



HAL
open science

Strategic adaptation to dual-task in verbal working memory: Potential routes for theory integration.

Clément Belletier, Jason Doherty, Agnieszka Graham, Stephen Rhodes, Nelson Cowan, Moshe Naveh-Benjamin, Pierre Barrouillet, Valérie Camos, Robert Logie

► **To cite this version:**

Clément Belletier, Jason Doherty, Agnieszka Graham, Stephen Rhodes, Nelson Cowan, et al.. Strategic adaptation to dual-task in verbal working memory: Potential routes for theory integration.. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 2023, 49 (1), pp.51-77. <10.1037/xlm0001106>. <hal-04321919>

HAL Id: hal-04321919

<https://hal.science/hal-04321919v1>

Submitted on 4 Dec 2023

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.



HAL Authorization

PREPRINT VERSION

Strategic adaptation to dual-task in verbal working memory: Potential routes for theory integration

Clément Belletier^{1,2}, Jason Doherty², Agnieszka Jaroslawska², Stephen Rhodes³, Nelson Cowan³, Moshe Naveh-Benjamin³, Pierre Barrouillet⁴, Valérie Camos¹, Robert Logie²

¹ Université de Fribourg

² University of Edinburgh

³ University of Missouri

⁴ University of Geneva

Word Count: 17,791 words; 7 Tables and 7 Figures.

Author Note:

This work was funded by the Economic and Social Research Council (ESRC) grant ‘Working memory across the adult lifespan: An adversarial collaboration’ (WoMAAC) ES/N010728/1 (see <https://womaac.py.ed.ac.uk> for more details). Data regarding participant performance in Experiments 1 and 2 were published in Doherty et al. (2019). The participant-reported strategies that are the focus of the current manuscript have not been published elsewhere, nor have the performance data for Experiment 3. Author contributions: Data were collected by JMD and CB, and analyzed by CB. Experiments were programmed by JMD, SR, and CB, collaboratively designed with the other authors. The manuscript was written by CB, VC, and RL with all the other authors providing feedback. Pre-registered material and data are available on the Open Science Framework https://osf.io/vh8xw/?view_only=3e1619ab142d4d8696b1bfe994c926ea. AJ is now at Queen’s University Belfast. SR is now at the Rotman Research Institute, Toronto. Correspondence should be addressed to Clément Belletier who is now at Université Clermont Auvergne, Clermont-Ferrand, France. clement.belletier@uca.fr or to Robert Logie at Department of Psychology, University of Edinburgh, UK, rlogie@ed.ac.uk.

Abstract (235 words)

How Working Memory (WM) supports dual task performance is the focus of a longstanding debate. Most previous research on this topic has focused on participant performance data. In three experiments, we investigated whether changes in participant-reported strategies across single and dual task conditions might help resolve this debate by offering new insights that lead to fruitful integration of theories rather than perpetuating debate by attempting to identify which theory best fits the data. Results indicated that AS was associated with reduced reports of the use of Rehearsal and Clustering strategies but to an increase of the reported use of a Visual Strategy. Elaboration and Clustering strategies were reported less for memory under dual task compared with single task. Under both dual task and AS, more participants reported attempting to remember fewer memory items than were presented (Memory Reduction strategy). For arithmetic verification, AS and dual task resulted in a reduction in reports of a Counting strategy, and an increase in reports of a Retrieval strategy for arithmetic knowledge. It is argued that experimenters should not assume that participants perform the same task in the same way under different experimental conditions, and that careful investigation of how participants change their strategies in response to changes in experimental conditions has considerable potential for resolving theoretical challenges. It is argued further that this approach points towards the value of attempting to integrate rather than proliferate theories of WM.

Key Words: Working Memory; Strategies; Adaptation; Dual-Tasking; Articulatory Suppression

1 Working memory (WM) refers to a cognitive system that supports the storage and
2 manipulation of information over periods of a few seconds, and is often assessed with tasks that
3 include the memorization of information and a concurrent processing task. There is widespread
4 agreement regarding the importance of WM in human cognition because it sustains high-level
5 cognitive activities (for reviews see Baddeley, 2007; Conway, Jarrold, Kane, Miyake, & Towse,
6 2007; Logie, Camos, & Cowan, 2021a) as well as many moment-to-moment interactions with
7 our environment. There is also a consensus that WM capacity is limited to a relatively small
8 amount of information (e.g., Baddeley, 2012; Barrouillet & Camos, 2015; Cowan, 2010; Logie,
9 2011; Oberauer, 2002). However, despite this general agreement, several models of WM have
10 been proposed that disagree as to how the combined memorization and processing of
11 information can be achieved (e.g. Baddeley, 1986; 2012; Baddeley, Hitch, & Allen, 2018;
12 Baddeley & Logie, 1999; Barrouillet, Bernadin, & Camos, 2004; Barrouillet & Camos, 2015,
13 2021; Cowan; 1999, 2005, 2015, 2016; Doherty et al., 2019; Logie, 2003; 2011; 2016; 2018;
14 For recent reviews, see Logie et al., 2021a).

15 To address the debate regarding the interpretation of dual-tasking in WM, we combined
16 the efforts of researchers associated with three different theoretical frameworks for WM,
17 specifically the Time-Based Resource Sharing (TBRS) model by Barrouillet & Camos (2010;
18 2015; 2021), the Embedded Processes (EP) model by Cowan (1999; 2016; see also: Cowan,
19 Morey & Naveh-Benjamin, 2021), and a version of the Multiple Component Model (MCM)
20 (Baddeley & Logie, 1999; Logie, 1995; 2011; 2016; Logie, Belletier & Doherty, 2021), in a
21 large project referred to as ‘WoMAAC’ for ‘Working memory across the adult lifespan: An
22 adversarial collaboration’ (<https://womaac.psy.ed.ac.uk>; Cowan et al., 2020; Logie et al.,
23 2021b). We are fully aware that there are other important theoretical frameworks for WM (for
24 reviews see: Cowan, 2017; Logie, et al., 2021a). However, as discussed in detail below, the
25 current paper focuses more on generally agreed principles of WM (for discussions see Cowan,

26 2017; Logie & Cowan, 2015; Logie et al., 2021b), and whether we can gain insight into how
27 these principles operate (e.g. Doherty & al., 2019; Jaroslawska et al., 2020; Rhodes et al., 2019)
28 from investigating how participants attempted to perform tasks under different conditions rather
29 than testing differential predictions from any specific theories for patterns of performance
30 among participants. In doing so, we aim to gain new insights into WM functions that are not
31 clear from performance data patterns alone, and that may place constraints on and provide leads
32 to future development of WM theory.

33 Although the use of different strategies in cognitive tasks has been considered
34 previously in a range of domains (e.g. Fazio, Dewolf, & Siegler, 2016; Logie, Della Sala,
35 Laiacona, Chalmers & Wynn, 1996; Morrison, Rosenbaum, Fair, & Chein, 2016; Siegler,
36 1987), the rationale for exploring the importance of strategies in working memory tasks was
37 articulated recently by Logie (2018) as follows: "...for many cognitive tasks, there might be
38 more than one way to achieve a high or a low level of performance. The same level of
39 performance might be achieved in different ways, or using different strategies" (p.2). For
40 example, when facing a difficult cognitive task, individuals tend to use strategies in a way that
41 maximizes task performance (e.g., Fazio et al., 2016). Most studies that investigate the impact
42 of dual-task demands in performance on a memory task and a processing task when they are
43 performed together compared with being performed separately, (i.e., dual-task costs) consider
44 only the possibility of concurrent use by both tasks of a cognitive function that is common
45 between them. Rarely do such studies consider changes in which cognitive functions are used
46 and how those functions are employed in dual-task situations in attempts to limit the
47 performance cost.

48 Our aim in this article was therefore to analyze strategies in dual tasks situations. For
49 this purpose, we used data on strategies reported by participants in Doherty et al. (2019) that
50 have so far been neither exploited nor published, as well as new data including a trial-by-trial

51 assessment of the reported strategies. In so doing, we hoped to shed additional light on the
52 observed performance data, and consider whether this might lead to new theoretical
53 developments. More generally, focusing on strategies might bring a new perspective on dual-
54 tasking in WM. First, we present a brief review of key previous studies on dual tasking in
55 working memory, and an overview of the three theoretical frameworks that led to the original
56 design of the experiments. Then we discuss previous research on strategy use in working
57 memory tasks, before turning to the background for the current study and presentation of our
58 results from the analyses of reported strategies of two already published experiments (Doherty
59 et al., 2019) and of an additional experiment.

60

61 **Dual-tasking in Working Memory**

62 A major challenge for understanding human cognition is to explain how human beings
63 manage dual-tasking or, more specifically, how WM, the cognitive system thought to support
64 both temporary memory and processing, can jointly achieve these two activities. The current
65 literature provides two distinct accounts for this issue. We have already stated above that our
66 focus is on MCM, EP, and TBRS conceptual models of WM, reflecting the theoretical
67 frameworks associated with the three teams of researchers involved in these studies. On the one
68 hand, models like MCM assume that separate resources can be devoted respectively to storage
69 or processing, and that these separate resources can function in parallel, but that they can work
70 together to support overall dual task performance (e.g. Baddeley, 1986; Baddeley & Hitch,
71 1974; Baddeley & Logie, 1999; Logie, 2011). On the other hand, early versions of the EP model
72 and the TBRS model assumed that a general resource has to be shared between the two activities
73 (Barrouillet, et al., 2004; Saults & Cowan, 2007). However, more recent versions of these
74 theories contain other components that are not assumed to conflict with concurrent processing
75 (e.g. rehearsal, and offloading information to activated LTM) (e.g. Barrouillet & Camos, 2015;

76 Camos, 2017; Cowan, Sauls, & Blume, 2014) or are assumed to conflict very little with it
77 (Cowan, 1988, 1999, 2016). There is currently insufficient evidence to settle the debate between
78 these theoretical views, because substantial evidence has been gathered to support each of them.
79 One possible reason why the debate has had such longevity, and why several other theoretical
80 perspectives on WM have been proposed (for reviews see Cowan, 2017; Logie et al., 2021a),
81 could be that competition between theories results in a given theory seeming superior in
82 accounting for one data set, whereas some other theory appears to provide the best account for
83 a different data set. This could serve simply to perpetuate debate indefinitely without
84 necessarily leading to substantial new insights into human cognition (Logie et al., 2021b). An
85 alternative is to consider the commonalities between theories, and explore whether attempting
86 to integrate rather than compete for theoretical dominance might yield those new substantial
87 insights, and be more fruitful for theoretical development. Therefore, one possible resolution
88 for the debate could be that all three types of theory are at least partially correct, but that they
89 each may embody different strategies for performing particular experimental tasks. Our
90 approach to attempting that resolution was for different labs to adopt the same experimental
91 methods, protocols, and materials, and hence avoid the potential for specific methods to
92 generate data patterns that are consistent with the assumptions only of a specific theoretical
93 position.

94 The absence of a dual-task cost (or minimal cost) when processing is performed while
95 holding information in memory has been considered as major evidence to support the existence
96 of distinct resources sustaining the different activities (Baddeley & Hitch, 1974; Doherty &
97 Logie, 2016; Logie, Cocchini, Della Sala, & Baddeley, 2004). Doherty and Logie (2016)
98 investigated the reciprocal effects of a verbal memory task (i.e., maintaining a series of digits)
99 while performing a spatial task (i.e., judging the location of a square above or below the center
100 of the screen) by manipulating the load induced by each task around the individual span level

101 for each task for each participant. They found that increasing the spatial processing load had no
102 effect on memory performance and that memory load did not affect performance in the
103 processing task when performed at individual span level. Only when memory load exceeded
104 the individual span level was a reduced accuracy in the spatial task observed. The authors'
105 interpretation was that memory and processing demands can be handled by independent
106 resources, as suggested earlier by Logie et al., 2004. However, when demands exceed capacity
107 of a given resource, additional resources were assumed to have been engaged, resulting in an
108 impairment of the concurrent processing.

109 Seeming to contradict the evidence of Doherty and Logie (2016), other studies have
110 shown more continuous tradeoffs between storage and processing as the demands of the two
111 tasks are manipulated, with increases in memory load slowing processing and with increased
112 speed of processing reducing the available resources for memory (Barrouillet et al., 2004;
113 Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Barrouillet, Portrat & Camos, 2011;
114 Camos, Johnson, Loaiza, Portrat, Souza & Vergauwe, 2018; Chen & Cowan, 2009; Vergauwe,
115 Barrouillet, & Camos, 2010). However, it is notable that those studies have tended not to adjust
116 task demands to the span of each individual participant, although most of these studies used
117 span procedures, avoiding memory overload. Moreover, in the original Baddeley and Hitch
118 (1974) experiments, memory loads of six items resulted in slowing of reasoning and language
119 processing whereas memory loads of three items did not. Consistent with the Baddeley and
120 Hitch (1974) finding, Chen and Cowan (2009), showed that a speeded choice reaction time task
121 with simple visual-spatial stimuli was increasingly impaired by an increasing verbal memory
122 load (digits) when the memory list exceeded three items. Similarly, Vergauwe, Camos and
123 Barrouillet (2014) systematically increased the number of memory items to be retained, and
124 reported a linear increase in the response times on spatial fit, color discrimination, and parity
125 judgment tasks (see also Camos, Mora, Oftinger, Mariz & Schneider, 2018a). This effect is

126 analogous to the cognitive load effect in which the increase in concurrent assumed attentional
127 demand results in a linear decrease in recall performance (see for reviews, Barrouillet & Camos,
128 2010, 2012, 2015, 2021).

129 To address these apparently contradictory findings, and to gather evidence that might
130 help resolve the debate, the WoMAAC group designed a series of experiments comparing
131 performance in single- vs. dual-task situations. Young adults performed serial recall of aurally
132 and visually presented letters, and a simple addition verification task either alone (single-task)
133 or in combination (dual-task) with the verification task performed between presentation and
134 recall of letter sequences (Doherty et al., 2019). Both tasks were presented at individual span
135 level of approximately 80% correct performance when performed alone.

136 The findings on participant performance (memory and processing errors) did not closely
137 fit any of the three contrasting theoretical views. Specifically, while memory performance
138 suffered from a dual-task cost as expected by the resource-sharing hypothesis, processing was
139 at most only minimally affected by the concurrent maintenance of information, as expected by
140 the MCM hypothesis. Although these results do not allow a simple decision between theories,
141 they show that each theoretical view may have merit that could lead to theoretical integration.
142 This could offer genuine advance in understanding rather than the more common approach of
143 aiming to show that one theory is correct and others are not. A systematic investigation of
144 possible use of strategies could indicate a path towards that integration.

145

146 **Memory Strategies in Working Memory**

147 A first and important distinction between strategies in WM contrasts the verbal (e.g.,
148 letters, words, numbers) vs visual (e.g., pattern of dots, shapes, colors) nature of the memoranda
149 that participants have to memorize. Here, we will focus on strategies in verbal WM that have
150 been more intensively studied and are relevant for the experiments we report (for research on

151 visual WM, see for example Atkinson, Baddeley & Allen, 2017; Bengson & Luck, 2016; Bor,
152 Duncan, Wiseman & Owen, 2003; Brown, Forbes & McConnell, 2006; Cusack, Lehman,
153 Veldsman, Mitchell, 2009; Linke, Vicente-Grabovetsky, Mitchell & Cusack, 2011; Logie,
154 Saito, Morita, Varma & Norris, 2016; Shimi & Logie, 2019; for a review of early work see
155 Logie, 1995).

156 Because one may expect that individuals try to maximize task performance in using
157 strategies (e.g., Fazio et al., 2016), these strategies may vary from one individual to another,
158 but also for the same individual on the same task presented on two separate occasions or in
159 different trials during the same session (Logie et al., 1996; Siegler 1987; 1995; for a recent
160 review and discussion see Logie, 2018). The flow of information in WM has long been assumed
161 to be at least in part under the immediate control of individuals (Atkinson & Shiffrin, 1971;
162 Broadbent, 1958; James, 1890). Hence, different strategies should sustain WM maintenance
163 depending on the characteristics of the task or the individual. At first glance, it may seem that
164 numerous strategies would then be identified and studied in the field of WM. However, a closer
165 look at this research indicates that these numerous strategies can be regrouped into a small
166 number of categories.

167 The most frequently reported strategy to maintain verbal information in WM is
168 phonological rehearsal, or simply *Rehearsal*, for which participants repeat the memoranda out
169 loud or sub-vocally (e.g., Bailey Dunlosky & Hertzog, 2009; Dunlosky & Kane, 2007;
170 Friedman & Miyake, 2004; Logie et al., 1996; Miller, McCulloch & Jarrold, 2015; Morrison et
171 al., 2016; Turley-Ames & Whitfield, 2003; Unsworth, 2016). Besides Rehearsal, four other
172 main strategies have been described in verbal WM. *Temporal Clustering* refers to the grouping
173 in clusters of 2 or 3 items, without any reference to prior knowledge, for example grouping
174 XQBPWM into XQB and PWM. This is likely to rely to some extent on rehearsal of the groups
175 and items within groups (Bor & Owen, 2007; Harris & De Qualls, 2000; Hitch, Burgess, Towse

176 & Culpin, 1996; Logie et al., 1996; Swanson, Kehler & Jerman 2010). On the contrary,
177 *Chaining* or *Elaboration* both refer to the formation of links between the memoranda using
178 some prior knowledge (Bor & Owen, 2007; Harris & De Qualls, 2000; Kaakinen & Hyönä,
179 2007; McNamara & Scott, 2001; Swanson et al., 2010). This can be achieved, for example, by
180 creating some semantic associations (Friedman & Miyake, 2004; Harris & De Qualls, 2000;
181 Logie et al., 1996; Swanson et al., 2010), or a sentence (Bailey et al., 2009; Bailey, Dunlosky
182 & Kane, 2008; Cokely, Kelley & Gilchrist, 2006; Dunlosky & Kane, 2007; McNamara & Scott,
183 2001; St Clair-Thompson, Stevens, Hunt & Bolder, 2010; Turley-Ames & Whitfield, 2003;
184 Unsworth, 2016; Unsworth & Spillers, 2010a). *Visual Imagery* can refer to the creation of a
185 mental image based on the item meaning (e.g. Borst, Niven & Logie, 2012; Carretti, Borella &
186 De Beni, 2007; Miller et al., 2015; Morrison et al., 2016; Paivio, 1971), but could also refer to
187 retention of the visual appearance of the shape of the letters and words (Logie Della Sala, Wynn,
188 & Baddeley, 2000; Logie et al., 2016; Saito, Logie, Morita, & Law, 2008). Finally, a *Memory*
189 *Reduction* strategy, in which participants try to remember only a subset of the presented items
190 in a given trial, has been shown to be helpful in the case of visual working memory (e.g., Cusack
191 et al., 2009). Similarly, participants in a verbal working memory task might use a form of
192 memory reduction to manage their performance under dual task conditions.

193 It should be noted that strategies from different categories can be used in combination
194 to maintain the same series of items. For example, Temporal Clustering and Elaboration may
195 be combined when individuals use a group of two or three memoranda following each other to
196 make a link with previous knowledge (for example, the string of letters WMCTDK may be first
197 clustered WMC-TDK, and then WMC can be elaborated as Working Memory Capacity).

198 The use of strategies can modulate memory performance, and the link between strategies
199 and performance has been mostly discussed in the context of studies that compare high- to low-
200 WMC individuals. Engle, Cantor, and Carullo (1992) were among the first to address this

201 question by measuring the time spent on different parts of two self-paced WM tasks (an
202 operation and a reading span task), these times being conceived as indirect indicators of the use
203 of strategies. Their results showed that individuals spent more time processing the to-be-
204 remembered words as the memory load increased, this effect being stronger in high-WMC
205 individuals. More recently, Kaakinen and Hyönä (2007) also examined the time spent on the
206 different elements of a reading span task, but also recorded eye movements and fixations. In
207 line with Engle et al.'s (1992) findings, they found that participants spent more time gazing at
208 the to-be-remembered words when memory load increased, but they did not observe any
209 difference as a function of participants' WMC. In a second experiment, asking participants to
210 report their strategies, they showed that high-WMC participants reported using more frequently
211 Chaining or Imagery than low-WMC individuals. Together, these results led the authors to
212 conclude that individual differences in performing a reading span task do not depend on the
213 allocation of the time to the different elements of the task, but on the capacity to use more
214 effective strategies.

215 McNamara and Scott (2001) found that training to use the Chaining strategy
216 significantly improved WM performance in comparison with a control group that completed
217 training trials without specific instructions. McNamara and Scott (2001) also noted that even
218 the less-strategic individuals were able to benefit from this training, which is consistent with
219 their strategy mediation hypothesis, according to which performance depends mainly on the
220 strategies used by participants. Turley-Ames and Whitfield (2003) showed that training to use
221 Rehearsal was beneficial only for low-WMC participants. Moreover, Dunlosky and Kane
222 (2007) showed that in an operation span task, trial-by-trial reports of strategies correlated with
223 recall performance in that effective strategies were associated with better recall than ineffective
224 strategies (see also, Bailey et al., 2008, 2009; Harris & De Qualls, 2000). Note that, in these
225 studies, Elaboration, Chaining or Imagery were considered as effective strategies to maintain

226 verbal information in WM. Rehearsal was considered an ineffective strategy, because the latter
227 typically leads to poorer performance than the former in complex span tasks in which the
228 concurrent task (reading sentences or operations) is performed aloud (e.g., Bailey et al., 2009;
229 Bailey et al., 2008; Dunlosky & Kane, 2007; Harris & Qualls, 2000; McNamara & Scott, 2001).
230 In line with Dunlosky and Kane (2007), Cokely et al. (2006) observed that the differences in
231 recall performance between high- and low-WMC individuals disappeared after training to use
232 the Chaining strategy, consistent with the idea that the superiority in recall performance of the
233 high-WMC individuals is due to the use of effective strategies

234 To sum up, recall performance depends at least in part on the type of strategies that
235 individuals employ. However, none of these studies examined whether participants adapt their
236 strategy to task constraints. Nonetheless, some findings can give some hints about strategic
237 adaptations. We noted before that Rehearsal was considered as an ineffective strategy in tasks
238 that require some overt verbal production concurrent with the maintenance of verbal items.
239 Other strategies that are not based on the speech production system such as Visual Strategies
240 and Elaboration, or that supplement Rehearsal with Temporal Clustering have been shown to
241 be effective. Hence, investigating strategies and how they change across WM tasks and
242 experimental conditions should help understanding of the type of cognitive resources that
243 support dual-tasking in WM.

244

245 **The Present Study**

246 In the present study, participants performed a memory task with memoranda presented
247 either visually (Exp. 1 and 3) or aurally (Exp. 2), and a visually presented simple arithmetic
248 verification task. These tasks were performed in isolation, then jointly with the arithmetic
249 performed during a ten second retention interval between presentation of the memoranda and
250 serial ordered recall, and then again in isolation. With visual presentation, participants recalled

251 the memoranda by typing on the keyboard. With aural presentation, recall was oral. Moreover,
252 tasks were performed with and without AS.

253 Given the evidence that individuals can adapt their strategies according to the task at
254 hand (Logie et al., 1996; Morrison et al, 2016), we might expect that, when facing an increased
255 cognitive demand in a dual-task compared to the single task condition, individuals should rely
256 less on cognitively demanding strategies, and more on low-demanding strategies. Nonetheless,
257 one could expect that participants should adapt their strategies not only to memorize items and
258 retain them in memory, but also to perform the concurrent processing task.

259 The introduction of AS that has been known for some time to disrupt rehearsal (e.g.
260 Baddeley, Lewis, & Vallar 1984; Murray, 1965) should lead participants to reduce the use of
261 Rehearsal and Temporal Clustering, but have no effect on, or possibly increase the use of,
262 Elaboration and Visual strategies. Supporting the notion of rehearsal as consuming few general
263 resources, Naveh-Benjamin and Jonides (1984) showed an effect on performance only for the
264 first few iterations of rehearsal. Therefore, a dual task in our paradigm, should have little or no
265 impact on the use of Rehearsal, but should affect the use of Elaboration and Visual strategies
266 (see Thalmann, Souza, & Oberauer, 2019 for an alternative view).

267 Note that almost all the studies cited in the previous section only assessed the effects of
268 strategies on memory. Although the vast majority of these studies used paradigms involving a
269 concurrent processing task, possible strategy changes in the processing task have rarely been
270 explored. Only a few studies have examined the effects of strategies on the concurrent task, but
271 only by assessing the time spent on it by participants, which is only an indirect measure of
272 strategies (Brébion, Smith & Ehrlich, 1997; Engle, et al, 1992; Kaakinen & Hyönä, 2007).

273 The concurrent processing in Experiments 1, 2 and 3 of a simple arithmetic verification
274 task (e.g. $6+7=14$ True or False?), has been shown in previous studies to be achieved through
275 two main strategies (DeStefano & Lefevre, 2004; Hecht, 2002; LeFevre, Sadesky & Bisanz,

1996). The first, Counting, refers to the algorithmic computing of the sum, and then its comparison with the displayed answer. The computation can be achieved either through “min counting” (i.e. counting from the larger addend the number of increments corresponding to the smaller addend; Hecht, 2002) or “decomposition” (i.e. using a known addition and then completing by counting, such as solving $6+7$ by first retrieving the result of $6+6$, and then add 1; Hecht, 2002). The second strategy, Retrieval, does not involve computation, but relies on automatic processes, either the retrieval of the answer from long-term memory (Hecht, 2002) or a plausibility judgment (i.e., the equation just looks correct or incorrect; De Rammelaere, Stuyven & Vandierendonck, 2001; Lemaire & Fayol, 1995). Contrary to Retrieval, Counting requires keeping track of a running total and retention in memory of the addends and the proposed solution (Butterworth, Cipolotti & Warrington, 1996; Camos & Barrouillet, 2004; Craik, Govoni, Naveh-Benjamin & Anderson, 1996; De Rammelaere, Stuyven & Vandierendonck, 1999; Hecht, 2002; Lemaire, Abdi & Fayol, 1996; Logie & Baddeley, 1987). Therefore, we predict that an increase in cognitive demand from a concurrent memory load would lead participants to favor the least demanding strategy, namely Retrieval, so a dual task should not disrupt the use of this strategy. Because of the use of subvocalisation during a counting but not a retrieval strategy, AS should disrupt the use of counting, but not the use of retrieval.

In the current study, our aim was thus to investigate four questions: 1) whether dual task would reduce the number of strategies reported, or would show a more specific effect on the reports of Elaboration and Visual strategies in memory, but not on reports of Rehearsal; 2) whether AS would reduce the number of strategies reported or have a specific effect on the reports of Rehearsal and Temporal Grouping, 3) whether dual task and AS together will show an additive or interactive effect on the reports of strategies, and 4) whether these adaptations would occur for the memory strategies only, and so would mimic the observed results in

301 performance (only memory performance was affected by dual-tasking in the analyses done by
302 Doherty et al, 2019), or whether strategy adaptations would occur for both processing and
303 memory strategies.

304 As noted above, Doherty et al. (2019) reported that, concerning the performance data of
305 Experiments 1 and 2 in the current manuscript, memory performance was affected by dual-
306 tasking, but there was little or no impact of dual task on arithmetic verification. Studying
307 strategy changes could reveal the source of this asymmetric effect. For example, if participants
308 chose to give priority to the performance of the concurrent processing, their performance in the
309 arithmetic verification task would remain relatively unaffected, but at the cost of a degraded
310 recall performance (Belletier, Camos & Barrouillet, 2020). An additional possibility is that
311 processing performance might be maintained under AS or dual task because participants switch
312 to relying more on a retrieval strategy and this compensates for the reduction in the use of a
313 counting strategy to help maintain performance levels.

314

315

Experiment 1

316 First, we summarize the methodology and main findings on participants' performance
317 from Doherty et al. (2019) Experiment 1. This sets the context for our analyses in the current
318 manuscript of reported strategies from that experiment. Full details are reported in the
319 previously published manuscript. Our methods, along with the predictions and analysis plan for
320 the performance data were preregistered on the Open Science Framework
321 (<https://bit.ly/2KTKMgb>). Strategy reports were the focus of additional exploratory analyses
322 after the experiments were completed when it became clear that theoretical closure could not
323 be achieved from considering the performance data alone.

324

325 Method

326 **Participants.** Participants were 64 undergraduate students (age: $M=22.19$; $SD=2.97$),

327 half of them being from University of Edinburgh, UK., who completed the tasks in English,
328 with an experimenter (JD) whose native language was English and half of them from Fribourg
329 and Geneva Universities, Switzerland, who completed the tasks in French with an experimenter
330 (CB) whose native language was French. The split of data collection across different labs,
331 different languages, and different experimenters allowed for parallel replication of the
332 experiment to ensure that our results were robust and generalized beyond a single lab.
333 Participants received financial compensation (£12) in the United Kingdom, and course credit
334 or a cinema voucher in Switzerland. Participants all had normal or corrected-to-normal vision,
335 and were naive concerning the purpose of the experiment, which was presented as a study on
336 memory. This experiment, and all subsequent experiments, were approved by the ethics
337 committees for The University of Edinburgh, The University of Fribourg, and The University
338 of Geneva. Experiment 3 was also approved by the ethic committee of University of Clermont
339 Auvergne (IRB-UCA).

340 **Material and Procedure.** The task was run using PsychoPy (Peirce, 2007), and the
341 experimenter remained in the experimental room during the experiment. All participants first
342 performed a recognition task to check if the letters used as memory items were distinguishable
343 from each other (all the consonants were used, except W, Y, and Z). The distance between the
344 participants and the screen was around 60 cm, and each visually presented stimulus subtended
345 approximately 1.3 degrees. Participants then completed two titration procedures for assessing
346 the span levels (set at 80% accuracy) for memory and for processing for each individual. The
347 order of the two was counterbalanced across participants. They then performed the experiment,
348 including 10 trials of the memory single task and 10 trials of the processing single task at their
349 span level. These were followed by 20 trials of the dual-task, combining memory for the letter
350 sequences with the addition verifications during a ten second retention interval. Finally,
351 participants performed again 10 trials of the two single tasks. The entire experimental procedure

352 was carried out twice, respectively with and without AS, the order of the two (without/with
353 AS), and of the single tasks (memory and processing) being counterbalanced. The first single
354 tasks (memory and processing) with AS and the two-dual tasks (with and without AS) included
355 3 trials of practice (the whole procedure is summarized in Figure 1). At the end of the
356 experiment, the participants completed an open-ended questionnaire about their strategies. We
357 chose to ask participants about their strategies after they had completed all of the experimental
358 conditions to ensure that their report of strategies did not prompt strategy changes that would
359 not have happened spontaneously.

360 **Titration Procedure.** A staircase procedure was implemented to evaluate the individual
361 span level of each participant for both the memory and the processing task. In the memory task,
362 5 letters were presented sequentially in the center of screen for 250ms each, with an inter-
363 stimulus-interval (ISI) of 750ms in the first pairs of trials. Participants had to remember the
364 letters for a duration of 10 seconds during which a blinking circle was displayed in the center
365 of the screen. Participants were then asked to recall the letters in their order of presentation by
366 using the keyboard. If their average performance for this pair of trials was greater than or equal
367 to 80%, the pair included one additional stimulus, in this case 6 letters, otherwise one less item
368 was presented, in this case 4 letters. This procedure was repeated for 8 pairs of trials. If the last
369 pair was the best score achieved (the highest number of letters remembered), additional pairs
370 of trials were presented until the participants failed to achieve the 80% criterion. The memory
371 span was defined as the highest number of letters remembered at 80% performance. Three
372 training trials with 4 letters were presented at the beginning of the task.

373 The titration procedure for processing was similar. In the first pair of trials, participants
374 saw five placeholders (diamond shapes) that appeared for 250ms with a 750ms ISI and then
375 performed five addition verifications ($7+4=12$?) in 10 seconds by pressing the left (or right)
376 key of a response box if the addition was incorrect (or correct). If the 80% criterion was

377 achieved on this pair, participants would have to perform one supplementary addition
378 verification in 10s, and one less if the criterion was not achieved. Additions were constructed
379 by picking at random two numbers between 1 and 9, the displayed results of each addition being
380 either correct or incorrect (50 % each). The incorrect results differed by 1 above or below the
381 correct response.

382 **Single Tasks.** In the memory single-task, a number of letters equal to the individual
383 span of the participant was presented sequentially in the center of screen. Each letter appeared
384 for 250ms, with an inter-stimulus-interval (ISI) of 750ms. As in the titration procedure,
385 participants had to remember the letters for a duration of 10 seconds during which a blinking
386 circle was displayed in the center of the screen. Participants were then asked to recall the letters
387 in their order of presentation by using the keyboard. In the processing single-task, participants
388 first saw five placeholders as in the titration procedure, and then had to verify during 10 seconds
389 a number of addition equal to their individual span. It should be noted that half of the trials of
390 the two single tasks were carried out before the dual-task, while the other half were carried out
391 afterwards. Fatigue or learning effects were therefore controlled by combining the data from
392 these two halves. The two single tasks were done once without and once with AS. In the latter
393 case, participants had to repeat “ba-ba-ba” from the beginning of the trial (before the letters or
394 the placeholders were displayed) and until the recall, at a rate of one syllable per second. Two
395 tones indicated to the participants when to begin and when to stop the concurrent articulation.

396 **Dual Task.** The procedure for the dual-task condition combined the two single tasks.
397 Participants first saw a number of letters equal to their individual memory span that were
398 visually displayed on the screen (as during the single task). They then had to judge for 10
399 seconds a number of additions equal to their individual processing span. They then recalled as
400 many letters as possible by typing them on the keyboard. Participants were asked to do their
401 best on the two components (“Remember the letters in the order that you heard them, and at the

402 same time decide as quickly and accurately as possible whether each equation is correct or
403 not”).

404 Figure 1 about here

405 **Strategy Questionnaire.** The questionnaire included 8 open-ended questions. The first
406 four questions were about the memory strategies used by the participants in each of the 4
407 experimental conditions: single and dual task without and with AS. The last four questions of
408 the questionnaire were about the strategies to verify the additions, and followed the same
409 rationale as the questions about the memory strategies (see Table 1 for the exact wording of all
410 questions).

411 Table 1 about here

412 **Results**

413 **Performance.** As noted earlier, the present paper focuses on strategic adaptation and
414 the results concerning performance (but not strategies) in the memory and arithmetic tasks are
415 reported in detail in Doherty et al. (2019). In summary, the titration procedure revealed a mean
416 span of 6.30 (SD=1.30) on the letter memory task and of 8.00 (SD=2.0) on the addition
417 verification task. Participants recalled fewer letters in the dual-task than in the single-task
418 condition (scaled effect size: -0.73). The main effect of concurrent articulation was also
419 significant, with fewer letters recalled under concurrent articulation than without concurrent
420 articulation (scaled effect size: -2.96). Performance on the processing task was not affected by
421 either the task condition or by the concurrent articulation. We also explored the presence of
422 possible fatigue effects by comparing the first and second blocks of simple tasks. The results
423 (see [Supp Text S1](#)) were in favor of the absence of such effects.

424 **Memory strategies.** Fifteen participants were excluded from analyses on the strategies
425 because they did not report any strategy or did not complete the questionnaire. Some of these
426 participants misunderstood the questions and instead reported how they felt about the task. The

427 analyses on the reported strategies were therefore based on 49 participants (20 from the UK,
428 and 29 from Switzerland).

429 *Classification of memory strategies.* As mentioned in the Introduction, four main
430 memory strategies have been described in the literature (Table 2). These strategies were also
431 reported by our participants and we classified participants' answers to the questionnaire in
432 accordance with the following definition of these strategies, consistent with previous literature
433 identified in the Introduction¹. When participants reported repetition of the letters (aloud or sub-
434 vocally), the strategy was classified as Rehearsal. When they reported grouping the letters, the
435 strategy was classified as Temporal Clustering. When they reported associating letters with
436 previous knowledge such as words (e.g., forenames) or acronyms, the strategy was classified
437 as Elaboration. When participants reported visualizing the letters (sometimes by looking at the
438 keyboard), it was classified as a Visual Strategy. Besides these four strategies, and based on our
439 participants' responses, we added three other categories of strategies. Some of our participants
440 reported having focused on the sound of the voice, and we thus classified this as an Acoustic
441 strategy. Note that such a strategy has been already observed by Morrison et al. (2016). Some
442 also reported reduction of memory load by attempting to remember only a subset of the letters
443 presented, and/or they reported focusing on the arithmetic verification task. We named this the
444 Memory Reduction strategy. Finally, miscellaneous strategies were labeled as other strategies.

¹ The classification of the strategies was submitted to an inter-judge procedure. In a first step, two judges independently classified participants' responses. In a second step, the way the strategy classes were understood was compared for the responses in which a discrepancy was observed. Finally, in a third step, the judges completed a new independent classification of participants' responses from which a correlation was calculated. This procedure was completed for all the English-speaking participants and for 15% of the French-speaking participants selected randomly. In Experiment 1, the correlation was .84 for the English-speaking participants and .94 for the French speaking-participants. In Experiment 2, the correlation was .86 for the English-speaking participants and .95 for the French speaking-participants. For remaining discrepancies, the judges agreed on which classification should be used for analyses. It is to be noted that we have chosen to process only 15% of the French-speaking participants for practical reasons, specifically difficulty in recruiting independent judges in Switzerland who were willing to spend the additional time required for checking all of the data for French-speaking participants. Nevertheless, the fact that Experiments 1 and 2 show similar results suggests that this did not impact the results. Even more convincingly, in Experiment 3, we used a trial-by-trial report of strategies in response to specific questions rather than open-ended reports at the end of the experiment, so there was no need for inter-judge ratings of reports, and yet the results are very similar to those from Experiments 1 and 2.

445 For each strategy and for each question, each participant's response was coded 1 when s/he
446 reported to have used a given strategy and 0 otherwise, allowing the use of several strategies
447 for each condition.

448 Table 2 about here

449 **Number of strategies.** Most of the strategies involved participants trying to maximize
450 the number of items recalled from the set presented. However, the Memory Reduction strategy
451 involved participants attempting to remember only a subset of those items, and therefore is a
452 different kind of strategy that reduces the overall memory load. So, we might expect that as the
453 demands on cognition increase, then the incidence of Memory Reduction also should increase.
454 In contrast, we might expect other strategies to be reduced when the cognitive demands
455 increase. Therefore, we did not include the Memory Reduction strategy in the analysis for
456 investigating whether the number of reported strategies decreased when AS or dual task (or
457 both) were introduced. It was analyzed separately when investigating the effect of each
458 condition on each strategy type.

459 The number of different strategies reported across all conditions ($M=1.03$; $SE=.06$) was
460 computed for each participant in each condition and analyzed using a repeated measures
461 ANOVA with AS (with vs. without) and Task (single vs. dual) as within-subject factors.
462 Notably, some participants reported no strategies, or only reported Memory Reduction, so some
463 means are less than 1.0. The main effect of the Task was significant $F(1,48)=12.39$; $p<.001$;
464 $\eta_p^2=.21$. Participants reported more strategies in the single Task ($M=1.17$; $SE=.07$) than in the
465 dual Task ($M=.89$; $SE=.08$). The main effect of AS was also significant $F(1,48)=10.31$; $p<.01$;
466 $\eta_p^2=.18$, with more strategies reported without AS ($M=1.16$; $SE=.07$) than with AS ($M=.90$;
467 $SE=.08$). The interaction between the Task and AS was not significant ($p=.24$).

468 In the single task without AS all the participants reported at least one strategy. No
469 participants reported using only the Memory Reduction strategy. In the dual task without AS

470 two participants reported no strategies, and six reported that they only used the Memory
471 Reduction strategy. In the single task with AS, six participants reported no strategies, and three
472 reported using only the Memory Reduction Strategy. Finally, in the dual task with AS condition
473 five participants reported no strategies, and 13 participants only reported the Memory
474 Reduction strategy.

475 **Strategy use.** Generalized Estimating Equations (GEE) were performed for each
476 strategy (including Memory Reduction) across conditions as within-participant factors,
477 specifically AS (with vs. without) and Task (single vs. dual). Data with dichotomous variables
478 do not conform to the assumptions of ANOVAs, because performance is constrained between
479 0 and 1. This can lead to unequal variance between conditions, and possibly confidence
480 intervals with limits larger than 1 or smaller than 0. In the case of repeated-measures designs,
481 one possibility to address these issues is to use GEE (Ballinger, 2004; Wang, 2014). The
482 factorial model (including the interaction between the two variables) was systematically tested
483 first. If the interaction was not significant, the additive model (the model without the
484 interaction) was tested and reported (see Figure 2 for an overview of the results). In the
485 following results sections, odds ratios (OR) are reported and provide an account for the change
486 between the two modalities, as predicted by the model. For example, an OR of .5 indicates a
487 reduction by two between the two modalities. Similarly, an OR of 1 indicates no change
488 between the two modalities, and a confidence interval (CI) including 1 indicates a non-
489 significant effect.

490 The results are illustrated in Figure 2, and details of the analyses are reported in Table
491 3. These results indicated that dual-task led to more reports of the use of the Memory Reduction
492 strategy than in the single-task ($OR = 9.42$; $CI\ 95\% = 4.23, 20.95$), accompanied by fewer reports
493 of the use of Elaboration ($OR = .53$; $CI\ 95\% = .30, .94$), and Temporal Clustering ($OR = .48$; CI
494 $95\% = .30, .78$). AS led to more reports of the use of Visual Strategy ($OR = 3.29$; $CI\ 95\% = 1.36,$

495 7.98) and Memory Reduction strategy ($OR = 3.07$; $CI\ 95\% = 1.39, 6.81$), but less report of the
496 use of Rehearsal ($OR = .28$; $CI\ 95\% = .15, .51$) and Temporal Clustering ($OR = .55$; $CI\ 95\% = .32,$
497 $.95$). No significant interactions between the task conditions and AS were found for any of the
498 memory strategies.

499 Figure 2 and Table 3 about here

500 **Processing Strategies.** We expected that the arithmetic verification task was solved
501 either by Counting, that is through a step-by-step computation, or by Retrieval of well-learned
502 mathematical ‘facts’ or a sense of familiarity (or "intuition") about whether or not the equations
503 looked as if they were correct (Table 4). In addition to these strategies, some of our participants
504 reported that they ignored some or all of the addition problems to focus on the memory task.
505 This was the equivalent behavior of what we observed for the memory strategies. We classified
506 this as a Processing Reduction strategy. Finally, miscellaneous strategies that did not
507 unambiguously fall within our strategy categories were labeled as other strategies. As for the
508 memory strategies, each participant’s response was coded 1 when s/he reported having used a
509 given strategy and 0 otherwise, allowing several strategies by condition.

510 Table 4 about here

511 **Number of strategies.** As for memory strategies, and for the same reasons, we did not
512 include Processing Reduction in this analysis. The number of different strategies reported
513 ($M = 1.07$; $SE = .07$) was computed for each participant in each condition. The same analyses
514 were used as for the memory strategies. Notably, some participants reported no strategies, or
515 only reported Processing Reduction, so some means are less than 1.0. The main effect of the
516 Task was significant $F(1,48) = 9.82$; $p < .01$; $\eta_p^2 = .17$. Participants reported more strategies in the
517 single task ($M = 1.17$; $SE = .07$) than in the dual task ($M = .96$; $SE = .08$). Neither the main effect of
518 AS nor the interaction between the two factors were significant, $ps > .32$.

519 In the single task without AS, four participants reported zero strategies, and none of the
520 participants reported only Processing Reduction. Six participants did not report at least one
521 strategy, and 2 reported only the Processing Reduction in the dual task without AS. In the single
522 task with AS, 3 participants did not report at least one strategy, and none of the participants
523 reported only Processing Reduction. Finally, in the dual task with AS, 8 participants did not
524 report at least one strategy, and 2 reported only the Processing Reduction Strategy.

525 **Strategy use.** The same analyses were performed as for the memory strategies (including
526 Processing Reduction). Results are illustrated in Figure 3, and details of the analyses are shown
527 in Table 5. For Counting, a factorial model was preferred, because the main effects of Task,
528 the main effect of AS and their interaction were significant. In single-task conditions, Counting
529 was less often reported under AS ($OR = .33$; $CI\ 95\% = .19, .56$). However, in the dual-task
530 conditions, no difference emerged in reporting Counting in the conditions with or without AS
531 ($OR = .83$; $CI\ 95\% = .59, 1.19$). A factorial model was also preferred for Retrieval, because the
532 Task x AS interaction was significant. The main effect of AS was also significant. In the single-
533 task conditions, Retrieval was more often reported under AS ($OR = 1.96$; with $CI\ 95\% = 1.20,$
534 3.22). In the dual-task conditions, reports of Retrieval did not differ between the conditions
535 with or without AS ($OR = 1.00$; $CI\ 95\% = .72, 1.39$).

536 Figure 3 and Table 5 about here

537 **Discussion**

538 Our main aim was to examine changes in strategies in both memory and processing to
539 gain new insights into the effects of dual-tasking and articulatory suppression (AS) reported for
540 performance data in Doherty et al. (2019) Experiment 1. For the memory task, there was an
541 overall reduction in the number of strategies reported when a concurrent arithmetic verification
542 task was introduced. Participants increasingly reported Memory Reduction, coupled with a
543 decrease in the reporting of Elaboration and Temporal Clustering, but there was no effect on

544 Visual Strategy reports, which was in any case reported by very few participants. There was no
545 impact on reported use of Rehearsal.

546 Under AS there was a reduction in number of strategies reported, consistent with our
547 expectation that AS would reduce the use of strategies that rely on rehearsal. Indeed, fewer
548 participants reported Rehearsal and Temporal Clustering. A few more participants reported use
549 of a Visual Strategy. However, as for the dual task condition, this strategy was reported by very
550 few participants so would merit replication. In this condition there was also an increase in
551 reports of Memory Reduction.

552 Dual task and AS together showed no interaction for any of the reported memory
553 strategies. There was a reduction in reports of Rehearsal under AS but no additional impact of
554 dual task. There was an increase in reports of a Visual Strategy under AS, but with no impact
555 of dual task. There was a reduction in reports of Elaboration under dual task but with no
556 additional impact of AS. These results are consistent with independent effects of AS and dual
557 task. Temporal Clustering was reduced for both AS and dual task, and Memory Reduction was
558 increased for both AS and dual task.

559 Concerning processing strategies, participants reduced their reports of Counting under
560 dual task. This is consistent with previous studies that have explored the impact of AS on
561 counting (Imbo & Vandierendonck, 2007; Logie & Baddeley, 1987). AS decreased the reports
562 of Counting in the single Task, but there was no effect of AS in the dual task. In contrast, reports
563 of Retrieval increased with AS, but were unchanged with dual task. However, again, there was
564 no AS effect under dual task. As with the reported memory strategies, this pattern of results for
565 arithmetic verification suggests that AS and dual task have distinct effects on the two strategies.

566 These results might offer some additional insight into why processing performance was
567 unaffected by AS as reported in Doherty et al. (2019). One possibility is that switching to a
568 retrieval strategy under AS allowed participants to maintain the same level of performance that

569 they also achieved using counting. The lack of an impact of dual task on retrieval might suggest
570 that consistent use of this strategy avoids the impact of dual task, even if participants have the
571 subjective impression that they rely less on counting under dual task conditions.

572 Before further discussing the implications of these results for our theoretical
573 understanding of WM, and in order to assess how robust were the results from our strategy
574 analyses of Doherty et al. (2019) Experiment 1, we examined the use of strategies in Doherty
575 et al.'s (2019) second experiment.

576 **Experiment 2**

577 In Doherty et al. (2019) Experiment 2, the letter memoranda were presented aurally and
578 participants recalled the items orally. This change was used to assess whether the presentation
579 modality of the letters (either visually or aurally) induces different or additional coding during
580 the presentation of the memoranda (e.g. Baddeley et al., 1984; Logie et al., 2000; Logie et al.,
581 2016; Saito et al., 2008), which could in turn trigger specific strategies, such as Visual or
582 Acoustic strategies. For example, aural presentation may result in direct phonological coding
583 of the memoranda, which favors the use of Rehearsal (Baddeley, 1992; Baddeley, et al., 1984),
584 whereas the visual presentation used in Experiment 1 typically involves translation to a
585 phonological code (Conrad, 1964), but can also result in use of a visual code, particularly under
586 AS (Logie et al., 2000; 2016; Saito et al. 2008). Therefore, the expectation is that rehearsal and
587 acoustic strategies will be widely reported by participants, but there would be few, if any reports
588 of visual strategies. We expected no increase in reports of visual strategies with AS, but we did
589 expect a decrease in reports of rehearsal and temporal grouping coupled with an increase in
590 reports of elaboration. As for Experiment 1, dual task was expected to reduce the reports of
591 elaboration. However, for Experiment 2, the expectation was that because previous studies have
592 suggested that aural presentation more readily leads to the use of rehearsal, then there will be
593 an increase in the reports of rehearsal under dual task. Because there was no change in the

594 modality of presentation of arithmetic verification, the expectations were the same as for
595 Experiment 1. Finally, Experiment 2 assessed how robust were our results on strategies by
596 investigating whether or which results from Experiment 1 would replicate with a different
597 modality of presentation and recall.

598

599 **Method**

600 **Participants.** Participants were 64 undergraduate students (age: $M=21.84$, $SD=2.73$),
601 half of them from University of Edinburgh, half of them from Fribourg and Geneva
602 Universities, with testing language and experimenter as for Experiment 1. They received
603 financial compensation (£12) in United Kingdom, and course credit or a cinema voucher in
604 Switzerland. They all had corrected-to-normal vision, and were informed concerning the purpose of
605 the experiment (which was presented as a study on memory). None of them participated in
606 Experiment 1.

607 **Procedure.** The procedure was similar to the procedure of Experiment 1 with the
608 following changes. Letters were aurally presented using headphones, participants recalled them
609 in serial order after a retention interval of 10 seconds by speaking out loud rather than using a
610 keyboard, and the experimenter recorded the response on a separate keyboard. Also, because
611 of the use of auditory presentation, AS began after the presentation of the letters to ensure that
612 the letters were encoded phonologically before the AS started. This was important because our
613 focus in these experiments was on retention in memory, not on encoding.

614 **Results**

615 **Performance.** As for Experiment 1, performance results are reported in detail in
616 Doherty et al. (2019). In summary, the titration procedure led to a mean span of 6.50 ($SD=1.00$)
617 on memory and of 8.60 ($SD=2.00$) on the addition verification task. Participants recalled fewer
618 letters in dual-task than single-task condition (scaled effect size: -1.21). The main effect of AS

619 was also significant, with fewer recalled letters under AS (scaled effect size: -2.00). The
620 performance in the addition verification task was only affected by the dual task condition
621 (scaled effect size: -0.43), but not by AS.

622 **Memory strategies.** Six participants were excluded from the analyses on strategies,
623 because they did not report any strategy or did not fill in the questionnaire correctly. These
624 latter participants generally misunderstood the questions and instead reported how they felt
625 about the task. The analyses on strategies were thus performed on 58 participants (29 from the
626 UK, and 29 from Switzerland).

627 **Classification of memory strategies.** The same classification of memory strategies as in
628 Experiment 1 was used to classify our participants' responses to the strategy questionnaire
629 (Table 2). For each strategy and in each condition, each participant's response was coded 1
630 when s/he reported using a given class of strategy and 0 otherwise, allowing coding of the use
631 of several strategies for each response.

632 **Number of strategies.** As in Experiment 1, the Memory Reduction strategy was not
633 included in this analysis. A repeated measures ANOVA was conducted on the number of
634 strategies ($M=1.39$; $SE=.08$) across conditions as within-participant factors, specifically AS
635 (with vs. without) and Task (single vs. dual). The main effect of Task was significant
636 $F(1,57)=21.15$; $p<.001$; $\eta_p^2=.27$ with a higher number of strategies reported in the single Task
637 ($M=1.59$; $SE=.09$) than in the dual Task ($M=1.20$; $SE=.09$). The main effect of AS and the
638 interaction between Task and AS were not significant ($ps>.41$).

639 In the single task condition without AS, all the participants reported at least one strategy,
640 and one participant reported only the Memory Reduction strategy. In the dual task without AS
641 two participants reported no strategies, and three participants reported only the Memory
642 Reduction strategy. In the single task with AS, two participants reported no strategies, and one
643 participant reported only the Memory Reduction strategy. Finally, in the dual task with AS, five

644 participants reported no strategies, and seven only reported the Memory Reduction strategy.

645 **Strategy use.** The same analyses were conducted as in Experiment 1 (Figure 4 and Table
 646 3). The dual-task condition led to fewer reports of Rehearsal ($OR = .55$; $CI\ 95\% = .36, .85$).
 647 Temporal Clustering and Elaboration were less reported in dual-task than in single task
 648 conditions ($OR = .53$ $CI\ 95\% = .34, .81$; and $OR = .51$; $CI\ 95\% = .30, .87$ respectively). There
 649 was no impact of dual task on reports of Visual Strategies. However, participants reported using
 650 the Memory Reduction strategy more often in the dual-task than in the single-task condition
 651 ($OR = 4.98$; $CI\ 95\% = 2.37, 10.48$). This was also the case for the Acoustic strategy ($OR = 2.34$;
 652 $CI\ 95\% = 1.00, 5.45$). Conditions with AS led to fewer participants reporting using Rehearsal
 653 and Temporal Clustering than in the condition without AS ($OR = .48$; $CI\ 95\% = .31, .75$; and OR
 654 $= .44$; $CI\ 95\% = .28, .68$ respectively). There was no impact of AS on reports of Elaboration,
 655 Visual, Acoustic or Memory Reduction strategies. No interactions were found.

656 Figure 4 about here

657 **Processing Strategies.**

658 The same categories for the strategies on addition verification were used as in
 659 Experiment 1. Results are reported in Table 3 and Figure 5. For each strategy and in each
 660 condition, each participant's response was coded 1 when s/he reported using a given class of
 661 strategy and 0 otherwise, allowing several classes of strategy for each response.

662 **Number of strategies.** As in Experiment 1, the Processing Reduction strategy was not
 663 included in this analysis. The number of strategies ($M = 1.00$; $SE = .07$) was submitted to a
 664 repeated measures ANOVA with Task (single vs. dual) and AS (with vs. without) as within-
 665 subjects factors. The main effect of the Task was significant $F(1,57) = 6.23$; $p < .05$; $\eta_p^2 = .10$.
 666 Participants reported more strategies in the Single Task ($M = 1.09$; $SE = .08$) than in the Dual Task
 667 ($M = .91$; $SE = .07$). The main effects of AS and the interaction between the two factors were non-
 668 significant, $ps > .33$.

669 In the single task without AS, ten participants reported no strategies, and none of the
670 participants reported only the Processing Reduction strategy. In the dual task without AS, nine
671 participants reported no strategies, and three participants reported only the Processing
672 Reduction strategy. In the single task with AS ten participants reported no strategies, and none
673 of the participants reported only the Processing Reduction strategy. Finally, in the dual task
674 with AS 13 participants report no strategies, and none of the participants reported using only
675 the Processing Reduction strategy.

676 **Strategy use.** The same analyses were conducted as in Experiment 1, including the
677 Processing Reduction strategy. For Counting, the interaction between Task and AS was
678 significant, so a factorial model was preferred. The main effects of Task, the main effect of AS
679 and their interaction were significant. In single-task conditions, participants reported using
680 Counting more often in the condition without AS than with AS ($OR = .42$; $CI\ 95\% = .26, .66$).
681 In the dual-task conditions, the percentage of participants reporting using Counting did not
682 differ between these two conditions ($OR = .79$; $CI\ 95\% = .52, 1.19$). For Retrieval, the interaction
683 between Task and AS was not significant, $p = .19$, so this led us to prefer the additive model.
684 Retrieval was reported more often in the dual- than the single-task conditions ($OR = 2.01$; CI
685 $95\% = 1.31, 3.09$). The effect of AS was not significant, $p = .27$.

686 Figure 5 about here

687 **Cross-experiment analyses.** One aim for these experiments was to investigate whether
688 changes in the modality of presentation of the memory items would impact the type of strategy
689 that participants report. Presenting verbal memory items aurally should favor their encoding in
690 a phonological format and their maintenance by Rehearsal, while their visual presentation
691 would require the recoding into a verbal code to be rehearsed, and might also include the use
692 of visual codes. Hence, we performed a series of cross-experiment comparisons to examine
693 whether the use of the different strategies, and in particular the use of Rehearsal, varied across

694 experiments. We report in the following section only the variations of the studied effects across
695 experiments (i.e., interactions with Experiments only).

696 A GEE was performed on each memory strategy with Task (single vs. dual), AS (with
697 vs. without) and Experiment (Exp. 1 vs. Exp. 2). A full factorial model was systematically
698 tested first. If the interactions terms with Experiment were not significant, a model including
699 the main effects and the Task x AS interaction was preferred. If none of the interaction terms
700 were significant, an additive model was tested.

701 For Rehearsal, Temporal Clustering, Elaboration and Memory Reduction, the same
702 pattern of findings emerged. The main effect of Experiment was never significant, $ps > .32$. None
703 of the interactions were significant, $ps > .11$, and the additive model with the main effects of
704 Task and AS was preferred. For the two last strategies, Visual and Acoustic, the additive model
705 was also preferred, because no interaction terms were significant, $ps > .14$. But, contrary to the
706 other strategies, the main effect of Experiment was significant for Visual and Acoustic
707 strategies. The visual presentation of letters in Experiment 1 led to fewer reports of using the
708 Visual ($M=.08$, $SE=.02$) and Acoustic ($M=.02$, $SE=.01$) strategies than with the auditory
709 presentation of letters in Experiment 2 ($M=.22$, $SE=.03$ and $M=.12$, $SE=.02$, respectively), Wald
710 $Z = 6.67$, $p < .01$, $OR = .33$ with $CI_{95} = [.14, .76]$, and Wald $Z = 6.04$, $p = .01$, $OR = .15$ with
711 $CI_{95} = [.03, .68]$, respectively.

712 The same analyses as for the memory strategies were conducted for the processing
713 strategies. However, the number of participants reporting Processing Reduction was too low to
714 perform an analysis on this strategy. For Counting and Retrieval, the pattern was similar. For
715 both strategies, the main effect of Experiment was non-significant, and all interaction terms
716 including Experiment were not significant, $ps > .05$.

717 **Discussion**

718 The aim of the analyses of reported strategies in Experiment 2 was twofold. First,
719 Experiment 2 allowed us to examine whether a change in modality of the presentation of the
720 memory items would impact the choice of strategies, and second we wanted to assess how
721 robust were the results of Experiment 1. Broadly, the results in Experiment 2 replicated those
722 in Experiment 1, a conclusion that was reinforced by the cross-experiment comparisons. One
723 difference between the two experiments affected the use of two particular strategies, Visual and
724 Acoustic. More participants reported the use of the acoustic strategy when the memory items
725 were presented aurally (Exp. 2) than visually (Exp. 1). This is consistent with the idea that
726 participants favored phonological coding of the letters in Experiment 2. Unexpectedly, a similar
727 pattern occurred for Visual Strategy, with a higher percentage of participants reporting use of
728 this strategy in Experiment 2 than in Experiment 1. A possible explanation is that some
729 participants reported using the keyboard as a visual cue to remember the letters, in addition to
730 some participants reporting that they visualized the appearance of the aurally presented letters.
731 When letters were presented through headphones in Experiment 2, it was easier to look at the
732 keyboard to support memory (e.g. Darling, Allen, & Havelka, 2017), or to visualize the letters
733 (Brooks, 1967; 1968) than when the letters were presented visually on screen in Experiment 1.
734 However, Visual and Acoustic strategies were reported by relatively few participants, so a
735 formal analysis was not possible, but future studies might address these strategies more directly.

736 Also, in line with Experiment 1, counting for arithmetic verification was reduced by
737 concurrent articulation and by dual task. Dual task resulted in an increase in reports of retrieval,
738 but AS did not.

739 Finally, as in Experiment 1, and as expected according to previous findings in
740 mathematical cognition, the number of memory strategies was reduced under the dual-task
741 condition. However, unlike Experiment 1, AS did not reduce the overall number of strategies
742 reported.

743 Taken together, the results of Experiments 1 and 2 support the idea that participants
744 change the strategies that they use to perform memory and processing tasks under different
745 experimental conditions. Nonetheless, one important limitation in these two experiments is that
746 participants were asked about their strategies only after they had completed all conditions
747 within each experiment. This was essential to ensure that reporting strategies did not affect
748 subsequent performance. However, the reports that we obtained do not distinguish between
749 participants who used the same strategy throughout a given experimental condition (e.g.
750 rehearsal in single task without AS), and those who spontaneously changed their strategies
751 across trials within a condition. We also do not know if the same actual strategy was used by
752 different participants even when they used the same words to describe their strategy. Moreover,
753 some participants might have felt obliged to describe one or more strategies because they were
754 asked to do so, even if they were not wholly aware of how they were performing the tasks in
755 each condition. Although there were clear shifts in the number of participants reporting each
756 kind of strategies, it is striking that only 55% of participants reported using some form of
757 rehearsal in single task memory without AS, raising the question as to how the other participants
758 were performing the task, although some participants reported more than one strategy. Finally,
759 although some participants reported several strategies, others were unable to report any
760 strategies.

761 Interestingly, in these two first experiments, we did not find any link between the
762 reported use of strategies and the task accuracy. This lack of a link could be due to a
763 compensatory mechanism, namely changing strategies to maintain a constant level of
764 performance. It could also be due to the fact that we used a final report to assess strategies.
765 Final reports may lead participants to report an average of the strategies they used across the
766 trials of a given condition, which could obscure a potential relationship with accuracy.

767 To respond to these limitations, we performed a third experiment using a trial-by-trial
768 report². The use of a Likert scales at the end of each trial provided converging evidence for the
769 conclusions of Experiment 1 and 2 by using a different procedure. Moreover, this new
770 procedure also allowed us to avoid the possible use by participants or different words to
771 describe a given strategy, as might have been the case in Experiments 1 and 2 that used free
772 reports. It is to be noted that the requirement to report strategies trial by trial in itself might act
773 as a dual task and might affect how the task is performed (for opposing views see Ericsson &
774 Simon, 1984; Nisbett & Wilson, 1977). Nonetheless comparing the results on performance of
775 this third experiment with the first two experiments should allow us to assess whether reported
776 strategies and/or performance differ when participants are asked to report trial by trial.

777 **Experiment 3**

778 This third experiment was similar to Experiment 1, but with a trial-by trial assessment
779 of the strategies instead of a final report. The goals of this experiment were 1) to evaluate the
780 robustness of our results on strategies by using another method to measure them 2) to use a
781 method allowing a better assessment of the link between the reported strategies and the actual
782 performance. We expected to observe the same strategic adaptation as before, but with a more
783 fine-grained analysis.

784 **Method**

785 **Participants.** Participants were 61 undergraduate students (age: $M=$, $SD=$), 29 of them
786 from University of Edinburgh (United Kingdom), and 32 of them from the Clermont Auvergne
787 University (France). In this case the language was appropriate for each country, but the
788 experimenter, who was bilingual, was the same (CB). Participants received financial
789 compensation (£12) in United Kingdom, and course credit in France. They all had corrected-

² We thank anonymous reviewers of an earlier version of this manuscript for suggesting this additional experiment

790 to-normal vision and were naive concerning the purpose of the experiment (which was
791 presented as a study on memory). None of them participated in Experiment 1 or 2.

792 **Procedure.** The procedure was similar to the procedure of Experiment 1 with the
793 following changes. At the end of each trial of the experimental blocks (but not during the
794 titrations), participants were asked about the strategies they used using 5-point Likert scales.
795 Based on the two previous experiments, the following memory strategies were assessed:
796 Rehearsal, Temporal Clustering, Elaboration, Visual, Acoustic and Memory Reduction. We
797 also assessed 3 processing strategies: Counting, Retrieval and Processing Reduction. For
798 example, for the rehearsal strategy, participants were asked: “to what extent did you repeat the
799 letters (aloud or in your head)?” and had to answer on a 5-point scale going from 0% to 100%.
800 The English wording of all the scales is presented in annex A. The French version was a direct
801 translation by the first author (CB) who is a French native speaker. Moreover, at the beginning
802 of the first memory single task each memory strategy was introduced by a short text describing
803 it. Similarly, the processing strategies were introduced at the beginning of the first processing
804 single task (see Annex A for the English wording of these texts).

805 Finally, because the evaluation of the strategies at the end of each trial greatly extended
806 the duration of the experiment, we reduced the number of trials. After the titration procedure
807 for memory and processing, participants performed 6 trials of the memory single task and 6
808 trials of the processing single task (instead of 10 trials for each task in Experiment 1). They
809 then performed 12 trials of the dual task (instead of 20 trials in Experiment 1). Finally, they
810 were again presented with 6 trials of the memory single task and 6 trials of the processing single
811 task (instead of 10 trials for each task in Experiment 1). As for Experiment 1, the procedure
812 was repeated twice, once without articulatory suppression (AS), and once with AS.

813 **Results**

814 **Performance.** We used similar analyses to those for Experiments 1 and 2, namely

815 logistic mixed effects regression using the R package lme4 (Bates, Mächler, Bolker, & Walker,
816 2015) allowing the use of log odds of a correct response as the dependent variable while
817 modelling repeated measures. Full models were first assessed for memory and processing
818 performance, including the two main effects and their interaction plus a random intercept for
819 each participant. The factors entered in the model were: the effect of the task (single *vs* dual
820 task) and Articulatory Suppression (without *vs* with). We then compared the full models with
821 simpler models in which the interaction was removed, by using BIC values (Schwarz, 1978).
822 The main effects were then considered in separate models. At each step of the model
823 comparison, a Bayes factor was computed to decide whether the simpler model should be
824 retained or not. The simpler model was always preferred except when the Bayes Factor was
825 clearly against the removal of the effect considered (i.e. >3).

826 The results replicated those of Experiment 1. The titration procedure revealed a mean
827 span of 6.34 (SD=1.22) on the letter memory task and of 6.87 (SD=2.0) on the addition
828 verification task. Concerning memory performance, the best model included the main effect of
829 the Articulatory Suppression (scaled effect size = -1.52), with fewer letters recalled under AS,
830 and the main effect of the Task (-0.33), with fewer letters recalled in the dual task than in the
831 single task. The null model was retained concerning the processing performance that was
832 affected neither by the Articulatory Suppression nor dual task.

833 **Memory strategies.**

834 *Number of strategies.* In Experiment 3, participants answered on a 5-point Likert scale
835 on the extent to which they used each strategy with answers going from 0% to 100%.
836 Consequently, to compute the number of strategies reported to be used on each condition, we
837 took into account any strategy reported to be used at least to some extent (namely 25%,
838 corresponding to the second point of the scale). As in Experiments 1 and 2, the Memory
839 Reduction strategy was not included in this analysis.

840 The overall number of strategies reported to be used at least to some extent (overall: $M=$
841 3.61 ; $SE=.07$) was higher than the number of reported strategies observed in Experiment 1
842 ($M=1.03$; $SE=.06$), consistent with the hypothesis that trial-by-trial reporting might offer a more
843 fine-grained analysis. Alternatively, having more clear options in the rating procedure, might
844 have resulted in such a higher number of reported strategies. The number of reported strategies
845 was analyzed by using a repeated measures ANOVA with AS (with vs. without) and Task
846 (single vs. dual) as within-subject factors. As in Experiment 1, participants reported using more
847 strategies in the single task ($M=3.80$; $SE=.12$) than in the dual task ($M=3.43$; $SE=.12$)
848 $F(1,60)=19.38$; $p<.001$; $\eta_p^2=.24$. However, neither the effect of Articulatory Suppression (AS)
849 nor the interaction between the Task and AS were significant.

850 **Strategy use.** The answers to the Likert scale were treated as ordinal variables rather
851 than continuous ones (Liddell & Kruschke, 2018), and were analysed using Bayesian
852 Regressions with a Cumulative Model (Bürkner & Vuorre, 2019) implemented in the BRMS
853 package in R. For each strategy, the scoring was entered as a dependant variable with the Task
854 (single vs dual), AS (without vs with articulatory suppression) and their interaction as predictors
855 plus a random intercept for each participant. The full model was then compared to simpler
856 models without the two-way interaction by using approximate leave-one-out cross-validation
857 (LOO; Bürkner & Vuorre, 2019). The models indicated that, as in Experiment 1, AS reduced
858 the reported use of the Rehearsal (scaled effect size = -1.56) and the Clustering (-0.93)
859 strategies. It also reduced the reports of the Acoustic strategy (-1.04), an effect we did not find
860 in Experiment 1, probably because few participants indicated that they used it. Moreover, and
861 more surprisingly, the Elaboration strategy was slightly less reported under AS (-0.11) but did
862 not change according to the task contrary to what we observed in Experiment 1. In contrast, the
863 Visual (0.79) and the Memory Reduction (1.81) strategies were more reported with than without
864 Articulatory Suppression in this experiment as well as in Experiment 1. Concerning the effect

865 of dual tasking, the Rehearsal (-.27) and the Clustering strategies (-.24) were less reported in
866 the dual task than in the single task, whereas the reports of the Memory Reduction strategy, in
867 contrast, increased (0.50). Experiment 1 produced similar results on the Clustering and Memory
868 Reduction Strategies, but not on the Rehearsal strategy.

869 Two of the winning models included the interaction between AS and the Task. The
870 effect of AS was smaller in the dual task (0.24) for the Clustering strategy, but larger for the
871 Memory Reduction Strategy.

872 Finally, as suggested by a reviewer, we looked at potential differences in the reports of
873 the strategies between participants that began under articulatory suppression and participants
874 that began without articulatory suppression. No noticeable difference were observed between
875 the two orders (See Supp Text S2, Figure S1 and Figure S2).

876 In summary (see Figure 6), we replicated most of the effects observed in Experiment 1
877 but with slight differences probably due to the fact that the participants reported a higher
878 number of strategies in general, allowing finer grained observation of the different variations
879 according to the experimental manipulations.

880 Figure 6 about here

881 ***Strategy and performance.*** Spearman's correlations between each strategy and the
882 performance on memory were first performed. The results (Table 6) indicated that all the
883 strategies positively correlated with the memory performance, with the exception of the Visual
884 strategy, and the Memory Reduction strategy that correlated negatively with the performance.
885 Interestingly, the rating of these two strategies also correlated negatively with the rating of the
886 Rehearsal, Temporal Clustering and Elaboration strategies, consistent with the idea that
887 participants shifted to the Visual and Memory Reduction strategies when the difficulty of the
888 task increased and that, consequently, the performance dropped.

889 Table 6 about here

890 We analyzed the memory performance again, by using logistic mixed effects regression
891 using the R package lme4 with the effect of the task (single vs dual task), the Articulatory
892 Suppression (without vs with) and the type of Strategy (Rehearsal, Temporal Clustering,
893 Elaboration, Acoustic, Visual and Memory Reduction) as factors, following the same rationale
894 for model simplification than when the performance was analysed without taking the strategies
895 into account. The model that was selected did not include the main effect of strategy, nor an
896 interaction between the strategies and the other factors.

897 **Processing strategies.**

898 *Number of strategies.* As for memory strategies, we took into account any strategy
899 reported to be used at least to some extent (25% corresponding to the second point of the scale)
900 to compute the number of strategies reported being used on each condition. As in Experiments
901 1 and 2, this number does not include the Processing Reduction strategy. Overall, the
902 participants reported using on average 1.93 strategies ($SE=.02$) over the two that were measured
903 (Counting and Retrieval), indicating that most of the participants always used these two
904 strategies (at least to some extent). As for the memory strategies, a repeated ANOVA was
905 performed with AS (with vs. without) and Task (single vs. dual) as within-subject factors.
906 Similarly to what was found in Experiment 1, participants reported using slightly more
907 strategies in the single task ($M=1.95$; $SE=.03$) than in the dual task ($M=1.91$; $SE=.03$)
908 $F(1,60)=5.36$; $p=.02$; $\eta_p^2=.08$, while neither the AS or the interaction reached significance
909 ($p>.05$).

910 *Strategy use.* The same analyses were performed as for the memory strategies. The
911 selected models indicated that, as in Experiment 1, AS led to a reduction in the reports of the
912 Counting strategy (-0.42) but to an increase of the reports of the Retrieval strategy (0.16). A
913 similar pattern was observed for the effect of Task, with fewer reports of the Counting strategy
914 (-0.38) in the dual task than in the single task, but slightly more reports of the Retrieval strategy

915 (0.06). Taken together, these results (Figure 7) are similar to those of Experiment 1. Moreover,
916 the Processing Reduction strategy was reported more often under AS (0.14), and in the dual
917 task rather than in the single task (0.48). The model for this strategy included an interaction
918 (.41) indicating that the effect of the Task was observed only when AS was absent.

919 Figure 7 about here

920

921 *Strategy and performance.* Spearman's correlations (Table 7) indicated that the
922 Counting and the Retrieval Strategies both correlated positively with the performance on
923 processing. In contrast, the Processing Reduction strategy negatively correlated with the
924 performance. Interestingly, the Counting and the Retrieval strategies negatively correlated with
925 each other at -.44, probably indicating a tradeoff between these two strategies. The Processing
926 Reduction strategy was negatively correlated with the two other strategies, which is probably
927 due to the fact that, as for the memory strategies, the Reduction strategy was used when the task
928 became too difficult for participants. It is however interesting to note that the Memory
929 Reduction strategy was more often reported than Processing Reduction, a phenomenon we also
930 observed on Experiments 1 and 2.

931 Finally, the processing performance was analyzed using logistic mixed effects
932 regression, as for the memory performance. The winning model did not include any effect of
933 the strategies or their interactions with the Task or AS.

934 Table 7 about here

935 **Discussion**

936 Experiment 3 was a replication of Experiment 1, but with a trial-by-trial assessment of
937 the strategies instead of a final report. Our goals were to evaluate the extent to which the results
938 we found in the two first experiments were due to the kind of assessment used, and whether the

939 strategies observed on the previous experiments were linked with changes in the performance
940 level.

941 A first important point to notice is that, in spite of the changes we have introduced
942 compared to Experiment 1 (namely a questionnaire on the strategies used at the end of each
943 trial and 6 trials per block instead of 10), our results for the performance level are remarkably
944 similar to those of Experiment 1. Performing a dual task at their own level in memory and
945 processing reduced the performance of the participants on memory but not on processing. This
946 is reassuring because it suggests that the introduction of the trial-by-trial assessment did not
947 impact the performance of the participants. Nonetheless, this experiment allows us to be more
948 confident about the conclusions from the two first experiments. The constraints of dual-tasking
949 and of articulatory suppression are not only observed in the performance levels, but also in the
950 way in which the participants carry out each task in each experimental condition.

951 With respect to the range of different strategies used by participants, Experiment 3
952 showed that participants reported less use of memory and processing strategies in the dual task
953 than in the single task, a result that we also found in Experiments 1 and 2. However, we did
954 observe an effect of AS in Experiment 1 only (but not in Experiments 2 and 3), which casts
955 doubt on the robustness of this result. Altogether, the results of the three experiments point to
956 distinctive effects of dual tasking and AS. That is, the number of reported strategies was reduced
957 by the introduction of a second task, not by AS.

958 Concerning the memory strategies, most of the effects observed in Experiment 1 were
959 replicated in Experiment 3. For instance, AS reduced the reports of Rehearsal and Clustering
960 strategies, but increased the reports of the Visual and the Memory Reduction strategies.
961 Moreover, the Clustering strategy was less reported in dual task than in single task while the
962 opposite was true for the Memory Reduction Strategy. However, the effect of the Task on
963 Elaboration that we observed in Experiments 1 and 2 was not replicated here, this strategy being

964 only slightly less reported under AS. Finally, the acoustic strategy that was hardly ever reported
965 in Experiment 1 was much more often reported in this experiment, which made it possible to
966 observe a decrease in the reports of this strategy under AS. This reduction seems to indicate
967 that the acoustic strategy is based on the phonological loop, which is disrupted by AS. Once
968 again, the results on Memory Reduction are interesting. Under what might be considered the
969 most demanding condition, namely dual task under AS, our participants reported that they did
970 use Memory Reduction to some extent in 73 percent of the trials. In other words, our
971 participants really did the task as we expected in only 27 percent of the most critical trials. We
972 will return in the general discussion to the importance of these results for the Memory
973 Reduction strategy, which we observed in our three experiments.

974 The reports on the processing strategies were also broadly similar to those of Experiment
975 1. AS and the introduction of a secondary task led to a reduction in the reports of the Counting
976 strategy, and to an increase in the reports of the Retrieval strategy. The Processing Reduction
977 strategy was more often reported under AS and in the dual task, but never to the extent of the
978 Memory Reduction strategy, suggesting that, in the dual-task situation, participants preferred
979 to focus on the processing rather than on the memory.

980 Finally, another goal of this experiment was to assess the link between the reported
981 strategies and the performance. Here our results are mixed. On one hand, we did observe that
982 some memory strategies (Rehearsal, Clustering, Elaboration, Acoustic) as well as some
983 processing strategies (Counting, Retrieval) were positively correlated with performance.
984 Moreover, the reports of these strategies were also negatively correlated with the report of other
985 strategies (for memory: Visual and Memory Reduction; for processing: Processing Reduction)
986 that are themselves negatively correlated with performance. Combined with what we observed
987 on the strategy reports, this pattern suggests that, under difficult conditions, participants might
988 shift toward less costly but also less efficient strategies. But on the other hand, when the

989 strategies were entered in a model to explain performance, they did not appear as significant
990 predictors. A possibility is that we lack statistical power to correctly assess this link, and more
991 work is probably needed on this particular point.

992 **General Discussion**

993 Obtaining widespread agreement among researchers regarding the understanding of
994 how WM facilitates concurrent storage and processing has proved to be a challenge for several
995 decades. Two broadly contrasting conceptions have been developed; either that the two
996 activities are relying to some degree on the same general resource that needs to be shared, as
997 assumed by a range of theories, notably Embedded Processing (Cowan, 2016) and Time-Based
998 Resource-Sharing (Barrouillet & Camos, 2015), or that each activity can be supported by
999 different sub-systems as assumed by Multiple Component Models (Baddeley & Logie, 1999;
1000 Logie, 2016). A major motivation for the current study was that none of the three models of
1001 WM considered by the current authors could account for all of the performance data in two
1002 experiments reported by Doherty et al. (2019) that were designed to test the different predictions
1003 of each of these models. This approach of directly comparing the predictions of three different,
1004 well supported WM theories using exactly the same experimental paradigms run in parallel
1005 across two labs had not been attempted before, as far as we are aware, and so the lack of clear
1006 theoretical closure that was obtained was always a possible outcome. But it highlighted the need
1007 to consider alternative approaches that could capitalize on the research collaboration rather than
1008 pursuing the more traditional practice of attempting to discriminate between competing
1009 theories. Our hypothesis in the current paper was that this lack of theoretical closure might be
1010 resolved by considering the strategies that participants reported adopting in response to the
1011 different experimental manipulations. This raised the possibility that evidence for differential
1012 strategies among participants might reflect the use of different cognitive functions, and this in
1013 turn might lead to a theoretical resolution based on integrating the theories rather than taking

1014 the more common approach of favoring one theory at the expense of the others. To our
1015 knowledge, the present study is the first one to examine this long-standing issue of dual-task
1016 effects in WM through the investigation of strategy use and strategic adaptation for both
1017 memory and for a concurrent processing task. Performance in itself is not the mere reflection
1018 of the capacity of a cognitive system, but reflects the way individuals use the available cognitive
1019 functions at their disposal within that capacity. As extensively shown in the study of
1020 mathematical cognition and cognitive development by Siegler (1987; 1995 for a review; Fazio
1021 et al., 2016), examining performance without taking into consideration the involved strategies
1022 could lead to misinterpretations (see Logie, 2018, for similar arguments in WM). In other
1023 aspects of WM, studies have demonstrated that participants change strategies across tasks, and
1024 that different participants may use different strategies for the same task (e.g. Logie et al. 1996;
1025 Morrison et al., 2016). Here, we first discuss the consistent results from this investigation
1026 observed in the three experiments, and their theoretical implications. Then we consider data
1027 patterns for reported strategy use that were specific to one or other of the experiments.

1028 It was clear from the results that we report in the current manuscript that the observed
1029 reduction in memory performance under dual task compared with single task conditions in the
1030 three experiments reported here (but see Doherty et al., 2019, for a complete analysis of
1031 performance data from the two first experiments) was accompanied by complex, but systematic
1032 changes in the reported strategies. Specifically, the introduction of simple arithmetic
1033 verification during a retention interval resulted in fewer participants reporting the use of
1034 Temporal Clustering strategies, and more participants reporting use of a strategy (Memory
1035 Reduction) that reduced the number of items that participants attempted to retain in memory.
1036 Moreover, in Experiments 1 and 2, the Elaboration strategy was less reported in the dual task
1037 than in the single task. These results are consistent with all three models of working memory
1038 that we considered. They can be interpreted by assuming that the arithmetic verification task

1039 shares at least some of the same resource as is required for Elaboration and Temporal Clustering
1040 of the memory items when memory load is close to span. For EP and TBRS, this is referred to
1041 as limited capacity attention. For MCM, this is a processing resource that can also provide
1042 partial support for memory as argued in Doherty and Logie (2016). Consistent with this
1043 interpretation, we observed a reduction in the number of different strategies reported being used
1044 in the dual task compared to the single task in all three experiments.

1045 The introduction of articulatory suppression (AS) resulted in fewer participants
1046 reporting use of Rehearsal and Temporal Clustering, but no change in reported use of
1047 Elaboration to support memory. These results also are consistent with all three theories of
1048 working memory that we considered. All three theoretical perspectives accept that AS disrupts
1049 the use of subvocal rehearsal of a sequence of verbal items, so can readily account for the impact
1050 of AS on reported Rehearsal and Temporal Clustering strategies. Both TBRS and MCM assume
1051 that subvocal rehearsal involves a separate system that does not require a domain-general
1052 cognitive resource. EP assumes that there is an initial demand on limited capacity attention
1053 when AS starts, but not thereafter (Naveh-Benjamin & Jonides, 1984), and so would not expect
1054 AS to have an impact on strategies that are assumed to demand attention, specifically
1055 Elaboration.

1056 Unlike memory performance, in the three experiments, performance on the arithmetic
1057 verification task showed little or no disruption when concurrent with a verbal memory load,
1058 and was unaffected by AS. From these results, we might expect no change in strategies across
1059 conditions. Nonetheless, there were clear changes in reported strategies observed. A first point
1060 to notice is that the introduction of a memory task led to a reduction on the number of strategies
1061 reported for the processing task in our three experiments, which suggests a reduction of the
1062 cognitive flexibility of our participants. Specifically, in all three experiments, a Counting
1063 Strategy was reported less frequently with a concurrent memory load, and with AS. The

1064 interaction between dual task and AS observed in Experiments 1 and 2 (Figures 3 and 5) could
1065 be explained on the grounds that a dual task may interfere with the start of rehearsal (Naveh-
1066 Benjamin & Jonides, 1984), whereas AS interferes with both the start and with continuing
1067 rehearsal. However, this interaction concerning the Counting Strategy should be interpreted
1068 with caution given that it was not replicated in Experiment 3. The alternative, direct Retrieval
1069 strategy showed a less consistent pattern. In Experiments 1 and 3, AS resulted in an increase in
1070 reported use of Retrieval, although in Experiment 1 it was only the case in the single-task
1071 condition. These results are consistent with all three theories given the assumption that the
1072 memory load would be maintained by rehearsal, and therefore would have a similar effect to
1073 that found with AS. Adding AS to a concurrent memory load would then have no additional
1074 impact on the reports of the retrieval strategy. However, participants might increase the use of
1075 Retrieval to compensate for the reduction in the use of Counting. In Experiments 2 and 3 reports
1076 of Retrieval increased with a concurrent memory load. Altogether, these results suggest at the
1077 very least the impact of demanding conditions such as a memory load or AS might lead to a
1078 shift from the Counting Strategy to the Retrieval Strategy, as also suggested by the negative
1079 correlation between them.

1080 Taken together, these results demonstrate that individuals can strategically adapt to
1081 changing experimental conditions, and that this adaptation occurred not only for memory, but
1082 also for processing. Moreover, our results have led to important new insights in that there is
1083 evidence for changes in reported strategies even when performance did not change across
1084 experimental manipulations, as well as when performance changes were observed. When
1085 observing no change in performance as a result of experimental manipulations, as Doherty et
1086 al. (2019) found for arithmetic verification, there could be the misleading conclusion that there
1087 is no impact on the cognition of the participants. Examining reported strategies revealed that
1088 this was not the case for the experiments that we considered. There is evidence, not only from

1089 Experiments 1 and 2 derived from Doherty et al. (2019) but also from Experiment 3 using a
1090 trial-by-trial evaluation, that participants adapted the way in which they performed the
1091 experimental tasks. In the case of arithmetic verification, this adaptation offers an explanation
1092 why participants showed little or no impact on performance when concurrent with a memory
1093 load and under AS. Moreover, the results for memory strategies revealed a possible reason why
1094 participants' performance was reduced by dual task and by AS. It might be that the constraints
1095 imposed by the experimental manipulations resulted in reduced performance, and participants
1096 changed strategies in order to minimize the impact of those constraints even under the most
1097 demanding experimental manipulations. Although each of the theoretical perspectives could
1098 provide an explanation for the results observed, one clear outcome was that it was not necessary
1099 to make theoretical assumptions in order to understand the underlying drivers for changes in
1100 performance levels across conditions. An account could be derived from considering what kind
1101 of cognitive resource would be needed to use each kind of strategy, and from considering how
1102 a given strategy might support performance of each task in each condition.

1103

1104 **Theoretical Integration?**

1105 In the Doherty et al. (2019) report, it was clear that none of the three models of working
1106 memory considered could account for all of the performance data patterns. This was also true
1107 for some related experiments from the same research team reported by Rhodes et al. (2019).
1108 This suggests that the traditional approach of eliminating theories that do not fit the data and
1109 retaining a theory that does, may not be the most fruitful approach when dealing with broad
1110 theoretical frameworks. An alternative would be to adopt a more extreme position of
1111 abandoning all three theories and seeking an alternative that we did not consider explicitly when
1112 designing the experiments. However, this too might not be the best approach, given that all
1113 three models can each point to large volumes of previously published data consistent with their

1114 associated assumptions and predictions. It also could be argued that an account based entirely
1115 on careful task analysis and strategy analysis describes the data rather than offering a theoretical
1116 framework that might generalize beyond the paradigms used here. A more positive approach
1117 might be to consider developing a new theory of working memory that is more integrative rather
1118 than adversarial, that incorporates features and assumptions drawn from all three models. We
1119 might then consider whether such a new theory might account for the data patterns that have
1120 been the focus of the current study, and have the potential to address apparently contrasting
1121 data patterns that have accumulated with the development of each model. Detailed development
1122 of such a new model is beyond the scope of the current paper (see discussion in Logie et al.,
1123 2021b), but we propose that our analyses of strategies offers a possible path to pursuit of this
1124 goal.

1125 The observation of strategy adaptation has allowed us to conclude that the MCM, EP,
1126 and TBRS models are perhaps more compatible than might have been assumed from the
1127 performance data. Most notably, the assumption by TBRS that subvocal rehearsal can be used
1128 as a verbal memory maintenance mechanism that does not demand attention is very similar to
1129 the concept of subvocal rehearsal within a phonological loop in MCM (Baddeley, et al., 1984).
1130 Indeed, recent developments in TBRS refer to a phonological buffer combined with an
1131 articulatory rehearsal mechanism (e.g. Barrouillet & Camos, 2015; Camos, Lagner &
1132 Barrouillet, 2009). This common approach readily accounts for the effects of AS on the reported
1133 use of Rehearsal and Temporal Clustering strategies, and fits neatly with the reduction in
1134 memory performance with AS. EP has indicated that there may be peripheral components of
1135 WM, notably a verbal buffer together with an automated rehearsal system that does not require
1136 much attention (e.g. Cowan, 1988; Cowan et al., 2014), compatible with the current
1137 assumptions of the other two models.

1138 Our investigation here indicated that there were some participants who reported using
1139 visual strategies to support memory, and there were differences in reported strategies between
1140 visual presentation used in Experiment 1 and aural presentation used in Experiment 2.
1141 Moreover, in Experiment 3, participants reported using a Visual strategy more often under AS.
1142 The recent version of TBRS includes the concept of a visuo-spatial buffer (Barrouillet &
1143 Camos, 2015, pp. 118-120), that might support temporary passive memory for the use of visual
1144 strategies. This is consistent with the concept of a visual cache (Logie, 1995) that can store
1145 visual codes that are subject to decay over a few seconds and are replaced by subsequent stimuli
1146 (Shimi & Logie, 2019). In the Logie (1995) proposal, maintenance of the material in the visual
1147 cache was thought to be supported by an inner scribe mechanism that could mentally ‘redraw’
1148 the contents of the cache. There was no explicit discussion of the exact nature and cognitive
1149 resource requirements of the inner scribe in Logie (1995), although other studies have
1150 demonstrated that retention of visual codes is more readily disrupted than is retention of
1151 phonological codes in the phonological loop of MCM (e.g. Phillips & Christie, 1977; Salway
1152 & Logie, 1995). This suggests that maintenance of the information in the visual cache to prevent
1153 decay or interference from new material requires some domain-general resource for the inner
1154 scribe concept. TBRS has argued that maintenance of visual codes requires a central shared
1155 attentional resource and that there is not a specific mechanism for doing so. Both approaches
1156 would be consistent with the reports of visual strategies, but the vulnerability to disruption
1157 would lead to a drop in memory performance in response to AS or dual task, even when visual
1158 strategies are available. However, only a small percentage of participants reported use of visual
1159 strategies. To be consistent with these ideas, EP might consider including a temporary, limited
1160 capacity visual buffer as a peripheral component. Whether that component is essentially
1161 activated LTM visual representations or a domain-specific system that is separate from LTM

1162 does not actually matter for the concept of a visual buffer to have explanatory utility, though
1163 activated LTM would presumably require some attention for maintenance.

1164 The integration of the models might at first have appeared very challenging given the
1165 MCM assumption that there is no attentional resource to share, and the assumption from TBRS
1166 and EP that when two tasks are performed concurrently, they will share a limited capacity
1167 system and the extent to which this affects performance will depend on the overall load on
1168 attention. However, our arguments above regarding MCM suggest that there can also be sharing
1169 of a cognitive resource to implement a given strategy. Several previous dual task studies within
1170 the MCM framework have reported, and acknowledged, both domain general and domain-
1171 specific contributions to performance (e.g. Baddeley & Hitch, 1974; Logie, Zucco, & Baddeley,
1172 1990; Salway & Logie, 1995), and the strategy analysis demonstrated how strategy adaptation
1173 could mitigate the impact of this sharing between two tasks performed concurrently. The
1174 strategy analysis, then, offers a theoretical bridge between theories. The remaining debate is
1175 then the nature of this shared resource rather than whether or not there is such a resource.

1176 Some very recent experimental work by Barrouillet, Gorin and Camos (2021) has taken
1177 this theoretical integration further by introducing what they refer to as a maxispans procedure.
1178 In those experiments, participants were presented with sequences of between 4 and 11 letters
1179 for immediate serial ordered recall. In one condition, participants were simply asked to try to
1180 remember all the letters. In a second condition participants were instructed to rehearse aloud
1181 only a subset of each list, and to remember the other items in any way they could. For example,
1182 they might be asked to rehearse only four items from a seven item list. Results were clear in
1183 showing that when asked to rehearse only a subset of items, participants could recall on average
1184 one extra letter from each list compared with when they were given no specific instructions.
1185 Results were interpreted to suggest that when items are explicitly rehearsed aloud, this uses the
1186 maximum capacity of around four items in the phonological store, and that other items were

1187 being retained by means of a shared, general resource. Without explicit rehearsal instructions,
1188 participants may not be using the full capacity of each system that can support memory.
1189 Therefore, when measuring span by the maxispan method, the typical span letter of six
1190 **approached a span of eight letters**. This can be interpreted to reflect the operation of two aspects
1191 of cognition that contribute to performance, namely a temporary verbal memory store with a
1192 capacity of four items, combined with an additional general resource that can retain the
1193 remaining four items. This finding that arose from the TBRS perspective is consistent with
1194 assumptions of MCM about the use of multiple resources that act in concert to support
1195 performance. The finding can also be seen as consistent with the EP assumption of a capacity
1196 of four items for the focus of attention as a general resource coupled with what Cowan et al,
1197 (2014) referred to as a peripheral component of working memory that might also have a
1198 capacity of four items.

1199 The suggestion that there are two systems in WM that contribute to verbal memory
1200 performance might also offer an account for the residual levels of memory performance even
1201 under conditions of high cognitive load. In most dual task studies, even when there is a large
1202 impact of dual task, memory performance rarely, if ever drops close to zero, suggesting that
1203 there remains a cognitive resource that is not completely shared across the tasks that are
1204 combined (Belletier et al., 2020; Logie et al., 2021b). For example in the Doherty et al. (2019)
1205 experiments, even under dual task and AS, mean performance did not drop below two letters
1206 recalled in the correct order from the sequence for recall. With a stimulus set of 18 items, the
1207 chance level for recalling two items in the correct order is very close to zero. One key difference
1208 between the three theoretical frameworks considered here is one of emphasis rather than
1209 substance. Specifically, EP and TBRS tend to focus on the observation of a drop in performance
1210 under dual task conditions. In contrast, MCM tends to focus on why, even under demanding
1211 conditions, there is a residual level of memory performance. Our analyses of reported strategy

1212 adaptation have offered an explanation for this residual performance under demanding
1213 experimental conditions. It was notable that many participants reported the Memory Reduction
1214 strategy in which they chose to remember only some of the letters presented. One possibility is
1215 that this allows for the use of one of the two systems in WM proposed by Barrouillet et al.
1216 (2021) that can support memory for around four items, and that is not affected by the
1217 experimental manipulation (see Camos, Mora & Oberauer, 2011 for a similar argument; see
1218 Camos, 2017, for a review). Specifically, under dual task there would be the availability of the
1219 phonological loop and subvocal rehearsal. Under AS there would be a general cognitive
1220 resource available. If, in addition, we assume as in the EP model, that there is activation of
1221 LTM representations of the presented letters, then recall based on those activations would
1222 support memory for a small number of items, even when the general cognitive resource and
1223 articulatory rehearsal are not available. This activation is assumed to include rapidly-
1224 memorized information from the trial itself (Cowan, 1999). This assumption of activated LTM
1225 contributions to immediate serial ordered verbal recall would be consistent with both TBRS
1226 (Barrouillet et al., 2004; Barrouillet & Camos, 2015; Camos et al., 2018a; Camos & Portrat,
1227 2015) and with MCM (e.g. Hulme, Maughan, & Brown, 1991; Hulme, Roodenrys, Brown, &
1228 Mercer, 1995; Shimi & Logie, 2019; Logie, 2016). This reinforces the importance of
1229 considering the Memory Reduction strategy when exploring performance changes in memory
1230 under high cognitive load. As a reminder, in Experiment 3, during the dual task combined with
1231 AS, our participants reported trying to recall all the presented letters in only 27% of the trials
1232 and reported giving up on all the letters in 25% of the trials.

1233 A similar argument for Memory Reduction has been made with regard to immediate
1234 memory for visual information. Atkinson et al. (2017) showed that participants performed
1235 significantly better in a visual WM task when they focused on a subset of items (see also Adam,
1236 Vogel & Awh, 2017). Thus, whatever the type of WM tasks participants perform, they can

1237 adapt the memory load of the task. Hence, examining dual-task costs without considering the
1238 actual number of items participants choose to retain could lead to biased conclusions. For
1239 example, the lack of effect of the dual task on the processing task that we observed in our three
1240 experiments might be simply due to the fact that participants prioritize the processing over the
1241 memory and give up on the letters (Belletier et al., 2020). This adds to the arguments that
1242 considering participant strategies is important to gain a full insight into what determines
1243 changes in performance as a result of experimental manipulations.

1244 **Limitations and Future Directions**

1245 We have argued that exploring reported strategies reveals important insights that help
1246 account for patterns of performance data that are otherwise difficult to interpret. We have also
1247 argued that the insights from strategies can help towards integrating theories, focusing on their
1248 common features rather than their differences. Interestingly, the results that we observed in
1249 Experiments 1 and 2 that used final reports and the one we observed in Experiment 3 that used
1250 a trial-by-trial assessment of the strategies are remarkably similar. Nonetheless, participants
1251 reported a higher number of different strategies in Experiment 3, consistent with the idea that a
1252 trial-by-trial approach offers a more fine-grained analysis. The simple fact that we used a rating
1253 scale rather than free reports might have helped participants to remember more strategies. It is
1254 notable that the results on performance did not vary in Experiment 3 compared to Experiment
1255 1, suggesting that the assessment of the strategies on a trial by trial basis did not impact the way
1256 that the participants performed the task.

1257 In the 3 experiments reported in this paper, we collected data in different countries (UK,
1258 Switzerland and France). However, given the variability of the answers on strategies, a much
1259 larger sample would be necessary to properly test the differences between the sites. The fact
1260 that all our experiments involved different samples, yet show similar results, nonetheless
1261 indicates that such differences are marginal at best.

1262 One approach might be to consider strategy adaptation at the level of individual
1263 participants. For example, did the same individuals who reported rehearsal in single task
1264 memory without AS, then shift to reporting Elaboration, Memory Reduction, or Visual
1265 Strategies with AS? Were the participants who reported Elaboration strategies also the
1266 participants who showed the largest impact of dual task on memory performance? We
1267 attempted to explore these individual differences but did not have a large enough sample to
1268 allow a systematic investigation or analysis. This would merit investigation in future studies.
1269 Future studies could also investigate the impact on performance of instructing participants to
1270 use specific strategies in single and dual task, with and without AS as has been used in training
1271 strategies for working memory span (e.g. McNamara & Scott, 2001; Turley-Ames & Whitfield,
1272 2003). Instructing a participant to use a strategy that he or she would not have spontaneously
1273 used might be counterproductive and impair rather than improve performance. However, Chooi
1274 and Logie (2020) have shown that examining strategies during working memory training can
1275 offer insights into what changes in the way that participants attempt to perform the tasks, and
1276 that this insight might help explain when transfer effects do and do not occur following training.

1277 Despite these caveats, we gain confidence in the analyses of reported strategies from the
1278 observation of systematic and interpretable changes in reported strategies across conditions and
1279 across experiments. In addition, as discussed, the strategy analyses revealed important insights
1280 that have theoretical implications that we have discussed.

1281 An interesting point from our results is the lack of participants' reports of a strategy that
1282 could be related to refreshing in Experiment 1 and 2 (that used an open-ended questionnaire).
1283 Refreshing is a mechanism whose existence is postulated by two of the three models discussed
1284 here (Barrouillet & Camos, 2021; Cowan, Morey & Naveh-Benjamin, 2021), and by which
1285 attention is shifted back on memory traces in working memory with the aim of reactivating
1286 them and avoiding their loss. There are at least two explanations to this lack of reports.

1287 A first explanation is the potential difficulty of verbalizing such a mechanism. Merely
1288 saying something like “I just thought of the letters” might seem trivial to the participants. In
1289 support of this account, Morison et al. (2016) did observe reports of a strategy that could relate
1290 to refreshing: the “Concentrate” strategy (“I simply concentrated on the words”). However,
1291 these authors used a questionnaire listing 10 strategies including the one we just mentioned. We
1292 did not include such a strategy in the questionnaire for our Experiment 3 since it was built on
1293 the verbal reports of the participants in our Experiments 1 and 2. However, future research
1294 focusing more on Refreshing may benefit from adding the “concentrate” strategy to their
1295 questionnaires.

1296 A second account of the lack of observed reports corresponding to the Refreshing
1297 mechanism could be that this mechanism is automatized to a certain level. The level of
1298 automatization of a process is generally defined through a certain number of features (Moors &
1299 De Houwer, 2006). Among these features, automatic processes are thought to be largely
1300 unconscious. If the mechanism of Refreshing has this feature, one should assume that
1301 participants are not able to report its use. In other words, during a dual-task condition
1302 participants might choose to pay more attention to the memoranda or to the processing task, but
1303 would not be aware of the precise way in which attention would shift rapidly back and forth
1304 between the two tasks. They would therefore be able to report their prioritization of the tasks
1305 (e.g., through reduction strategies), but not the precise amount of refreshing they did. In other
1306 words, refreshing might not be deliberate (which is another feature of automatic processes) and
1307 might not be conscious. This is exactly how “swift refreshing” has been described in the
1308 literature before (Camos et al., 2018). Nonetheless, the question of the automaticity of
1309 refreshing remains to be explored.

1310 One other limitation of our study is that we have chosen to focus on only three models
1311 of working memory. These are arguably three of the most established models, although there

1312 are others (e.g. Anderson, Bothell, Byrne, Douglass, Lebiere & Quin, 2004; Engle, 2018;
1313 Oberauer, 2009; Oberauer, Farrell, Jarrold & Lewandowsky, 2016; Unsworth & Engle, 2007;
1314 Unsworth & Spillers, 2010b; see Cowan, 2017 and Logie & al., 2021a for reviews). However,
1315 our primary goal in the studies reported here and in related papers (Doherty et al., 2019; Rhodes
1316 et al., 2019) was to explore the approach of three groups who have developed different models
1317 of working memory collectively designing and running experiments across labs to test different
1318 predictions on a common paradigm. We would argue that this relatively rare approach to
1319 experimental cognitive psychology appears to have generated some novel insights that are
1320 unlikely to have arisen from any individual lab working in isolation when using paradigms that
1321 are typical of their individual theoretical framework.

1322 **Conclusion**

1323 To conclude, our results showed that participants are able to adapt their strategies for
1324 memory and processing in verbal WM tasks. This reported adaptation appears to be systematic
1325 and sensitive to concurrent cognitive demands as well as to concurrent articulation. Other
1326 factors such as the modality of presentation of memory items can also impact on reported
1327 strategy choice. The exploration of strategies has helped interpret data patterns that were not
1328 predicted by each of the three models of working memory that we considered, and has pointed
1329 to ways in which there is potential for important advances in the understanding of dual task
1330 performance in working memory through theoretical integration rather than perpetuating
1331 theoretical adversity.

Acknowledgments

We thank Karim Rivera Lares and Ophélie Lucas for their help in collecting the data.

References

- Adam, K. C., Vogel, E. K., & Awh, E. (2017). Clear evidence for item limits in visual working memory. *Cognitive Psychology*, *97*, 79-97.
- Anderson, J. R., Bothell, D., Byrne, M. D., Douglass, S., Lebiere, C., & Qin, Y. (2004). An integrated theory of the mind. *Psychological Review*, *111*(4), 1036-1060.
- Atkinson, A. L., Baddeley, A. D., & Allen, R. J. (2017). Remember some or remember all? Ageing and strategy effects in visual working memory. *The Quarterly Journal of Experimental Psychology*, 1-41.
- Atkinson, R. C., & Shiffrin, R. M. (1971). The control of short-term memory. *Scientific American*, *225*(2), 82-91.
- Baddeley, A. (1986). *Working memory*. New York/Oxford: Clarendon Press/Oxford University Press.
- Baddeley, A. (1992). Working memory. *Science*, *255*(5044), 556-559.
- Baddeley, A. (2007). *Working memory, thought, and action*. Oxford, UK: Oxford University Press.
- Baddeley, A. (2012). Working memory: theories, models, and controversies. *Annual Review of Psychology*, *63*, 1-29.
- Baddeley, A. D., & Hitch, G. (1974). Working memory. In G. A. Bower (Ed.) *Psychology of learning and motivation* (Vol. 8, pp. 47-89). New York: Academic press.
- Baddeley, A. D., Hitch, G. J., & Allen, R. J. (2018). From short-term store to multicomponent working memory: The role of the modal model. *Memory & Cognition*, 1-14.
- Baddeley, A., Lewis, V., & Vallar, G. (1984). Exploring the articulatory loop. *The Quarterly Journal of Experimental Psychology Section A*, *36*(2), 233-252.

- Baddeley, A & Logie, R. H. (1999) Working memory: The multiple-component model. in A Miyake & P Shah (eds.), *Models of Working Memory* (pp. 28-61). New York: Cambridge University Press.
- Bailey, H., Dunlosky, J., & Hertzog, C. (2009). Does differential strategy use account for age-related deficits in working-memory performance? *Psychology and Aging*, *24*(1), 82-92.
- Bailey, H., Dunlosky, J., & Kane, M. J. (2008). Why does working memory span predict complex cognition? Testing the strategy affordance hypothesis. *Memory & Cognition*, *36*(8), 1383–1390.
- Ballinger, G. A. (2004). Using generalized estimating equations for longitudinal data analysis. *Organizational Research Methods*, *7*(2), 127-150.
- Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time constraints and resource sharing in adults' working memory spans. *Journal of Experimental Psychology: General*, *133*(1), 83-100.
- Barrouillet, P., Bernardin, S., Portrat, S., Vergauwe, E., & Camos, V. (2007). Time and cognitive load in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*(3), 570-585.
- Barrouillet, P. N., & Camos, V. (2010). Working memory and executive control: A time-based resource-sharing account. *Psychologica Belgica*, *50*(3/4), 353-382.
- Barrouillet, P., & Camos, V. (2012). As time goes by: Temporal constraints in working memory. *Current Directions in Psychological Science*, *21*(6), 413-419.
- Barrouillet, P., & Camos, V. (2015). *Working memory: Loss and reconstruction*. New York, NY, US: Psychology Press.
- Barrouillet, P., & Camos, V. (2021). The Time-Based Resource-Sharing Model of Working Memory. In R. H. Logie, V. Camos & N. Cowan (Eds.) *Working Memory State of the Science*. Oxford University Press.

- Barrouillet, P., Gorin, S., & Camos, V. (2021). Simple spans underestimate verbal working memory capacity. *Journal of Experimental Psychology: General*, 150(4), 633-665.
- Barrouillet, P., Portrat, S., & Camos, V. (2011). On the law relating processing to storage in working memory. *Psychological Review*, 118(2), 175-192.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1–7. 2014.
- Belletier, C., Camos, V., & Barrouillet, P. (2020). Is the cognitive system much more robust than anticipated? Dual-task costs and residuals in working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 47(3) 498-507.
- Belletier, C., Doherty, J. M., Jaroslawska, A. J., Rhodes, S., Cowan, N., Naveh-Benjamin, M., ... Logie, R. (2021, March 31). WoMAAC - Strategic adaptation in Verbal Working Memory. Retrieved from osf.io/vh8xw
- Bengson, J. J., & Luck, S. J. (2016). Effects of strategy on visual working memory capacity. *Psychonomic Bulletin & Review*, 23(1), 265–270.
- Bor, D., Duncan, J., Wiseman, R. J., & Owen, A. M. (2003). Encoding strategies dissociate prefrontal activity from working memory demand. *Neuron*, 37(2), 361–367.
- Bor, D., & Owen, A. M. (2007). A common prefrontal–parietal network for mnemonic and mathematical recoding strategies within working memory. *Cerebral Cortex*, 17(4), 778–786.
- Borst, G., Niven, E.H. & Logie, R.H. (2012). Visual mental image generation does not overlap with visual short-term memory: A dual task interference study. *Memory and Cognition*, 40, 360-372.
- Brébion, G., Smith, M. J., & Ehrlich, M. F. (1997). Working memory and aging: Deficit or strategy differences? *Aging, Neuropsychology, and Cognition*, 4(1), 58–73.
- Broadbent, D (1958). Perception and Communication. London: Pergamon Press.

- Brooks, L. R. (1967). The suppression of visualisation by reading. *Quarterly Journal of Experimental Psychology*, 19, 289-299.
- Brooks, L.R. (1968). Spatial and verbal components in the act of recall. *Canadian Journal of Psychology*, 22, 349-368.
- Brown, L.A., Forbes, D. & McConnell, J. (2006) Limiting the Use of verbal coding in the Visual Patterns Test. *The Quarterly Journal of Experimental Psychology*, 59 (7), 1169-1176.
- Bürkner, P. C., & Vuorre, M. (2019). Ordinal regression models in psychology: A tutorial. *Advances in Methods and Practices in Psychological Science*, 2(1), 77-101.
- Butterworth, B., Cipolotti, L., & Warrington, E. K. (1996). Short term memory impairment and arithmetical ability. *The Quarterly Journal of Experimental Psychology Section A*, 49(1), 251-262.
- Camos, V. (2017). Domain-Specific Versus Domain-General Maintenance in Working Memory: Reconciliation Within the Time-Based Resource Sharing Model. In *Psychology of Learning and Motivation* (Vol. 67, pp. 135-171). Academic Press.
- Camos, V., & Barrouillet, P. (2004). Adult counting is resource demanding. *British Journal of Psychology*, 95(1), 19-30.
- Camos, V., Lagner, P., & Barrouillet, P. (2009). Two maintenance mechanisms of verbal information in working memory. *Journal of Memory and Language*. 61, 457-469.
- Camos, V., Johnson, M., Loaiza, V., Portrat, S., Souza, A., & Vergauwe, E. (2018b). What is attentional refreshing in working memory?. *Annals of the New York Academy of Sciences*. 1424(1), 19-32.
- Camos, V., Mora, G., & Oberauer, K. (2011). Adaptive choice between articulatory rehearsal and attentional refreshing in verbal working memory. *Memory & Cognition*, 39(2), 231–244.

- Camos, V., Mora, G., Oftinger, A. L., Mariz, S. E., Schneider, P., & Vergauwe, E. (2018a). Does semantic long-term memory impact refreshing in verbal working memory?. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(9), 1664-1682
- Camos, V., & Portrat, S. (2015). The impact of cognitive load on delayed recall. *Psychonomic Bulletin & Review*, *22*(4), 1029-1034.
- Carretti, B., Borella, E., & De Beni, R. (2007). Does strategic memory training improve the working memory performance of younger and older adults? *Experimental Psychology*, *54*(4), 311–320.
- Chen, Z., & Cowan, N. (2009). Core verbal working-memory capacity: The limit in words retained without covert articulation. *Quarterly Journal of Experimental Psychology*, *62*(7), 1420–1429.
- Chooi, W. T., & Logie, R. (2020). Changes in error patterns during n-back training indicate reliance on subvocal rehearsal. *Memory & cognition*, *48*(8), 1484-1503.
- Cokely, E. T., Kelley, C. M., & Gilchrist, A. L. (2006). Sources of individual differences in working memory: Contributions of strategy to capacity. *Psychonomic Bulletin & Review*, *13*(6), 991–997.
- Conrad, R. (1964). Acoustic confusions in immediate memory. *British journal of Psychology*, *55*(1), 75-84.
- Conway, A.R.A., Jarrold, C., Kane, M.J., Miyake, A., & Towse, J.N. (Eds.) (2007). *Variation in working memory*. New York: Oxford University Press.
- Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin*, *104*, 163-191.

- Cowan, N. (1999). An Embedded-Processes Model of Working Memory. In: A. Miyake & P. Shah. *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control* (pp. 62-101). Cambridge: Cambridge University Press.
- Cowan, N. (2005). Working-memory capacity limits in a theoretical context. In C. Izawa & N. Ohta (Eds.), *Human learning and memory: Advances In theory and applications* (pp. 155-175). The 4th Tsukuba international conference on memory. Erlbaum
- Cowan, N. (2010). The magical mystery four: How is working memory capacity limited, and why? *Current Directions in Psychological Science*, 19(1): 51-57.
- Cowan, N. (2015). George Miller's magical number of immediate memory in retrospect: Observations on the faltering progression of science. *Psychological Review*, 122(3): 536-541.
- Cowan, N. (2016). *Working Memory Capacity: Classic Edition*. New York, NY: Routledge.
- Cowan, N. (2017). The many faces of working memory and short-term storage. *Psychonomic Bulletin & Review*, 24, 1158–1170.
- Cowan, N., Morey, C. C. & Naveh-Benjamin, M. (2021). An Embedded-Processes Approach to Working Memory. In R. H. Logie, V. Camos & N. Cowan (Eds.) *Working Memory State of the Science*. Oxford University Press.
- Cowan, N., Belletier, C., Doherty, J. M., Jaroslawska, A. J., Rhodes, S., Forsberg, A., Naveh-Benjamin, M., Barrouillet, P., Camos, V., & Logie, R. H. (2020). How Do Scientific Views Change? Notes From an Extended Adversarial Collaboration. *Perspectives on psychological science* 15(4), 1011–1025.
- Cowan, N., Saults, J. S., & Blume, C. L. (2014). Central and peripheral components of working memory storage. *Journal of Experimental Psychology: General*, 143(5), 1806-1836.

- Craik, F. I., Govoni, R., Naveh-Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General*, *125*(2), 159-180.
- Cusack, R., Lehmann, M., Veldsman, M., & Mitchell, D. J. (2009). Encoding strategy and not visual working memory capacity correlates with intelligence. *Psychonomic Bulletin & Review*, *16*(4), 641–647.
- Darling, S., Allen, R. & Havelka, J. (2017) Visuospatial Bootstrapping: When Visuospatial and Verbal Memory Work Together. *Current Directions in Psychological Science*, *26*(1), 3-9.
- De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (1999). The contribution of working memory resources in the verification of simple mental arithmetic sums. *Psychological Research*, *62*(1), 72-77.
- De Rammelaere, S., Stuyven, E., & Vandierendonck, A. (2001). Verifying simple arithmetic sums and products: Are the phonological loop and the central executive involved?. *Memory & Cognition*, *29*(2), 267-273.
- DeStefano, D., & LeFevre, J. A. (2004). The role of working memory in mental arithmetic. *European Journal of Cognitive Psychology*, *16*(3), 353-386.
- Doherty, J., Belletier, C., Rhodes, S., Jaroslawska, A., Barrouillet, P., Camos, V., Cowan, N., Naveh-Benjamin, M. & Logie, R. (2019). *Journal of Experimental Psychology: Learning, Memory and Cognition*, *45*, 1529-1551.
- Doherty, J. M., & Logie, R. H. (2016). Resource-sharing in multiple-component working memory. *Memory & Cognition*, *44*(8), 1157-1167.
- Dunlosky, J., & Kane, M. J. (2007). The contributions of strategy use to working memory span: A comparison of strategy assessment methods. *Quarterly Journal of Experimental Psychology*, *60*(9), 1227–1245.

- Engle, R. W. (2018). Working memory and executive attention: A revisit. *Perspectives on Psychological Science, 13*(2), 190-193.
- Engle, R. W., Cantor, J., & Carullo, J. J. (1992). Individual differences in working memory and comprehension: A test of four hypotheses. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(5), 972-992.
- Ericsson, K.A. & Simon, H.A. (1984). *Protocol analysis: Verbal reports as data*. Cambridge, MA, USA: MIT Press.
- Fazio, L. K., DeWolf, M., & Siegler, R. S. (2016). Strategy use and strategy choice in fraction magnitude comparison. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(1), 1-16.
- Friedman, N. P., & Miyake, A. (2004). The reading span test and its predictive power for reading comprehension ability. *Journal of Memory and Language, 51*(1), 136–158.
- Harris, J. L., & De Qualls, C. (2000). The association of elaborative or maintenance rehearsal with age, reading comprehension, and verbal working memory performance. *Aphasiology, 14*(5–6), 515–526.
- Hecht, S. A. (2002). Counting on working memory in simple arithmetic when counting is used for problem solving. *Memory & Cognition, 30*(3), 447–455.
- Hitch, G.J., Burgess, N., Towse, J.N. & Culpin, V. (1996). Temporal grouping effects in immediate recall: A working memory analysis. *Quarterly Journal of Experimental Psychology, 49A*, 116-139.
- Hulme, C., Maughan, S., & Brown, G. D. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language, 30*(6), 685-701.
- Hulme, C., Roodenrys, S., Brown, G., & Mercer, R. (1995). The role of long-term memory mechanisms in memory span. *British Journal of Psychology, 86*(4), 527-536.

- Imbo, I., & Vandierendonck, A. (2007). The role of phonological and executive working memory resources in simple arithmetic strategies. *European Journal of Cognitive Psychology, 19*(6), 910-933.
- James, W. (1890). *The principles of psychology*. New York: H. Holt and Company.
- Jaroslawska, A. J., Rhodes, S., Belletier, C., Doherty, J. M., Cowan, N., Neveh-Benjamin, M., Barrouillet, P., Camos, V., & Logie, R. H. (2021). What affects the magnitude of age-related dual-task costs in working memory? The role of stimulus domain and access to semantic representations. *Quarterly Journal of Experimental Psychology, 74*(4), 682–704.
- Kaakinen, J. K., & Hyönä, J. (2007). Strategy use in the reading span test: An analysis of eye movements and reported encoding strategies. *Memory, 15*(6), 634–646.
- LeFevre, J.-A., Sadesky, G. S., & Bisanz, J. (1996). Selection of procedures in mental addition: Reassessing the problem size effect in adults. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22*(1), 216-230.
- Lemaire, L., Abdi, H., & Fayol, M. (1996). Working memory and cognitive arithmetic: Evidence from the disruption of the associative confusion effect. *European Journal of Cognitive Psychology, 8*, 73-103.
- Lemaire, P., & Fayol, M. (1995). When plausibility judgments supersede fact retrieval: The example of the odd-even effect on product verification. *Memory & Cognition, 23*(1), 34–48.
- Liddell, T. M., & Kruschke, J. K. (2018). Analyzing ordinal data with metric models: What could possibly go wrong?. *Journal of Experimental Social Psychology, 79*, 328-348.
- Linke, A. C., Vicente-Grabovetsky, A., Mitchell, D. J., & Cusack, R. (2011). Encoding strategy accounts for individual differences in change detection measures of VSTM. *Neuropsychologia, 49*(6), 1476–1486.

- Logie, R.H. (1995). *Visuo-Spatial Working Memory*. Hove, UK: Lawrence Erlbaum Associates.
- Logie, R. H. (2003) Spatial and Visual Working Memory: A mental Workspace. In D. Irwin & B. Ross (Eds.) *Cognitive Vision: The Psychology of Learning and Motivation* (Vol 42, pp. 37-38). USA: Elsevier Science.
- Logie, R. H. (2011). The functional organization and capacity limits of working memory. *Current Directions in Psychological Science*, 20(4), 240–245.
- Logie, R. H. (2016). Retiring the central executive. *The Quarterly Journal of Experimental Psychology*, 69(10), 2093-2109.
- Logie, R. (2018). Human Cognition: Common Principles and Individual Variation. *Journal of Applied Research in Memory and Cognition*. 7(4), 471-486.
- Logie, R. H., & Baddeley, A. D. (1987). Cognitive processes in counting. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 13(2), 310-326.
- Logie, R.H., Belletier, C. & Doherty, J.D. (2021b). Integrating theories of working memory. In R.H. Logie, V. Camos, & N. Cowan, (Eds.) *Working Memory: State of the Science*, pp 389-429. Oxford, UK: Oxford University Press.
- Logie, R.H., Camos, V., & Cowan, N. (Eds.) (2021a). *Working Memory: State of the Science*. Oxford, UK: Oxford University Press.
- Logie, R. H., Cocchini, G., Della Sala, S., & Baddeley, A. D. (2004). Is there a specific executive capacity for dual task coordination? Evidence from Alzheimer's disease. *Neuropsychology*, 18(3), 504-513.
- Logie, R.H. & Cowan, N. (2015). Perspectives on working memory. *Memory and Cognition*, 43, 315–324.
- Logie, R. H., Della Sala, S., Laiacona, M., Chalmers, P., & Wynn, V. (1996). Group aggregates and individual reliability: The case of verbal short-term memory. *Memory & Cognition*, 24(3), 305–321.

- Logie, R. H., Della Sala, S., Wynn, V., & Baddeley, A. D. (2000). Visual similarity effects in immediate verbal serial recall. *The Quarterly Journal of Experimental Psychology Section A*, 53(3), 626-646.
- Logie, R.H., Saito, S., Morita, A., Varma, S. & Norris, D. (2016). Recalling visual serial order for verbal sequences. *Memory and Cognition*, 590-607.
- Logie, R.H., Zucco, G. and Baddeley, A.D. (1990). Interference with visual short-term memory. *Acta Psychologica* 75, 55-74.
- McNamara, D. S., & Scott, J. L. (2001). Working memory capacity and strategy use. *Memory & Cognition*, 29(1), 10–17.
- Miller, S., McCulloch, S., & Jarrold, C. (2015). The development of memory maintenance strategies: training cumulative rehearsal and interactive imagery in children aged between 5 and 9. *Frontiers in Psychology*, 6, 524.
- Moors, A., & De Houwer, J. (2006). Automaticity: a theoretical and conceptual analysis. *Psychological bulletin*, 132(2), 297-326.
- Morrison, A. B., Rosenbaum, G. M., Fair, D., & Chein, J. M. (2016). Variation in strategy use across measures of verbal working memory. *Memory & Cognition*, 44(6), 922–936.
- Murray, D. J. (1965). Vocalization-at-presentation and immediate recall, with varying presentation-rates. *Quarterly Journal of Experimental Psychology*, 17(1), 47-56.
- Naveh-Benjamin, M., & Jonides, J. (1984). Maintenance rehearsal: A two-component analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 10, 369-385.
- Nisbett, R.E. & Wilson, T.D. (1977). Telling more than we can know: verbal reports on mental processes. *Psychological Review*, 84, 231-259.
- Oberauer, K. (2002). Access to information in working memory: exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(3), 411-421.

- Oberauer, K. (2009). Design for a working memory. *Psychology of learning and motivation*, 51, 45-100.
- Oberauer, K., Farrell, S., Jarrold, C., & Lewandowsky, S. (2016). What limits working memory capacity?. *Psychological Bulletin*, 142(7), 758-799.
- Paivio, A. (1971). Imagery and verbal processes. New York: Holt, Rinehart and Winston.
- Peirce, J. W. (2007). PsychoPy—psychophysics software in Python. *Journal of Neuroscience Methods*, 162(1–2), 8–13.
- Phillips, W. A., & Christie, D. F. M. (1977). Interference with visualization. *Quarterly Journal of Experimental Psychology*, 29(4), 637-650.
- Rhodes, S., Jaroslawska, A.J., Doherty, J.M., Belletier, C., Naveh-Benjamin, M., Cowan, N., Camos, V., Barrouillet, P., & Logie, R.H. (2019). Storage and processing in working memory: Assessing dual task performance and task prioritization across the adult lifespan. *Journal of Experimental Psychology: General*, 148, 1204-1227
- Saults, J. S., & Cowan, N. (2007). A central capacity limit to the simultaneous storage of visual and auditory arrays in working memory. *Journal of Experimental Psychology: General*, 136(4), 663-684.
- Saito, S., Logie, R. H., Morita, A., & Law, A. (2008). Visual and phonological similarity effects in verbal immediate serial recall: A test with kanji materials. *Journal of Memory and Language*, 59(1), 1-17.
- Salway, A. F., & Logie, R. H. (1995). Visuospatial working memory, movement control and executive demands. *British Journal of Psychology*, 86(2), 253-269.
- Schwarz, G. (1978). Estimating the dimension of a model. *The annals of statistics*, 461-464.
- Shimi, A., & Logie, R. H. (2019). Feature binding in short-term memory and long-term learning. *Quarterly Journal of Experimental Psychology*, 72(6), 1387-1400.
<https://doi.org/10.1177/1747021818807718>

- Siegler, R. S. (1987). The perils of averaging data over strategies: An example from children's addition. *Journal of Experimental Psychology: General*, *116*(3), 250-264.
- Siegler, R. S. (1995). How does change occur: A microgenetic study of number conservation. *Cognitive Psychology*, *28*(3), 225–273.
- St Clair-Thompson, H., Stevens, R., Hunt, A., & Bolder, E. (2010). Improving children's working memory and classroom performance. *Educational Psychology*, *30*(2), 203–219.
- Swanson, H. L., Kehler, P., & Jerman, O. (2010). Working memory, strategy knowledge, and strategy instruction in children with reading disabilities. *Journal of Learning Disabilities*, *43*(1), 24–47.
- Thalmann, M., Souza, A. S., & Oberauer, K. (2019). Revisiting the attentional demands of rehearsal in working-memory tasks. *Journal of Memory and Language*, *105*, 1-18.
- Turley-Ames, K. J., & Whitfield, M. M. (2003). Strategy training and working memory task performance. *Journal of Memory and Language*, *49*(4), 446–468.
- Unsworth, N. (2016). Working memory capacity and recall from long-term memory: Examining the influences of encoding strategies, study time allocation, search efficiency, and monitoring abilities. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(1), 50-61.
- Unsworth, N., & Engle, R. W. (2007). The nature of individual differences in working memory capacity: active maintenance in primary memory and controlled search from secondary memory. *Psychological Review*, *114*(1), 104-132.
- Unsworth, N., & Spillers, G. J. (2010a). Variation in working memory capacity and episodic recall: The contributions of strategic encoding and contextual retrieval. *Psychonomic Bulletin & Review*, *17*(2), 200–205.

- Unsworth, N., & Spillers, G. J. (2010b). Working memory capacity: Attention control, secondary memory, or both? A direct test of the dual-component model. *Journal of Memory and Language*, *62*(4), 392-406.
- Unsworth, N. (2016). Working memory capacity and recall from long-term memory: Examining the influences of encoding strategies, study time allocation, search efficiency, and monitoring abilities. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *42*(1), 50-61.
- Vergauwe, E., Barrouillet, P., & Camos, V. (2010). Do mental processes share a domain-general resource?. *Psychological Science*, *21*(3), 384-390.
- Vergauwe, E., Camos, V., & Barrouillet, P. (2014). The impact of storage on processing: How is information maintained in working memory?. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *40*(4), 1072-1095.
- Wang, M. (2014). Generalized estimating equations in longitudinal data analysis: a review and recent developments. *Advances in Statistics*, 2014.

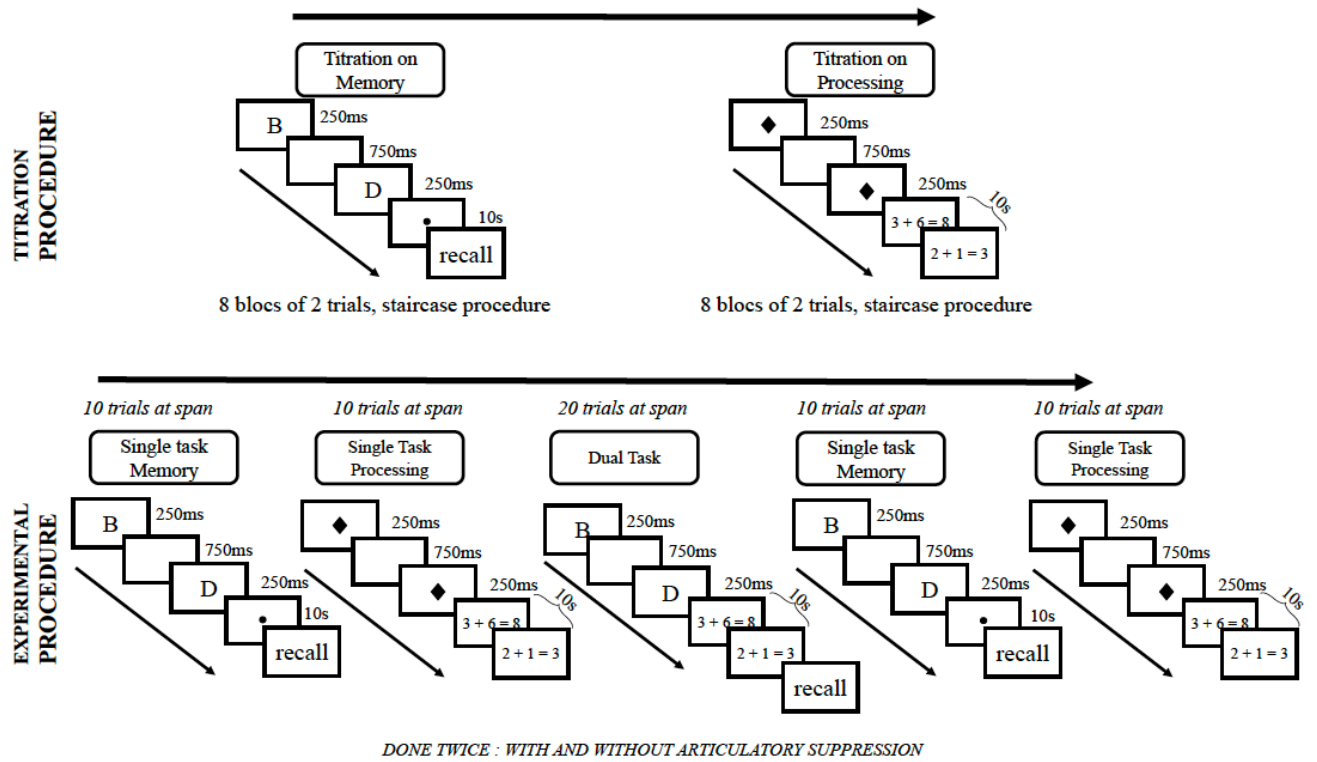


Figure 1: General procedure of Experiment 1.

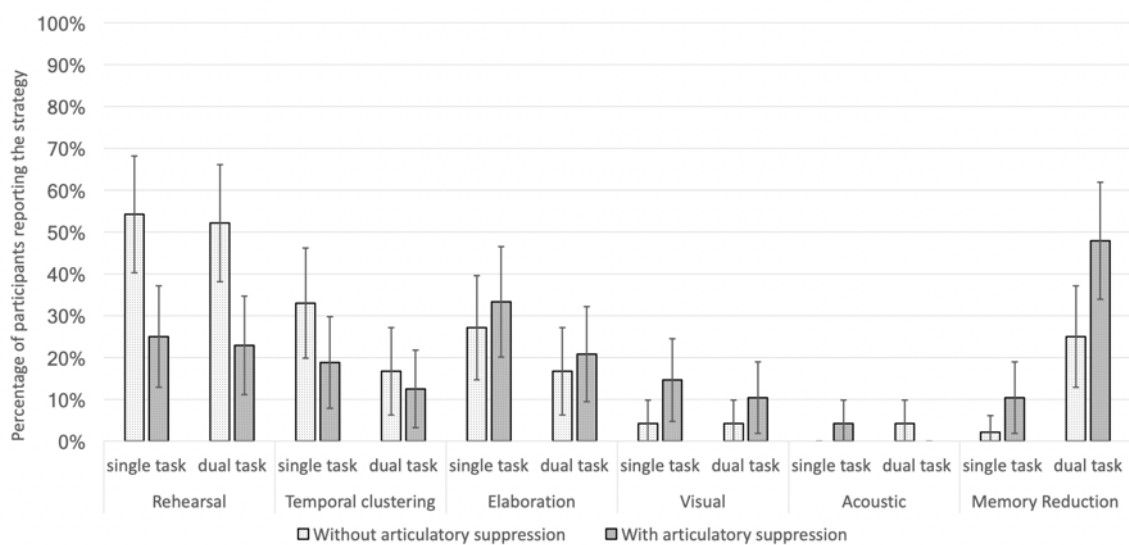


Figure 2: Percentages of participants reporting each memory strategy in each condition of Experiment 1 (with visually presented letters). Error bars represent confidence intervals at 95%.

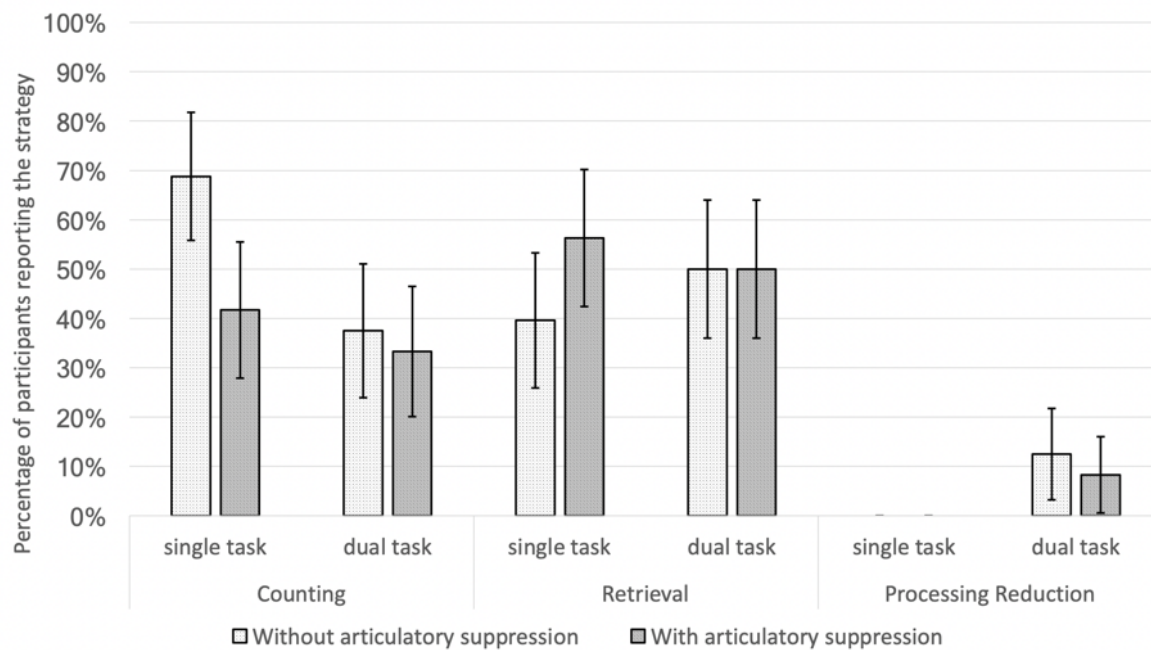


Figure 3: Percentages of participants reporting each processing strategy in each condition of Experiment 1 (with visually presented letters). Error bars represent confidence intervals at 95%.

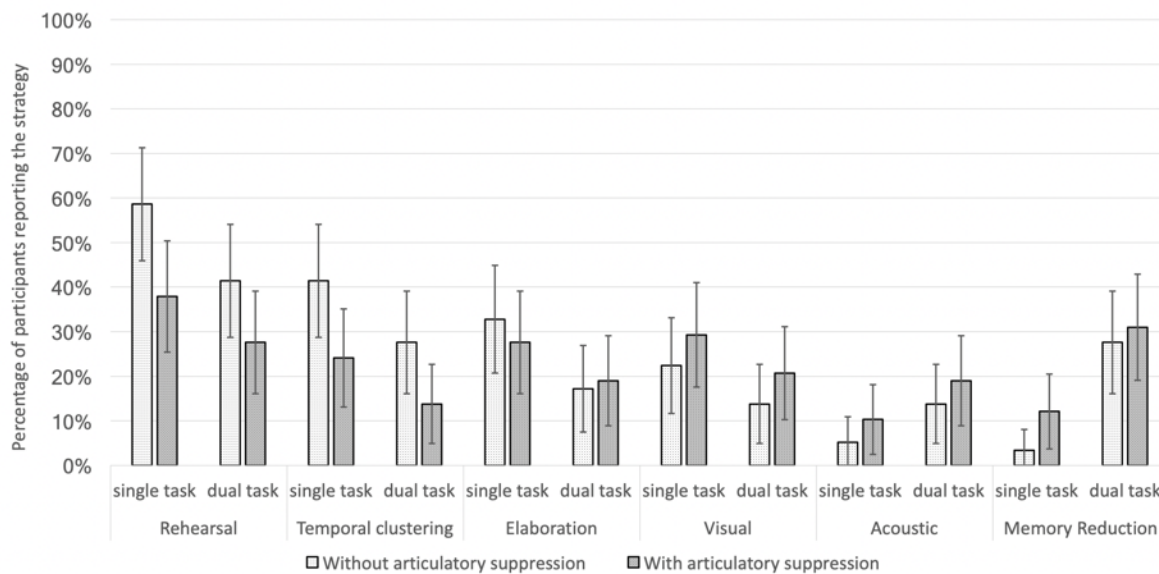


Figure 4: Percentages of participants reporting each memory strategy in each condition of Experiment 2 (with auditory presented letters). Error bars represent confidence intervals at 95%.

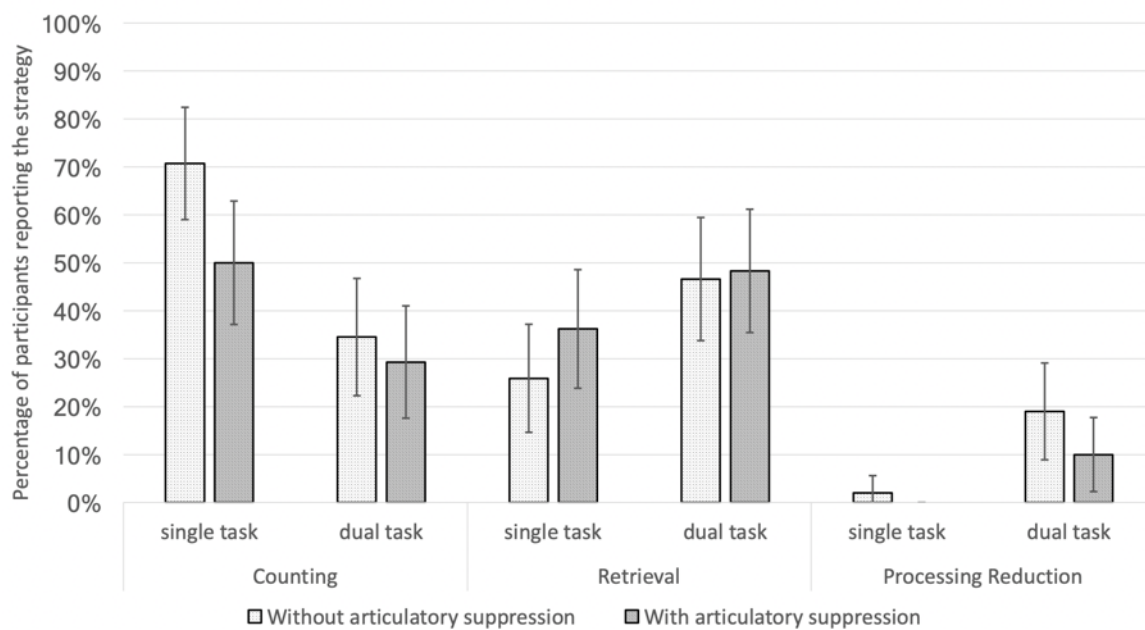


Figure 5: Percentages of participants reporting each processing strategy in each condition of Experiment 2 (with auditory presented letters). Error bars represent confidence intervals at 95%.

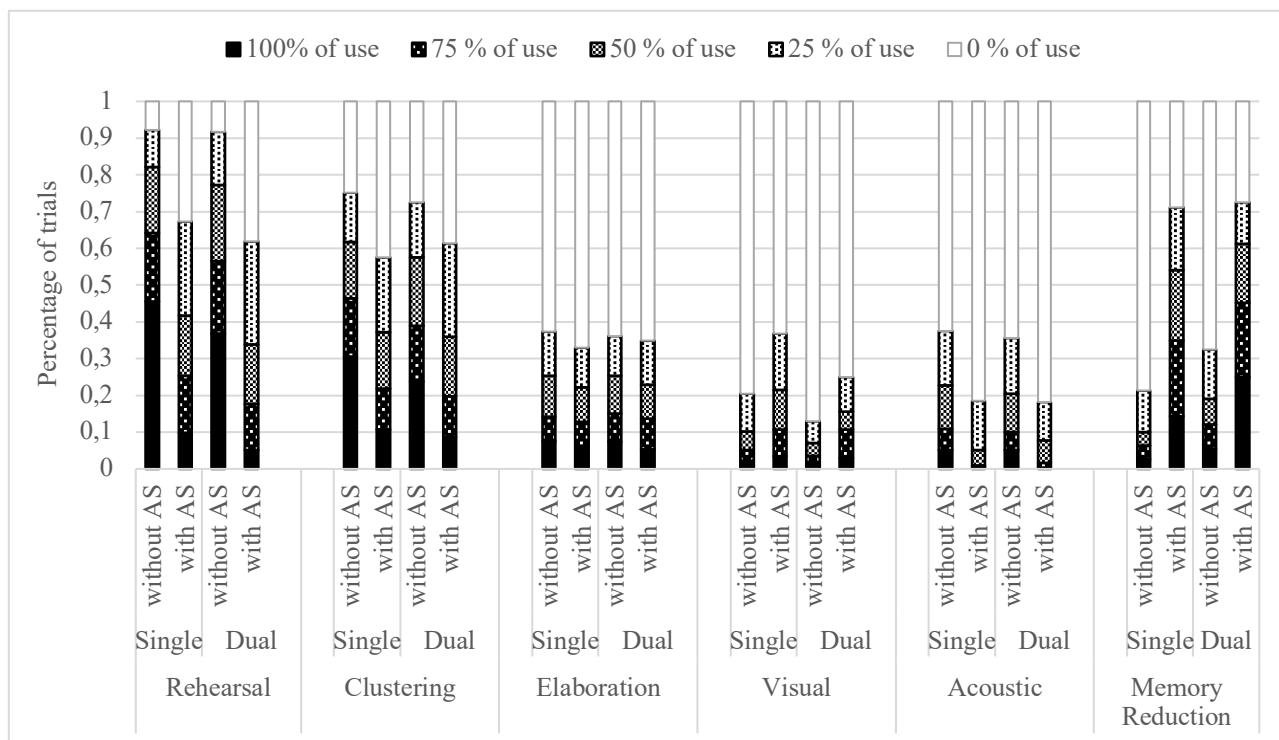


Figure 6: Rating for each memory strategy in each condition of Experiment 3 (with a trial-by-trial assessment). Participants were asked to which extent they used each strategy in the last trial and answered on a 5 point-Likert scale going from 0% to 100%.

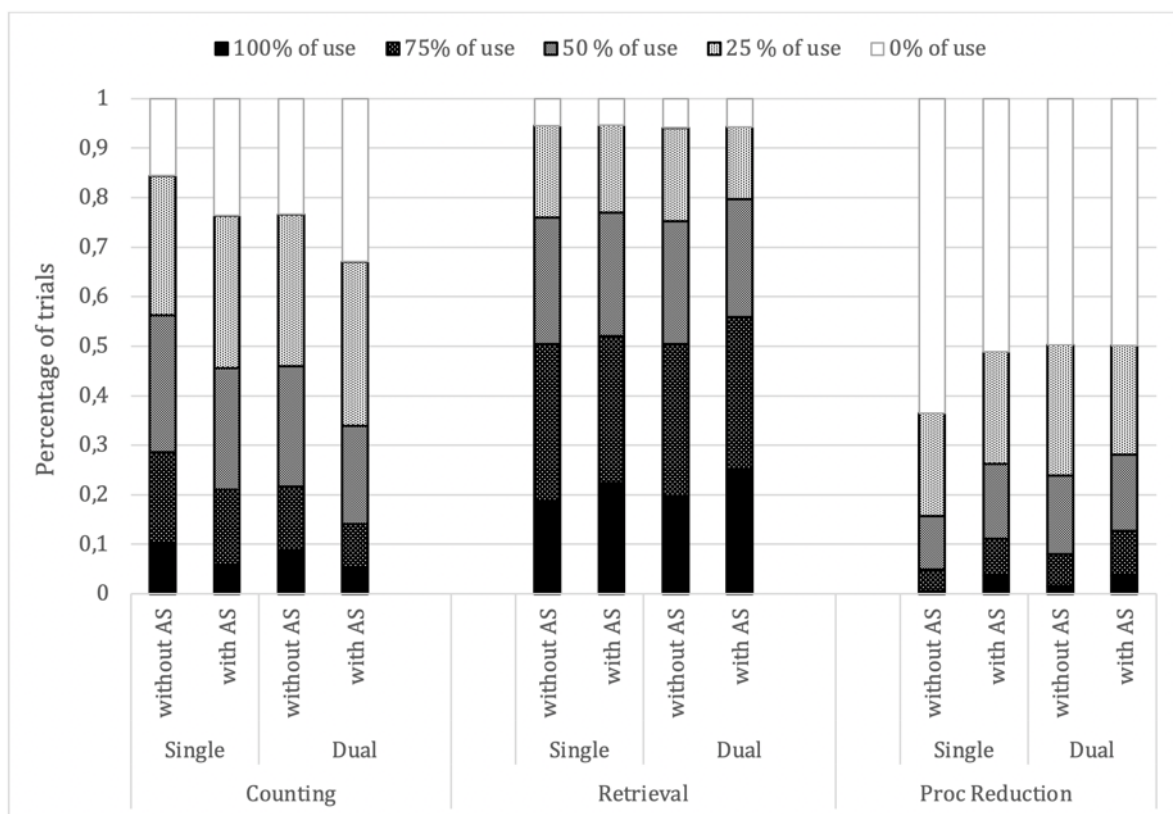


Figure 7: Rating for each processing strategy in each condition of Experiment 3 (with a trial-by-trial assessment). Participants were asked to which extent they used each strategy in the last trial and answered on a 5 point-Likert scale going from 0% to 100%.

Table 1. Open-ended questions at the end of each experiment.

Questions	Verbatim
Q1	How did you remember the series of letters when the letters were presented alone, without any other task at the same time?
Q2	How did you remember the letters when you had also to say 'ba-ba-ba'?
Q3	How did you remember the letters when you also had to verify the sums?
Q4	How did you remember the letters when you had to say 'ba-ba-ba' and verify the sums at the same time?
Q5	How did you verify the sums alone?
Q6	How did you verify the sums when you had also to say 'ba-ba-ba'?
Q7	How did you verify the sums when you also had to remember the letters?
Q8	How did you verify the sums when you had to say 'ba-ba-ba' and remember the letters at the same time?

Table 2. Classification of the memory strategies.

Name	Description	Example of participants' responses
Rehearsal	Repeating letters successively as in a loop	“repeating the letters mentally”
Temporal Clustering	Grouping letters by 2, 3 or 4	“I would try to remember them in groups of twos or threes”
Elaboration and Chaining	Associating letters with words or acronyms.	“looked for common acronyms or initials within the pattern to help me remember”
Visual	Memorizing visually the letters (sometimes by using the keyboard)	“I tried to visualize them on the screen”
Acoustic	Memorizing the sound of the letters and focusing on the sound itself	“I tried to recall the sound of the letter sequence”
Memory Reduction	Reducing the memory load by prioritizing addition verifications or by dropping some or all letters	“just focused on some letters, rarely tried to remember all”
Others	Other strategies	“I tried to associate a letter with a single finger”

Table 3: Effects of the task condition and the articulatory suppression (AS) on the use of each memory strategies in Experiments 1 and 2.

		Experiment 1		Experiment 2	
		Wald Z	<i>p</i>	Wald Z	<i>p</i>
Task Condition	Rehearsal	ns	ns	7.35	<.01
	Clustering	8.68	<.01	8.53	<.01
	Elaboration	4.76	.03	6.19	.01
	Visual	ns	ns	ns	ns
	Acoustic	NA	NA	3.90	.05
	Memory Reduction	30.19	<.001	17.87	<.001
Articulatory Suppression	Rehearsal	17.33	<.001	10.73	<.001
	Clustering	4.69	.03	13.23	<.001
	Elaboration	ns	ns	ns	ns
	Visual	6.95	<.01	ns	ns
	Acoustic	NA	NA	ns	ns
	Memory Reduction	7.64	<.01	ns	ns

Note: NA indicated that the number of participants reporting this strategy was too low to perform analysis, ns for non-significant effects. Interactions between Task condition and AS were not reported, because they were never significant.

Table 4. Classification of the strategies used for the addition verification task.

Name	Description	Example of participants' responses
Counting	Verifying additions through a step-by-step calculation	“try and solve the first two numbers mentally first”
Retrieval	Verifying additions “intuitively” or knowing them "by heart"	“answered those I remembered by heart”
Processing Reduction	Reducing the processing load by prioritizing memory or by giving up some or all addition verifications	“I tend to remember the letters and not focusing on the sums”
Others	Other strategies	“based on even and odd numbers”

Table 5: Effects of the task condition and the articulatory suppression on the use of each processing strategies in Experiments 1 and 2.

		Experiment 1		Experiment 2	
		Wald Z	<i>p</i>	Wald Z	<i>p</i>
Task	Counting	11.75	<.01	21.35	<.001
	Retrieval	ns	ns	10.17	<.001
Condition	Processing	NA	NA	NA	NA
	Reduction				
Articulatory	Counting	13.87	<.001	13.13	<.001
	Retrieval	4.26	.04	ns	ns
Suppression	Processing	NA	NA	NA	NA
	Reduction				
Interaction	Counting	8.91	<.01	4.09	.04
	Retrieval	5.92	.02	Add Mod	Add Mod
	Processing	NA	NA	NA	NA
	Reduction				

Note: NA indicated that the number of participants reporting this strategy was too low to perform analysis, ns for non-significant effects. Add Mod specified that an additive model was preferred; the interaction term was therefore not computed.

Table 6: Spearman's correlations between the reported memory strategies and of these strategies with the memory performance in Experiment 3.

Variable	Rehearsal	Clustering	Elaboration	Acoustic	Visual	Memory Reduction
Rehearsal	—					
Clustering	0.282 ***	—				
Elaboration	-0.185***	0.035	—			
Acoustic	0.216 ***	0.131 ***	-0.004	—		
Visual	-0.070***	-0.039 *	-0.080 ***	0.045 *	—	
Memory Reduction	-0.269***	-0.171 ***	-0.194 ***	0.107***	0.083***	—
Memory Performance	0.367 ***	0.263 ***	0.205 ***	0.151***	0.115***	-0.462 ***

Table 7: Spearman's correlations between the reported processing strategies and of these strategies with the processing performance in Experiment 3.

Variable	Counting	Retrieval	Processing Reduction
Counting	—		
Retrieval	-0.443***	—	
Processing Reduction	-0.183***	-0.178***	—
Processing Performance	0.063***	0.120***	-0.225***

ANNEX A: Verbatim of the questionnaire in experiment 3

Text displayed before the first memory single-task:

“In the following sections, at the end of each trial you will be asked about the strategies that you used to memorize the letters. More specifically, you will be asked about the following strategies:

REHEARSAL, that refers to the repeating of the letters out loud or silently

TEMPORAL CLUSTERING, that refers to the grouping in groups of 2 or 3 letters, without any reference to prior knowledge, for example grouping XQBPWM into XQB and PWM

ELABORATION, that refers to the linking of the letters with previous knowledge. For example, for the letters NHSCLM, one may remember the acronym NHS and/or the word CaLM

ACOUSTIC STRATEGY, that refers to the focusing on the sound of the letters

VISUAL STRATEGY, that refers to the focusing on the visual appearance of the letters (their shape)

MEMORY REDUCTION, that refers to trying to remember only some letters (for example the first 2 or 3 letters) and to not try to remember all of them.

After each trial you will be asked to rate the extent to which you used particular strategies on that trial. For each strategy you will provide a rating of 0%, 25%, 50%, 75%, or 100%. The ratings you give **do not** need to sum up to 100% and should be an estimate of the extent to which you used the strategy in question on that trial.

For example, if you repeated either aloud or in your head the first three letters in a sequence of six you could respond 50% to the rehearsal strategy; or if you did not try to remember the last two letters in a sequence of seven you could respond 25% to the memory reduction strategy. The ratings you give do not have to precisely match the degree to which you used a strategy but should be a rough estimate. Go with your quick intuition or feeling regarding each rating rather than taking a long time to be exact on each one.”

Text displayed before the first processing single-task:

“In the following sections, at the end of each trial you will be asked about the strategies that you used to verify the additions. More specifically, you will be asked about the following strategies:

COUNTING, that refers to the fact to first compute the sum, and then to compare the result with the displayed answer

RETRIEVAL, that refers to relying on intuition or to the fact to just know the additions by heart

PROCESSING REDUCTION, that refers to trying to verify only some additions and/or to guess

After each trial you will be asked to rate the extent to which you used particular strategies on that trial. For each strategy you will provide a rating of 0%, 25%, 50%, 75%, or 100%. The ratings you give **do not** need to sum up to 100% and should be an estimate of the extent to which you used the strategy in question on that trial.

For example, if you computed the sums for 3 additions in a sequence of six you could respond 50% to the counting strategy; or if you did not try to answer the last two additions in a sequence of seven you could respond 25% to the processing reduction strategy. The ratings you give do not have to precisely match the degree to which you used a strategy but should be a rough estimate. Go with your quick intuition or feeling regarding each rating rather than taking a long time to be exact on each one. “

Text displayed before the first dual-task:

At the end of each trial, you will be asked about the strategies that you used to remember the letters AND the strategies that you used to verify the additions

Likert Scales for the memory strategies:

Please answer the following questions as spontaneously and honestly as possible. When you have answered all the questions, press CONTINUE.

In the last trial...

...to which extent did you repeat the letters?

...to which extent did you group the letters? For example, to remember TGPLKM did you group the letters in two groups: TGP and LKM, or perhaps in three groups TG PL KM?

...to which extent did you associate letters with words, known acronyms or nouns to help you remember? For example, for the letters NHSCLM, did you remember the acronym NHS and/or the word CaLM?

...to which extent did you remember how the letters sounded?

...to which extent did you picture the letters (their shape) in your head? For example, for the letters TLGRBS, did you mentally picture the shape of each letter?'

...to which extent did you try to remember only some letters (for example only the first 2 or 3 letters), and did not try to remember all of them?'

Likert Scales for the processing strategies:

Please answer the following questions as spontaneously and honestly as possible. When you have answered all the questions, press CONTINUE.

In the last trial...

...to which extent did you try to compute the sum and then to compare it with the displayed answer?

...to which extent did you answer the additions intuitively or by heart?

...to which extent did you try to solve only some additions and/or did you try to guess?

1334