51 encoded in WM is still controversial. In 2008, Tan and Ward examined to what extent the time
52 available for rehearsal during an immediate serial recall task influences the way memoranda is
53 maintained and structured by the participants. They observed that at fast presentation rates (1
54 sec/word), participants had little time to rehearse and generally used a fixed rehearsal strategy,
55 i. e., they solely rehearsed the most recent presented item (e.g., for ABC, they rehearsed “A” or
56 “AAA” after the presentation of A, then “B” or “BBB” after the presentation of B and so on).
57 At medium (2.5 sec/word) and slow (5 sec/word) rates, participants essentially used a
58 cumulative rehearsal strategy (e.g., “ABC ABC ABC”) especially for the early items of the list.
59 Moreover, it was observed that toward the end of the list at serial positions 5 and 6, cumulative
60 rehearsal decreased, and fixed rehearsal increased. These observations suggest that the
61 encoding strategies used in immediate serial recall tasks are strongly dependent on the time
62 available for rehearsal. In a recent study, Barrouillet et al. (2021) suggested that rehearsal is not
63 the only mechanism involved in memory encoding, but that several systems of maintenance
64 (i.e., the phonological loop plus the central attentional system) can come into play during
65 complex memory measures such as maxispan tasks. The combined use of both systems has
66 been shown to allow the maintenance of at least 8 items (4 items via the phonological loop plus
67 4 items via the attentional system). This finding suggests that commonly used simple span
68 measures tend to underestimate the capacity of verbal WM, because they do not force
69 participants to engage multiple maintenance strategies during encoding. Previous studies
70 (Lewandowsky & Oberauer, 2015; Souza & Oberauer, 2018), on the other hand, have
71 questioned the beneficial effect of phonological rehearsal on immediate serial recall. Indeed, in
72 their study, Lewandowsky and Oberauer did not find convincing evidence for a favorable effect

73 of rehearsal on recall performance. This finding has been confirmed by Souza and Oberauer
74 (2018) who observed no significant difference in performance in a condition in which
75 participants were instructed to rehearse memoranda overtly and in an articulatory suppression
76 condition that blocked rehearsal of memoranda. All these studies show that, to date, it is still
77 unclear how sequence material is encoded in WM and what systems support encoding of
78 sequence material in WM. Moreover, when reviewing the literature on serial order encoding, it
79 appears that this mechanism has been extensively studied in the area of memory and perception
80 separately but there has been little integration across areas (Logan, 2021).

81 In the WM literature, contextual/temporal models of serial order WM consider that
82 information in WM is encoded via dynamic signals that change over time, meaning that each
83 item of a sequence is associated with a different state of the signal (Brown et al., 2000; Burgess
84 & Hitch, 1999, 2006; Hartley et al., 2016; Henson, 1998; Hurlstone et al., 2014). These models
85 are particularly relevant for a sequential encoding mode as adopted in commonly used memory
86 span tasks and predict a specific transposition gradient, with serial order errors being more
87 likely for temporally close items (i.e., adjacent items) as they will be associated with a more
88 similar contextual/temporal signal. These models are more difficult to apply to a simultaneous
89 presentation mode as frequently used in visual WM studies or in perception tasks. We could
90 however predict that according to these models, the entire sequence would be associated with
91 the same contextual/temporal signal and hence coding of serial order information may be less
92 precise, resulting in a flatter transposition gradient reflecting an increase in serial position
93 exchange errors over non-adjacent serial positions. Another type of model that has been
94 proposed involves spatial coding of serial position information (Abrahamse et al., 2014; De
95 Belder et al., 2015; Ginsburg & Gevers, 2015; Guida et al., 2016; van Dijck et al., 2013;
96 van Dijck & Fias, 2011) and may be particularly relevant for simultaneous encoding conditions.
97 van Dijck and colleagues have proposed the mental whiteboard hypothesis according to which

98 each successive item is associated with a position on a mental horizontal line, organized from
99 left-to-right (for populations with a left-to-right reading system; Guida et al., 2018), with early
100 items being associated with leftward positions and final items with rightward positions. This
101 implies that the serial position of items is recoded using a permanently available spatial grid
102 enabling the parallel encoding of serial position, and hence this mechanism would be facilitated
103 by a simultaneous list presentation condition in which items are already organized from left-to-
104 right. In sum, based on these two hypotheses, a sequential presentation mode may favor
105 discrete, temporal encoding processes, with one item being processed at a time and associated
106 with a distinct temporal signal, resulting in a steeper transposition gradient, while a
107 simultaneous presentation mode may favor spatial encoding processes encouraging parallel
108 processing of all list items and a flatter transposition gradient (Marcer, 1967).

109 Regarding perception, the question of how sequence material is encoded in memory has
110 been extensively studied in the domain of reading (Grainger, 2018; Pegado & Grainger, 2021;
111 Snell et al., 2017; Snell & Grainger, 2019). While some authors assume that written words of a
112 sentence are processed one-by-one (i.e., *sequentially*) from left to right (Reichle et al., 1998,
113 2009), others suggest that word order encoding during text reading occurs at least partly in
114 parallel, that is, multiple words being processed *simultaneously* (McClelland & Mozer, 1986;
115 Mozer, 1983; Snell et al., 2017; Snell & Grainger, 2019). According to the sequential
116 hypothesis, a sequential system prevents the reader from incorrectly encoding the order of
117 words in a sentence (Reichle et al., 1998, 2009). However, recent evidence suggests that word
118 order information is not encoded as precisely as a serial system predicts (e.g., Mirault et al.,
119 2018). In response to these recent findings, Snell et al. (2018) proposed a model of reading,
120 *OBI-reader*, in which word order is controlled by the interaction between location-independent
121 activation of words and sentence-level representations in WM. According to this model,
122 “feedback is provided to individual words based on top-down syntactic and semantic

123 expectations” (Snell & Grainger, 2019, p. 6). That is, when readers encounter a determiner at
124 position 1, they may expect a noun at position 2 and so on. Thus, according to these authors,
125 the reader keeps track of the position of words in a sentence by associating word identities with
126 spatiotopic coordinates in WM. This implies that sentence processing takes place in WM by
127 involving several words of the sentence simultaneously and not one word at a time.

128 Serial order encoding having been examined separately for these two research areas, it
129 remains unclear whether the way serial order information is encoded during perceptual tasks
130 such as reading (where memoranda are commonly presented simultaneously) differs from the
131 way it is encoded during WM tasks such as immediate serial recall (where memoranda are
132 commonly presented one-by-one at the center of the screen). In a recent study, Logan (2021)
133 has examined this question by presenting the participants with a whole report task (measuring
134 perception) and an immediate serial recall task (measuring WM performance). In these tasks,
135 participants were presented with sequences of letters that were displayed for 100ms and
136 1,000ms respectively. In the whole report task, participants were told to begin typing as soon
137 as the first item appeared at the screen, while they had to wait until the sequence disappeared
138 from the screen to begin typing in the immediate serial recall task. Analyses revealed that serial
139 order in perception and memory are governed by the same underlying mechanism. In that study,
140 sequences were presented simultaneously in both tasks. However, as seen earlier in the
141 Introduction, new information can enter WM either sequentially, when presented auditorily
142 (e.g., as in common WM tasks), or simultaneously, when presented visually (e.g., as in reading).
143 Thus, although it seems that the way information enters WM has major implications on the
144 mechanisms used to structure and maintain the memoranda, few studies have examined this
145 question in a specific manner by directly comparing a sequential versus simultaneous
146 presentation mode. While numerous research studies exist comparing recall performance on
147 sequentially versus simultaneously presented sequences of e.g., colors or objects in visual WM

148 or sequences of faces in long-term memory (Ahmad et al., 2017; Bhatarah et al., 2008; Carretti
149 et al., 2013; Finley et al., 2015; Mammarella et al., 2006; Ricker & Cowan, 2014), little work
150 has been done on the serial order encoding of *linguistic* material such as written and spoken
151 words or letters. Furthermore, many studies still try to compare performance on WM tasks
152 involving linguistic material but using different presentation modes. However, encoding spoken
153 letters, for example, differs fundamentally from encoding seen letters and the encoding of
154 sequentially presented letters differs fundamentally from encoding simultaneously presented
155 letters (Marcer, 1967). Also, visual material can either be presented sequentially or
156 simultaneously, while auditory material can only be presented sequentially. Yet, when having
157 to encode sequentially presented material there might be far less chance to encode it as a single
158 chunk compared to when all items are presented simultaneously (Marcer, 1967).

159 Interestingly, one of the few studies comparing sequential versus simultaneous
160 presentation modes (Frick, 1985) has shown that simultaneously presented sequences naturally
161 lead to a visual encoding of memoranda, while sequentially presented material rather leads to
162 an auditory encoding. More precisely, in his study, Frick observed that a sequential presentation
163 increased auditory errors and reduced visual errors, while the opposite was true for the
164 simultaneous condition. Frick (p. 354) explains these findings by suggesting that “a sequential
165 presentation represents the order of the items temporally [like in auditory material (e.g., spoken
166 language)], whereas a simultaneous presentation represents the order of the items spatially [like
167 in visual material (e.g., written language)]”. This assumption is in line with the
168 contextual/temporal and spatial (spatiotopic) models of WM and reading presented earlier in
169 the Introduction. In another study comparing sequential versus simultaneous list presentation
170 (Battacchi et al., 1990), it has been shown that when sequences of visual stimuli are presented
171 sequentially in a fixed location, small recency effects are generally observed. On the contrary,
172 when stimuli are distributed over space, as e.g., in simultaneous list presentations, the observed

173 recency effect is much larger. However, again, findings are controversial, as LeCompte (1992)
174 did not find an enhanced recency effect when stimuli are distributed over space, even though
175 they meticulously followed the method used by Battacchi et al. Moreover, some studies have
176 shown that visual information (e.g., letters or shapes), when presented simultaneously, leads to
177 better recall performance compared to when it is presented sequentially, that is, one item at a
178 time (Crowder, 1966; Dalmaijer et al., 2018; Marcer, 1967). Marcer observed that presenting
179 all stimuli simultaneously encouraged participants to encode the entire sequence as a single
180 chunk which in turn led to more similar recall performance between positions (i.e., flatter serial
181 position curves) compared to situations in which stimuli are presented sequentially, rather
182 encouraging the encoding of each stimulus as a single chunk leading to differences in terms of
183 recall performance per position (e.g., primacy and/or recency effects). These findings suggest
184 that the presentation mode not only affects overall recall performance but more specifically the
185 very nature of the encoding and maintenance of serial order information. In sum, the observed
186 advantage for simultaneous presentation has been suggested to involve the spontaneous use of
187 chunking mechanisms facilitated by the left-to-right spatial arrangement of the simultaneous
188 list of items (Crowder, 1966; Dalmaijer et al., 2018; Marcer, 1967).

189 Given the contradictory findings obtained in prior research, in the present study we aim
190 to bridge the gaps identified in the WM literature by trying to understand whether the encoding
191 of visually presented verbal sequence material in WM is affected by the presentation mode, that
192 is, when memoranda is presented sequentially (like in verbal WM tasks) versus simultaneously
193 (like in perspective tasks such as reading). We further provide a detailed examination of serial
194 recall performance in terms of serial position curves, transposition gradients, input-output
195 position matrix and transition matrix between consecutive items.

196 In this study, we compared immediate serial recall performance for sequentially or
197 simultaneously presented lists of words. Based on recent WM models, we hypothesized that the
198 sequential presentation condition should encourage temporal encoding (i.e., one item at a time),
199 resulting in steep transposition gradients with few serial position exchanges over non-adjacent
200 items. We hypothesized that the simultaneous presentation condition should encourage a spatial
201 encoding resulting in flatter transposition gradients. The latter prediction is also supported by
202 recent findings of the reading literature (Grainger, 2018; Grainger et al., 2014; Snell et al., 2017)
203 showing that the default strategy, under limited exposure durations, might be to encode all list
204 items in parallel, leading furthermore to an overall advantage of encoding and maintaining
205 simultaneously presented lists over sequentially presented lists. Indeed, when list items are
206 spatially encoded on a mental line, all list items are available at the same time, allowing each
207 item to be processed several times hence strengthening its representation in WM.

208 2. Method

209 2.1 Participants

210 We recruited 116 adults via *Prolific* (www.prolific.ac), a platform for online recruitment
211 of participants in behavioral studies. To determine the number of participants, we used the
212 BFDA (Bayes Factor Design Analysis) package (Schönbrodt, 2016) implemented in R (Version
213 3.6.1). This analysis showed that if the effect of interest exists, the minimal sample size needed
214 for reaching minimal evidence ($BF_{10} = 3$) in favor of the effect in 95% of simulated samples
215 was $N = 60$. For this sensitivity analysis, we assumed a medium effect size of Cohen's $d = 0.5$.
216 Three participants had to be excluded due to non-compliance with task instructions. Data were
217 retained for a total of 113 participants (*Age*: 28.15 years, *SD*: 8.95, *Range* (18-64 years), 47
218 females, 62 males, 4 "other"). All participants had to be native French-speakers and their French
219 proficiency was checked using *Lextale* (Brysbaert, 2013), a receptive vocabulary test. The study
220 was approved by the Comité de Protection des Personnes SUD-EST IV and was performed in

221 accordance with the ethical standards described in the Declaration of Helsinki (1964). All
222 participants gave their written informed consent before their inclusion in the study and received
223 monetary compensation (8£/h).

224 **2.2 Materials and procedure**

225 Data collection took place online via the experiment builder *LabVanced* (Finger et al.,
226 2017).

227 **2.2.1 Lextale**

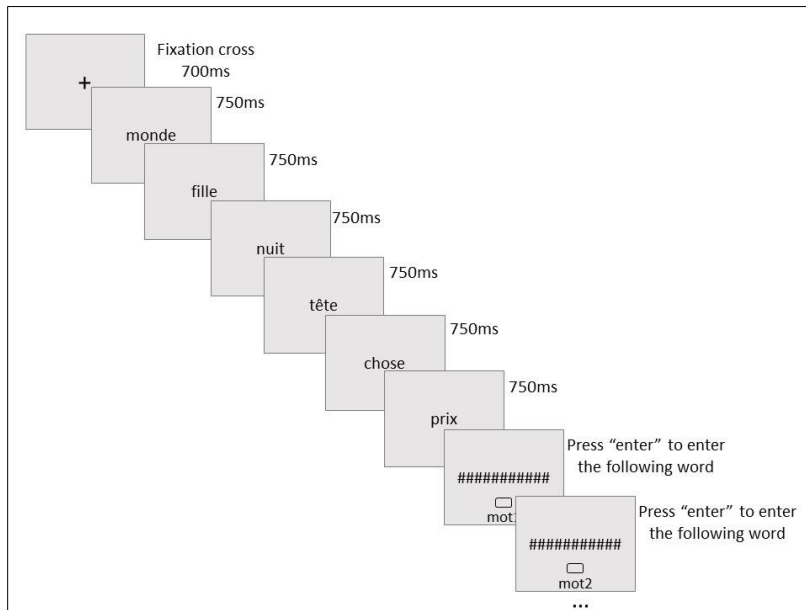
228 We used the French version of Lextale (Brysbaert, 2013) developed to measure
229 language proficiency in French from very little knowledge to adult native-speaker level
230 proficiency. The test contains words and nonwords selected from the *Lexique 3.72* project
231 (New, Pallier, Brysbaert, & Ferrand, 2004) and the *French Lexicon Project* (Ferrand et al.,
232 2010). It is composed of 56 French words of varying difficulty and from different lexical
233 frequency levels and 28 nonwords matched for phonological structure. In the present study,
234 words and nonwords were presented in random order. Each (non)word was displayed on the
235 center of the screen and participants had to make a yes/no decision to all items by pressing “O”
236 (for “oui” [yes]) as a response to an existing word and “N” (for “non” [no]) as a response to a
237 nonword. The dependent variable was the proportion of correct responses.

238 **2.2.2 Immediate serial recall task**

239 This task was composed of two lists of 20 sequences, containing each six frequent,
240 monosyllabic, and semantically unrelated nouns (i.e., 120 nouns per list). Two consecutive
241 nouns of a sequence could not start with the same letter. The nouns were selected from the data
242 base *Lexique 3.83* (New et al., 2004) and were of high lexical frequency (freqlemfilm2 variable;
243 range = 26 to 1031 per million words). The two lists were matched for lexical frequency (M_{List1} :
244 160.55, M_{List2} : 157.78, $p = .92$) from the data base *Lexique 3.83* (see Appendix for the word

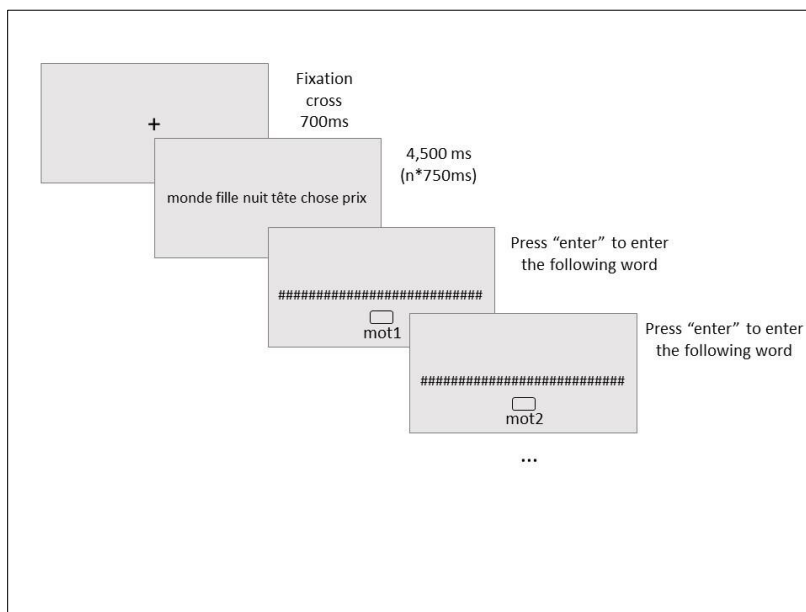
245 lists). The two lists were counterbalanced across conditions (i.e., if List 1 was presented in the
246 simultaneous condition, List 2 was presented in the sequential condition).

247 Participants performed two immediate serial recall tasks. In a first condition (see Figure
248 1 A), the *sequential condition*, the items composing the sequences were presented one-by-on
249 on the center of the screen. Each item was presented for a total of 750ms. In the second
250 condition (see Figure 1 B), the *simultaneous condition*, items were presented all at one time,
251 structured from left to right on the screen. Each sequence was presented for a total of 4,500ms,
252 which corresponds to 6 x 750ms in order to hold the total time of sequence presentation
253 comparable between conditions. Each sequence was immediately followed by a mask.
254 Participants had to recall each word in its correct serial position by typing it into an answer box
255 centered on the bottom of the screen. Participants had to press “enter” to type the next word of
256 the sequence and to proceed to the next trial. The order of conditions was counterbalanced
257 across participants. For each condition, we calculated a *serial order score*, (number of items
258 recalled in correct serial position) and an *item score* (number of items recalled regardless of
259 serial position). Moreover, we computed *transposition gradients* on serial order errors for each
260 participant and each condition by determining the number of negative displacements (items
261 recalled ahead of their correct positions) and positive displacements (items recalled after their
262 correct position). Taking the example of “time god day mom” recalled as “time mom god day”,
263 “time” will result in a displacement score of 0 (no displacement), “mom” will result in a
264 displacement score of -2, “god” will result in a displacement score of +1, and “day” will result
265 in a displacement score of -1. Finally, we conducted *detailed analyses on output order* by
266 computing an input-output position matrix representing the distribution of items recalled in the
267 different output positions and an item-item transition matrix representing the distribution of
268 transitions of successive pairs of responses. These analyses allowed us to obtain more precise
269 information about the dynamics of serial order encoding and retrieval in both conditions.



270

271 **Figure 1. A.** A typical trial for the sequential condition.



272

273 **Figure 1. B.** A typical trial for the simultaneous condition.

274 The statistical analysis conducted in the present study adopted a Bayesian model
 275 comparison approach (Dienes, 2011, 2016; Wagenmakers, 2007; Wagenmakers et al., 2008).
 276 This approach directly compares the null hypothesis to the alternative hypothesis (i.e., the effect
 277 of interest) and assesses evidence for the null effect and the effect of interest simultaneously
 278 (Dienes, 2014). Results are interpreted using the Bayes factor (BF), which reflects the
 279 likelihood ratio of two compared models. The BF_{10} is used to determine the likelihood ratio of

280 the alternative model relative to the null model. We relied on the guidelines proposed by
 281 Jeffreys (1961) for interpreting Bayes factors. A $BF_{10} > 3$ provides anecdotal evidence; a BF_{10}
 282 > 10 provides strong evidence, and a $BF_{10} > 100$ provides decisive evidence for the alternative
 283 hypothesis. All the analyses were conducted with the JASP software package (JASP Team.,
 284 2021), using default settings for Cauchy prior distribution (Wagenmakers et al., 2018).

285 **3. Results**

286 See Table 1 for the descriptive statistics of the Lextale and the immediate serial recall
 287 task.

288 **Table 1.**

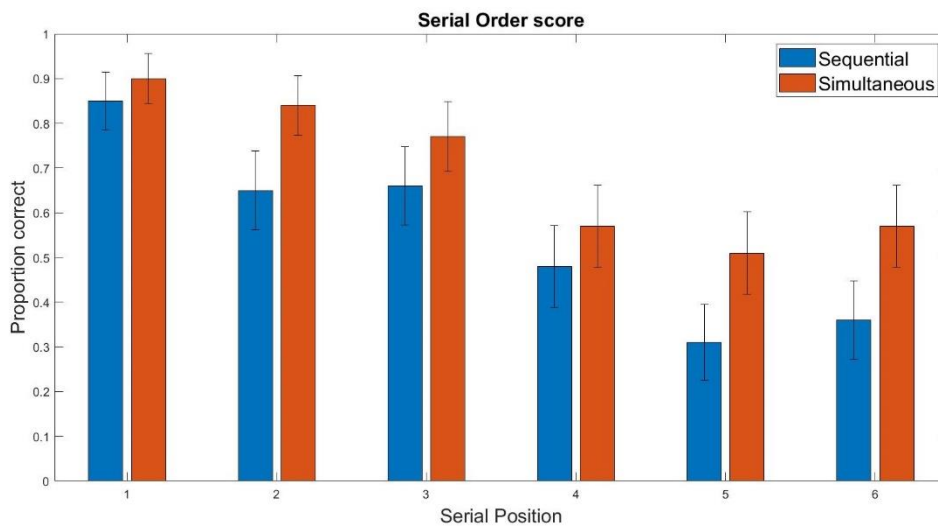
289 Descriptive statistics for the Lextale and the serial recall task. Means and Standard Deviation
 290 (in brackets) are represented for the sequential and the simultaneous condition as well as BF_{10}
 291 for Bayesian paired sample t-test between conditions.

N = 113	Sequential	Simultaneous	BF_{10}
Serial order score	.55(.17)	.69(.17)	> 100
Item score	.63(.14)	.73(.14)	> 100
Lextale	.83(.10)		

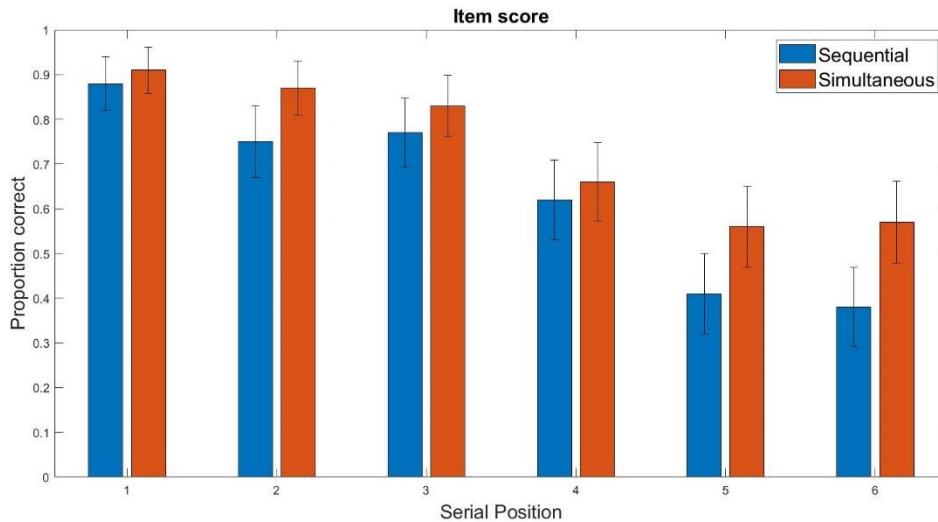
292 *Note.* All scores reflect proportion of correct responses.

293 We first compared overall recall performance between the sequential and simultaneous
 294 conditions, by running a 2 (Condition: Sequential vs. Simultaneous) \times 6 (Position: 1 to 6)
 295 Bayesian repeated measures ANOVA on the **serial order score** as dependent variable (see
 296 Figure 2). Results revealed decisive evidence for an effect of Condition ($BF_{10} = 1.06e^{+23}$) with
 297 better performance for the simultaneous ($M = .69$, $SD = .17$) compared to the sequential
 298 condition ($M = .55$, $SD = .17$), decisive evidence for an effect of Position ($BF_{10} = 4.89e^{+165}$),
 299 and decisive evidence for an interaction between Condition and Position ($BF_{10} = 1.51e^{+6}$).
 300 Bayesian paired t-tests showed decisive evidence for an effect of Condition at all positions but
 301 with particularly large effects for end-of-list positions as well as position 2 (Position 1: $BF_{10} =$
 302 1,120; Position 2: $BF_{10} = 3.65e^{+22}$; Position 3: $BF_{10} = 255,485$; Position 4: $BF_{10} = 715$; Position

303 5: $BF_{10} = 4.57e^{+12}$; Position 6: $BF_{10} = 4.46e^{+11}$). Similar results were observed when considering
 304 the item score (see Figure 3). Indeed, a 2 x 6 Bayesian repeated measures ANOVA on the **item**
 305 **score** showed decisive evidence for an effect of Condition ($BF_{10} = 3.02e^{+11}$) with again better
 306 performance for the simultaneous condition ($M = .73$, $SD = .14$) compared to the sequential
 307 condition ($M = .63$, $SD = .14$), decisive evidence for an effect of Position ($BF_{10} = 6.57e^{+171}$),
 308 and decisive evidence for an interaction between Condition and Position ($BF_{10} = 1.81e^{+6}$).
 309 Bayesian paired t-tests showed strong evidence for a difference at position 1 ($BF_{10} = 32.95$),
 310 decisive evidence for a difference at position 2, 3, 5, and 6 ($BF_{10} = 2.66e^{+17}$, $BF_{10} = 201$, BF_{10}
 311 $= 1.84e^{+8}$, and $BF_{10} = 6.54e^{+10}$ respectively), and no evidence for a difference at position 4 (BF_{10}
 312 $= 0.63$). Thus, item recall performance was higher in the simultaneous than in the sequential
 313 condition, and this for all serial positions except for positions 4 where the effect was absent. In
 314 sum, we observed better recall performance for serial order and item recall in the simultaneous
 315 compared to the sequential condition and this especially for end-of-list items.



316
 317 **Figure 2.** Proportions correct per position for the serial order score. Error bars represent 95%
 318 confidence intervals.

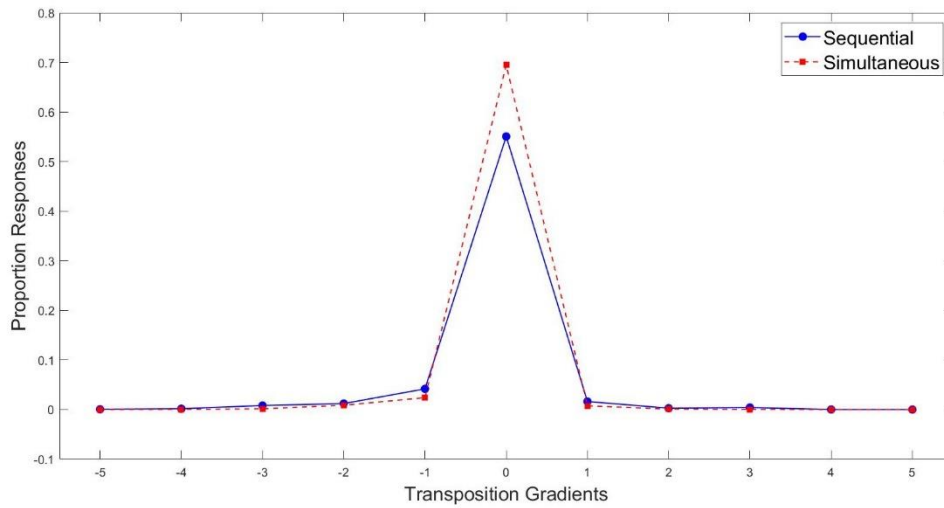


319

320 **Figure 3.** Proportions correct per position for the item score. Error bars represent 95%
 321 confidence intervals.

322 Next, we examined the **transposition gradients** for serial order recall errors as a
 323 function of condition by running a 2 (Condition: Sequential vs. Simultaneous) × 11
 324 (Transposition gradients: -5 to 5) Bayesian repeated measures ANOVA (see Figure 4). Results
 325 revealed no evidence for an effect of Condition ($BF_{10} = 0.09$), decisive evidence for an effect
 326 of Transposition ($BF_{10} = 3.95e^{+124}$), and decisive evidence for an interaction between Condition
 327 and Transposition ($BF_{10} = 2.41e^{+69}$). Analyses showed decisive evidence for a difference
 328 between conditions for displacements of -3, -1, 0, 1, and 3, with more transposition errors in
 329 the sequential compared to the simultaneous condition (see Table 2). Again, this interaction
 330 reveals more precise serial order encoding for the simultaneous compared to the sequential
 331 condition. Interestingly and as already reported earlier, we observed that items that were
 332 recalled in the wrong position were recalled close to their correct position in both conditions
 333 but in contrast with our hypothesis, with more transposition errors between distant items
 334 (transposition errors of +/-3) in the sequential compared to the simultaneous condition. Thus,
 335 contrary to our hypothesis, we did not observe steeper transposition gradients in the sequential

336 compared to the simultaneous condition, as the tendency for transposition errors to cluster
 337 around their correct position was more pronounced in the simultaneous condition.



338
 339 **Figure 4.** Transposition gradients for each condition.

340 **Table 2.**

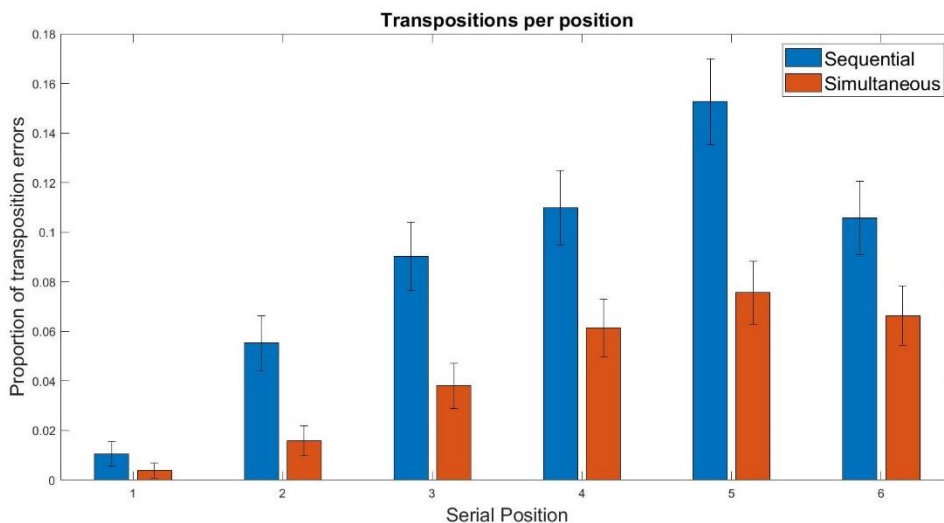
341 Bayesian paired t-test on transposition gradients between conditions.

Transposition gradient	Sequential condition Mean(SD)	Simultaneous condition Mean(SD)	BF ₁₀
-5	5.9e ⁻⁴ (0.003)	7.37e ⁻⁵ (7.83e-4)	0.33
-4	0.001(0.007)	2.33e ⁻³ (0.000)	0.61
-3	0.008(0.011)	0.001(0.006)	77,026***
-2	0.012(0.018)	0.008(0.020)	0.40
-1	0.041(0.037)	0.024(0.032)	18,773***
0	0.551(0.176)	0.695(0.174)	1.63e ⁺¹⁷ ***
1	0.016(0.014)	0.007(0.014)	3,935***
2	0.003(0.008)	0.001(0.003)	0.79
3	0.004(0.005)	5.16e ⁻⁴ (0.002)	1,62e ⁺⁷ ***
4	0.001(0.000)	NAN	NAN
5	NAN	NAN	NAN

342 *Note.* ***decisive evidence for the alternative hypothesis.

343 Moreover, we examined how serial order errors are distributed over serial position in
 344 both conditions by running a 2 (Condition: Sequential vs. Simultaneous) × 6 (Position: 1 to 6)
 345 Bayesian repeated measures ANOVA on **transposition errors** (see Figure 5). In accordance
 346 with our previous findings, we again observed decisive evidence for an effect of Condition
 347 (BF₁₀ = 1.45e⁺²⁰) with more transposition errors in the sequential compared to the simultaneous

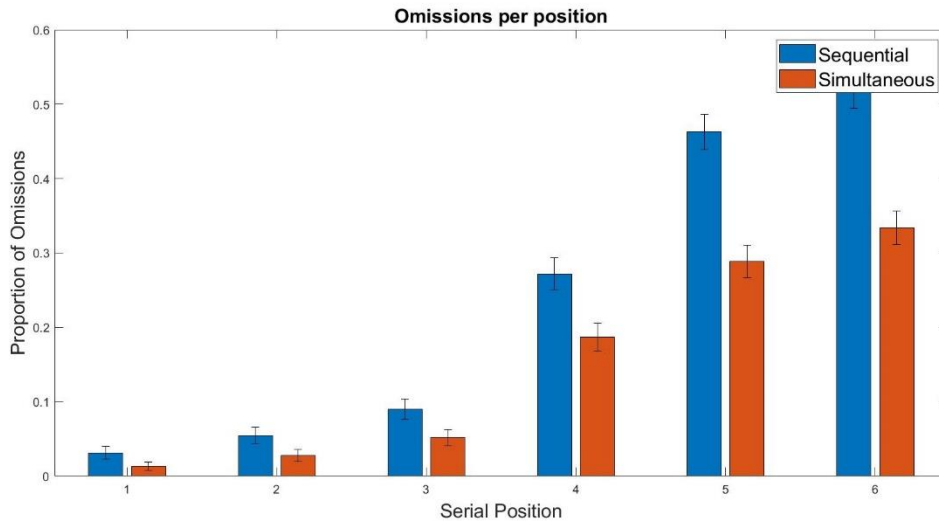
348 condition, decisive evidence for an effect of Position ($BF_{10} = 1.22e^{+54}$), with transposition errors
 349 increasing with serial position. We observed decisive evidence for an interaction between
 350 Condition and Position ($BF_{10} = 547$) with at least two times more transposition errors in the
 351 sequential ($M_{Pos1} = .011$, $M_{Pos2} = .055$, $M_{Pos3} = .090$, $M_{Pos5} = .153$) compared to the simultaneous
 352 condition ($M_{Pos1} = .004$, $M_{Pos2} = .016$, $M_{Pos3} = .038$, $M_{Pos5} = .076$) for all positions apart from
 353 positions 4 and 6 ($M_{Pos4} = .110$, $M_{Pos6} = .106$ and $M_{Pos4} = .062$, $M_{Pos6} = .066$ for the sequential
 354 and simultaneous condition respectively) which are more comparable between conditions.
 355 These findings highlight more transposition errors in the sequential compared to the
 356 simultaneous condition and more transposition errors at the end of the sequence compared to
 357 the start of the sequence, especially in the sequential condition.



358 **Figure 5.** Proportion of transposition errors per position for the sequential and the simultaneous
 359 condition. Error bars represent 95% confidence intervals.
 360

361 We computed the same analysis for **omission errors**. A 2 (Condition: Sequential vs.
 362 Simultaneous) \times 6 (Position: 1 to 6) Bayesian repeated measures ANOVA on omission errors
 363 (see Figure 6) revealed an effect of Condition ($BF_{10} = 3.32e^{+8}$) with more omission errors in the
 364 sequential compared to the simultaneous condition, decisive evidence for an effect of Position
 365 ($BF_{10} = 4.09e^{+168}$), with omission errors increasing with serial position for both conditions, and

366 decisive evidence for an interaction between Condition and Position ($BF_{10} = 7.66e^{+7}$). This
 367 interaction reveals a particularly large difference for positions 1 and 2 compared to the
 368 remaining positions between both conditions with mean proportions of omissions errors being
 369 about two times larger for the sequential condition ($M_{Pos1} = .031$; $M_{Pos2} = .055$) compared to
 370 the simultaneous condition ($M_{Pos1} = .013$; $M_{Pos2} = .027$).



371
 372 **Figure 6.** Proportion of omission errors per position for the sequential and the simultaneous
 373 condition. Error bars represent 95% confidence intervals.

374 Finally, in order to better understand the observed differences between conditions in
 375 terms of transposition gradients, we computed an input-output matrix for each condition (see
 376 Table 3), tabulating each input position by output position as done by Bhatarah et al. (2008).
 377 This table represents the number of items recalled at the different output positions (Howard &
 378 Kahana, 1999). In this table, “blank” refers either to an omission or an intrusion error. As shown
 379 in Table 3 as well as in Figures 7 and 8, typical transposition gradients are observed for all serial
 380 positions and both sequential and simultaneous conditions: When an item is recalled at the
 381 wrong position, it is most often recalled at the position directly following its expected position
 382 (e.g., serial position 1 recalled at serial position 2).

383

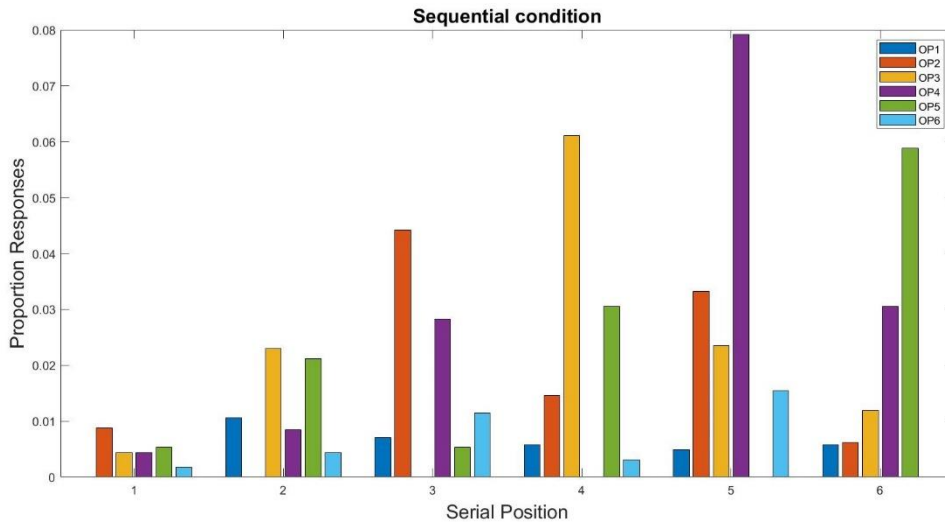
384 **Table 3.**

385 Distribution of list items recalled in the different output positions for both conditions. “Blank”
 386 refers to the participants writing an “x” or recalling a word that was not part of the sequence
 387 (intrusion error).

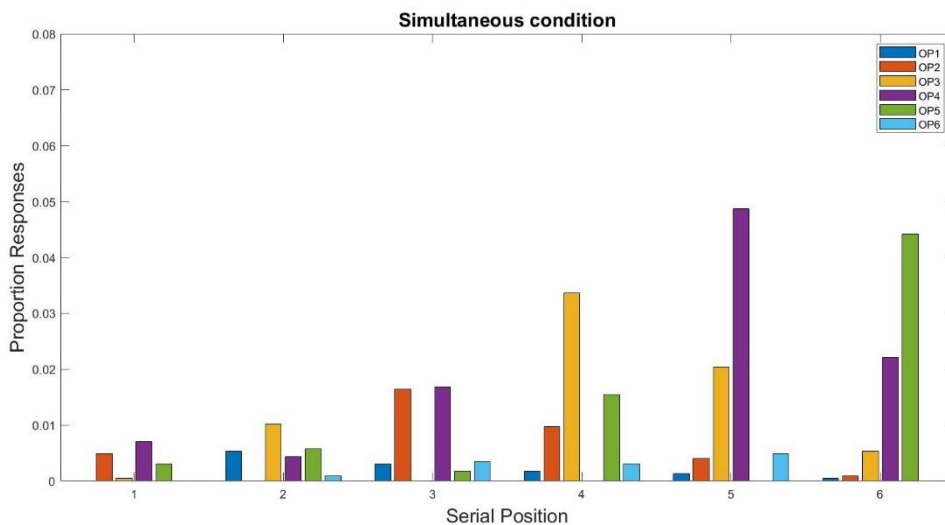
<i>Sequential condition: Output Position</i>							
Serial Position	1	2	3	4	5	6	Total
1	1,916	20	10	10	12	4	1,972
2	24	1,464	52	19	48	10	1,617
3	16	100	1,484	64	12	26	1,702
4	13	33	138	1,087	69	7	1,347
5	11	75	53	179	695	35	1,048
6	13	14	27	69	133	821	1,077
Blank	267	554	496	832	1,291	1,357	4,797
Total	2,260	2,260	2,260	2,260	2,260	2,260	13,560
<i>Simultaneous condition: Output Position</i>							
Serial Position	1	2	3	4	5	6	Total
1	2,030	11	1	16	7	0	2,065
2	12	1,914	23	10	13	2	1,974
3	7	37	1,737	38	4	8	1,831
4	4	22	76	1,295	35	7	1,439
5	3	9	46	110	1,158	11	1,337
6	1	2	12	50	100	1,286	1,451
Blank	203	265	365	741	943	946	3,463
Total	2,260	2,260	2,260	2,260	2,260	2,260	13,560

388

389



390
 391 **Figure 7.** Distribution of words recalled by serial position and output position (OP) for the
 392 sequential condition. Note that correct responses (i.e., serial position = output position) are not
 393 represented on the graph.



394
 395 **Figure 8.** Distribution of words recalled by serial position and output position (OP) for the
 396 simultaneous condition. Note that correct responses (i.e., serial position = output position) are
 397 not represented on the graph.

398 Moreover, we calculated the transitions between consecutive words recalled (see Table
 399 4). From these transitions, the Lag (difference between the serial positions of the successively
 400 recalled items, see Howard & Kahana, 1999; Kahana, 1996 for more information) can be
 401 calculated by subtracting the serial position of the word recalled in output position n from the

402 word recalled in output position $n-1$. Note that positive values of lag correspond to forward
403 recalls and negative values of lag correspond to backward recalls. Large absolute values of lag
404 correspond to the successive recall of items that are widely spaced in the sequence and small
405 absolute values correspond to the successive recall of items that are close together in the to-be-
406 recalled sequence (Kahana, 1996). Our data shows a predominance of lag +1 responses, i.e.,
407 responses that are output in forward serial order. Crucially, the total number of positive lags
408 was far greater than the total number of negative lags (see Table 4), suggesting that recall was
409 mainly in a forward order in both conditions, (e.g., when the item from a given position was
410 recalled in a wrong position, there was a strong tendency for this item being recalled after than
411 before an item from an earlier position).

412

413 **Table 4.**

414 Distribution of transitions of successive pairs of responses (items $n-1$ and n) for both conditions.
 415 This table contains the number of times a serial position has been recalled immediately after a
 416 given serial position. For instance, serial position 2 has been recalled 1,325 times immediately
 417 after serial position 1 for the sequential condition.

<i>Sequential condition: Serial Position of Prior Item (Output Position $n-1$)</i>								
Serial Position of Output position n	1	2	3	4	5	6	-	Blank
1	0	10	5	9	9	3	1916	20
2	1,325	3	41	43	11	5	24	165
3	88	1,139	1	43	54	12	16	349
4	25	89	962	1	46	5	13	206
5	64	26	114	611	0	27	11	195
6	6	43	35	89	556	5	13	330
-	4	10	26	7	35	821	0	1,357
Blank	460	297	518	544	337	199	267	2,175
<i>Simultaneous condition: Serial Position of Prior Item (Output Position $n-1$)</i>								
Serial Position of Output position n	1	2	3	4	5	6	-	Blank
1	0	5	12	7	1	0	2030	10
2	1,781	1	14	10	4	0	12	146
3	25	1,591	1	24	9	0	7	174
4	14	54	1,183	1	27	7	4	149
5	16	29	76	936	1	12	3	264
6	3	19	24	40	1,001	3	1	360
-	0	2	8	7	11	1,286	0	946
Blank	220	273	513	414	283	143	203	1,414

418 *Note.* Note that we retained the repetitions of a given item in the present table, which is why
 419 the diagonal (in bold) is not 0 for all columns. However, these repetitions have been scored as
 420 incorrect in all scores calculated in this article. The column “-” corresponds to an item being
 421 recalled at the first position, and thus contains the number of times no item has been recalled
 422 before the given serial position, as this position has been recalled as first item of the sequence.
 423 The line “-” corresponds to an item being recalled at the last position, and thus contains the

424 number of times no item has been recalled after the given serial position, as this position has
425 been recalled as last item of the sequence.

426 In sum, as expected, our findings showed better recall performance for the simultaneous
427 compared to the sequential condition and this especially for serial order information recall
428 compared to item information recall. More precisely, we observed weaker serial order recall
429 performance especially for end-of-list items in the sequential condition. Moreover, results
430 showed typical transposition gradients for both conditions but, contrarily to our hypothesis,
431 with more transpositions between distant positions for the sequential compared to the
432 simultaneous condition. Also, we observed more transposition errors for the last serial positions
433 in both conditions. Furthermore, analyses revealed more omission errors in the sequential
434 compared to the simultaneous condition, especially for the two first positions and with more
435 comparable performance for the last position between conditions. However, even though the
436 presentation mode seems to lead to differences in terms of recall performance as well as in
437 terms of the nature of serial order errors, we observed some similarities regarding the dynamics
438 of encoding and retrieval between both conditions. Indeed, our results revealed that recall
439 proceeded mainly in a forward serial order in both conditions.

440 **4. Discussion**

441 In the present study, we investigated the influence of two presentation modes (sequential
442 versus simultaneous) on the way memoranda is structured and maintained in WM. In most WM
443 studies, to-be-recalled sequences are presented sequentially, that is, one item at a time, like in
444 oral language. However, in some WM studies, the material is presented simultaneously, that is,
445 all items at a time, like in written language. Nevertheless, the influence of presentation mode
446 (sequential versus simultaneous) on recall performance has barely been investigated and it is
447 unclear whether WM performance and the nature of encoding mechanisms differ between
448 sequentially versus simultaneously presented sequences. A few prior studies have observed

449 differences in WM performance between these two presentation modes, but empirical evidence
450 allowing to understand these differences remains scarce and is sometimes contradictory
451 (Battacchi et al., 1990; Crowder, 1966; Dalmaijer et al., 2018; Frick, 1985; LeCompte, 1992;
452 Marcer, 1967). In the present study, we therefore examined performance in both sequentially
453 and simultaneously presented list material and proposed detailed analyses by comparing serial
454 position curves for recall performance and the nature of recall errors between conditions. Based
455 on recent models of WM encoding (i.e., temporal versus spatial models), we hypothesized that
456 a sequential presentation mode should encourage a temporal encoding (i.e., one item at a time),
457 which may manifest itself by a steep transposition gradient with more serial position exchanges
458 over adjacent compared to non-adjacent items. On the other hand, we expected a spatial
459 encoding when the material is presented simultaneously, leading to a flatter transposition
460 gradient.

461 In line with prior studies, our findings revealed higher recall performance in the
462 simultaneous compared to the sequential condition (Crowder, 1966; Dalmaijer et al., 2018;
463 Marcer, 1967), especially for the recall of serial order information compared to item
464 information. Interestingly, the observed difference in performance between conditions was
465 especially observed for end-of-list items. Indeed, recall performance was weaker for end-of-list
466 items in the sequential condition. Our observation of better recall for end-of-list items in the
467 simultaneous compared to the sequential condition is also in line with a previous study in the
468 visual WM domain (Battacchi et al., 1990). That study showed that, when sequences of visual
469 stimuli are presented simultaneously, i.e., when stimuli are distributed over space, a larger
470 recency effect is observed compared to when sequences of visual stimuli are presented
471 sequentially and in fixed locations.

472 Further analyses showed typical transposition gradients with more serial position
473 exchange errors over adjacent compared to distant serial positions and with more transposition

474 errors at the end of the sequence for both conditions. However, contrarily to our temporal and
475 spatial encoding hypotheses assuming steeper transposition gradients for sequentially presented
476 material and flatter transposition gradients for simultaneously presented material, we observed
477 more transposition errors between distant positions for the sequential compared to the
478 simultaneous condition. Moreover, we observed more omission errors for the sequential
479 compared to the simultaneous condition, and this in a particularly more pronounced manner for
480 the two first positions. We suggest that these findings may rather be explained by differences
481 in refreshing opportunities of initial items during encoding. Indeed, when a sequence is
482 presented sequentially, participants can only process one item at a time, which may rapidly lead
483 to forgetting of earlier presented items. Forgetting of start-of-list items may subsequently
484 disrupt accurate encoding of the overall structure of sequence, increasing the likelihood of non-
485 adjacent serial position exchanges. On the contrary, when the memory list is presented
486 simultaneously, all list items are available at any time during encoding, allowing each part of
487 the sequence to be processed several times during encoding, strengthening both item
488 representations and the representation of their serial order within the list. This situation will
489 particularly advantage start-of-list items in the simultaneous condition relative to the sequential
490 condition given that in the latter condition, start-of-list items will be subject to the highest
491 amount of decay/forgetting over the encoding process and hence are the most in need of
492 repeated encoding. This is in accordance with Tan and Ward (2008) suggesting that the
493 encoding strategies used in immediate serial recall tasks are strongly dependent on the time
494 available for refreshing. Moreover, we suggest that the higher recall performance for the
495 simultaneous condition may also be due to the use of a reading-related parallel encoding
496 strategy (Grainger, 2018; Grainger et al., 2014; Snell et al., 2017), in which the reader keeps
497 track of the position of words in a sequence by associating word identities with spatiotopic
498 coordinates in WM. Also, similar to sentence processing, we suggest that the processing of

499 simultaneously presented sequences takes place in WM by involving several items of the
500 sequence simultaneously, and not one item at a time, allowing to strengthen the links between
501 words and encouraging the spontaneous use of chunking mechanisms.

502 Note that even though we observed differences in performance and serial order error
503 patterns in both conditions, important similarities also characterize both conditions. Indeed, the
504 data indicated that forward serial recall was prevalent in both conditions, meaning that, when
505 items were incorrectly recalled, participants most frequently recalled them after earlier items of
506 the list rather than the reverse (e.g., the sequence 1 2 3 4 5 6, would rather be recalled 1 4 5 **2 3**
507 6 than 1 4 5 **3 2** 6). These findings are in accordance with the assumption that forward serial
508 recall is a general property of memory, as shown in previous studies of free recall (Bhatarah et
509 al., 2008; Howard & Kahana, 1999; Kahana, 1996) and serial recall (Klein et al., 2005; Nairne,
510 2002).

511 Finally, note that in their article Barrouillet et al. (2021) claim that commonly used
512 simple span measures tend to underestimate working memory capacity, because participants try
513 to maintain all list items via the phonological loop which has a limited capacity of about four
514 or five items. Barrouillet et al. suggest that splitting the items into two maintenance systems,
515 that is, the phonological loop and the central attentional system, would allow to retain at least
516 up to eight items (as the capacity of the attentional system is also estimated to more or less
517 four). Indeed, they observed a dramatic increase in spans (from 6 letters in simple span measures
518 to 8 letters with maxispan instruction) when asking participants to maintain the first four items
519 via the phonological loop, while studying (looking at) the following (four) items (via the central
520 attentional system). Based on this, it is likely that processing in the sequential condition in the
521 present study may have been suboptimal and would have benefitted from maxispan instructions.
522 However, the aim of the present study being to examine how simultaneous and sequential
523 encoding conditions impact working memory encoding via default cognitive processing

524 strategies, and not via an optimized procedure, we have not used a maxispan procedure in the
525 current experiment. Note also that the design of the current study does not directly tell us
526 whether the observed superiority of the simultaneous presentation is due to opportunity to re-
527 encode items several times or to the presence of additional spatial cues. To tease apart the
528 impact of the two factors, it would be interesting in future work to adopt a design similar to
529 Guitard et al. (2021), in which the items of the sequential condition appear at the same location
530 as in their simultaneous presentation. However, the overall pattern of results is more in line
531 with the hypothesis of a processing and re-encoding advantage in the simultaneous condition
532 than a purely spatial processing hypothesis.

533 In sum, our study revealed that the presentation mode of a sequence of stimuli can have
534 implications on WM performance and on the way the memoranda are structured and refreshed
535 in WM. Beside these observed differences, we also observed some similarities between both
536 conditions regarding the dynamics of serial order encoding and retrieval. Our findings have
537 important implications for furthering our understanding of maintenance mechanisms of verbal
538 material in WM and indicate that the way to-be-memorized material is presented in WM tasks
539 should be taken into account when comparing recall performance between tasks or studies.

540

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549 Conflicts of interest/Competing interests

550 The authors have no conflicts of interest to declare that are relevant to the content of this
551 article.

552 Ethics approval

553 This study was performed in line with the principles of the Declaration of Helsinki. Approval
554 was granted by the Comité de Protection des Personnes SUD-EST IV.

555 Consent to participate

556 All participants have given prior written consent before their inclusion in the study.

557 Consent for publication

558 All participants have given written informed consent for publication.

559 Availability of data and materials

560 The datasets generated and/or analyzed during the current study are available in the OSF
561 repository: https://osf.io/c7vzs/?view_only=012b21b8ae5944b6b528bb6b3e423208.

562 Code availability

563 Not applicable.

564 Authors' contributions

565 **Laura Ordonez Magro** conceptualized the design, collected the data, conducted the data
566 analyses, and wrote the paper; **Jonathan Mirault** helped conducting the data analyses; **Steve**
567 **Majerus and Jonathan Grainger** helped conceptualizing the design and writing the paper.

568

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729 Appendix

List1_item	List1_freqfilm2	List2_item	List2_freqfilm2
cris	26.79	bague	26.14
race	27.09	souffle	26.55
poil	27.09	date	26.88
maire	27.91	job	27.24
somme	28.27	pause	27.30
star	28.91	herbe	27.64
coupe	29.16	patte	28.16
caisse	29.46	cible	28.69
gorge	29.78	corde	28.89
mur	30.04	croix	29.10
offre	30.23	membre	29.34
sucre	30.57	note	29.40
trace	30.98	aube	30.04
style	31.08	perte	30.20
lac	31.16	choc	30.22
geste	31.41	mode	30.79
haine	31.49	parc	31.02
arbre	32.40	soif	31.28
douche	32.56	soupe	31.72
note	33.42	titre	32.40
gloire	34.78	chaise	32.70
ombre	35.98	test	34.87
veste	36.00	don	35.47
vache	36.24	coffre	35.97
gaz	36.33	chair	36.01
mine	36.84	poche	36.23
champ	38.05	source	37.34
doigt	38.83	neige	37.52
couple	41.13	front	38.81
pluie	42.91	taille	41.32
piste	43.01	tombe	41.33
code	43.58	crise	43.51
risque	45.98	prince	44.83
marche	46.61	plage	44.99
chasse	46.80	ventre	46.07
zone	46.97	voie	47.01
ange	47.90	bombe	48.70
nord	50.38	pont	50.45
goût	50.51	bain	50.52
bus	50.63	centre	53.46
base	51.69	soin	54.45
fil	51.83	juge	56.40
reine	56.26	glace	58.09
lait	59.41	lune	58.29
blague	60.33	pain	62.81
preuve	60.79	tas	65.28
club	61.99	jambe	67.51

gosse	62.92	signe	67.74
pote	65.03	bière	68.55
art	65.93	clé	68.73
flic	67.53	bande	69.10
thé	67.84	tante	70.69
fleur	74.56	joie	71.07
nez	75.18	vent	71.50
trou	75.32	poste	72.64
bord	77.06	ferme	73.53
vin	80.92	vol	74.14
forme	82.61	garde	76.76
vue	84.42	balle	77.32
loi	87.37	bruit	78.94
bon	90.13	crime	81.77
coin	93.43	peau	83.83
scène	96.66	dame	86.50
doute	97.51	bouche	87.75
rêve	99.39	groupe	90.16
dos	100.34	carte	96.11
calme	105.08	œil	97.13
peuple	105.65	sorte	98.33
sac	105.96	mer	99.49
lettre	108.79	honte	103.26
pièce	110.66	pied	105.51
table	111.44	camp	105.92
bois	115.56	force	108.29
gueule	118.45	fric	108.99
plan	119.54	fond	110.07
âme	122.22	salle	111.10
face	124.33	livre	112.43
prix	126.55	arme	114.40
rue	127.35	sens	117.57
choix	130.83	maître	118.88
voix	130.83	bout	121.12
fête	138.03	oncle	124.11
ciel	142.22	faim	127.49
paix	144.86	ordre	132.50
bras	149.26	compte	138.88
route	152.83	cours	143.05
verre	154.13	âge	150.45
jeu	156.79	lieu	153.12
faute	163.19	sœur	155.22
aide	171.41	chien	158.77
tour	175.56	roi	166.34
lit	176.10	mot	174.83
chef	189.79	droit	175.60
film	195.10	point	186.70
fin	207.34	peine	193.42
cause	213.51	reste	203.10
genre	219.66	guerre	212.82

train	244.40	feu	215.87
mec	252.94	cœur	224.98
suite	274.18	corps	250.15
terre	276.29	chambre	263.93
place	280.54	truc	274.94
type	280.62	ville	277.98
part	299.31	cas	280.59
frère	311.45	main	286.62
yeux	315.89	eau	290.61
mort	372.07	sang	304.30
coup	389.49	mois	312.31
tête	453.13	mal	318.27
fil	480.15	chance	334.02
peur	551.83	heure	415.40
nuit	557.56	air	473.50
gens	594.29	nom	528.17
fil	627.59	soir	555.85
jour	635.22	femme	806.57
mère	672.00	père	879.31
homme	781.11	peu	894.78
monde	823.62	fois	899.25
dieu	852.91	vie	986.59
temps	1031.05	chose	1321.79