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1 **The respective contribution of cognitive control and working memory to semantic and**
2 **subjective organization in aging**

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23 **Declaration of interest**

24 None.

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28 **Author Note**

29 The data, the analytic code and the list of words used for the memory tasks used in this
30 article can be found on the Open Science Framework depository at

31 https://osf.io/sbqvp/?view_only=c97a3ff072594934861bc3110d4bc531

32 The findings presented here have not being disseminated elsewhere.

33

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38

39

40 **Abstract**

41 Organizing information is beneficial to episodic memory performance. Among several
42 possible organizational strategies, two consist of organizing the information in semantic
43 clusters (semantic organization) or self-organizing the information based on new associations
44 that do not exist in semantic memory (subjective organization). Here, we investigated in a
45 single study how these two organizational behaviors were underlined by different controlled
46 processes and whether these relations were subjected to age-related differences. We tested
47 123 younger adults ($n = 63$) and older adults ($n = 60$) on two episodic memory tasks, one
48 where the words were organizable and another where the words were not organizable,
49 allowing for semantic and subjective organization, respectively. Additionally, participants
50 were tested on three cognitive control tasks (Wisconsin Card Sorting Test, Stroop Test and
51 Trail Making Test) and three working memory tasks (Backward Digit Span, Alpha Span and
52 N-back test). Results revealed well-established age-related differences in terms of recall
53 performance and organizational strategy implementation. More importantly, we found
54 evidence that the different cognitive tests statistically yielded two different latent factors, a
55 cognitive control factor and a working memory factor. Based on this dissociation, we found
56 that only cognitive control contributed to semantic organization in all age groups whereas
57 only working memory contributed to subjective organization, also in all age groups. These
58 results shed new lights on our understanding of how controlled processes differently
59 contribute to organizational behaviors in episodic memory.

60

61 Key words: semantic organization, subjective organization, cognitive control, working
62 memory, aging

63

64 **Public Significance Statement**

65 This article shows that cognitive control and working memory are dissociable processes
66 based on the cognitive tests used here. Importantly, it was found that these processes
67 contribute differently to different mnemonic organization strategies. Cognitive control
68 contributes more to the organization of words based on their semantic categories whereas
69 working memory contributes more to the self-organization of unrelated words. These
70 findings appear to be found similarly in younger and older adults.

71

72 **Introduction**

73 Episodic memory refers to remembering personal past events associated with their spatial
74 and temporal contexts (i.e., what, when, where; Tulving, 2002). This specific memory system
75 is particularly altered with aging (for reviews, see Nyberg, 2017; Oswald et al., 2020,
76 Rhodes et al., 2019), especially due to a decline in using adapted memory strategies (e.g.,
77 Guerrero Sastoque et al., 2019; Shing et al., 2008; Tacconnat et al., 2009). Indeed, memory
78 strategies are known to increase memory performance when they are used, through semantic
79 processing (e.g., Craik & Lockhart, 1972; Craik & Tulving, 1975), creating mental images of
80 verbal stimuli (e.g., Burger et al., 2017; Paivio & Csapo, 1973), and organizing information
81 (e.g., Bousfield, 1953; Tacconnat et al., 2020). As a function of the nature of the material or of
82 the memory task, a particular strategy can be more or less efficient (for a review, see Froger
83 et al., 2014). For a free recall task, the most difficult episodic memory test, organizing the
84 information is particularly well-adapted to improve performance (e.g., Denney, 1974;
85 Mulligan, 2004; Puff, 1979; Tacconnat et al., 2020; Zaromb & Roediger, 2010). In this study,
86 we investigated the effect of age on the use of two different organizational strategies, namely
87 subjective and categorical organization, as well as their underlying cognitive processes.

88 Two important organizational components affecting the structure of memory retrieval
89 have been highlighted. In free recall tasks, where no cues are provided to aid retrieval,
90 individuals may rely on pre-existing knowledge of semantic relationships (based on semantic
91 memory), which may be present in a list of items, and/or on newly formed contextual
92 associations among the list of items (based on episodic memory). These two organizational
93 strategies are generally expressed by the output order of recall. In the former case, categorical
94 organization leads individuals to recall categorically related words in clusters, even when the
95 items are presented in random order (Bousfield, 1953; Denney, 1974; Frick et al., 2022;
96 Romney et al., 2016; Sauz on et al., 2006; Tacconnat et al., 2009, 2020). Contrastingly, in the

97 latter case, episodic memory makes individuals to engage in a subjective organization of a
98 list of unrelated items (i.e., items not constrained by pre-existing categorical or associative
99 relations), as evidenced by the tendency to recall consecutively the same words across
100 successive recall trials (Sauz on et al., 2006; Sternberg & Tulving, 1977; Tacconnat et al.,
101 2020; Tulving, 1962). Note that it is also possible that individuals use subjective organization
102 when items are categorically associated, and that they could also use a “subjective semantic”
103 organization to learn an unrelated word-list, although these cases are not addressed here and
104 are beyond the scope of the current paper. Critically, the use of either organizational strategy
105 is dependent upon the materials to be learnt and the methodological procedure of the memory
106 test. Indeed, if the items are not categorically associated, then subjective organization based
107 on personal associations is possible, but not categorical organization. Moreover, contrary to
108 categorical organization which needs only one trial to be assessed, subjective organization
109 needs several trials to be examined (Sternberg & Tulving, 1977).

110 In aging, a decrease of organizational processes is classically observed, but subjective
111 organization seems to be more impaired than categorical organization (hereafter termed
112 semantic organization). Indeed, to our knowledge, all studies tackling subjective organization
113 have reported a negative effect of age on this process (e.g., Hultsch, 1974; Kausler, 1994;
114 Light, 1991; Sauz on et al., 2006; Stuss et al., 1996; Tacconnat et al., 2020; Witte et al.,
115 1990). Conversely, findings have been mixed for semantic organization with some studies
116 reporting impairments with age (Denney, 1974; Froger et al., 2009; Howard et al., 1981;
117 Tacconnat et al., 2020; West & Thorn, 2001; Zivian & Darjes, 1983), or only in very old age
118 (Cherry et al., 2012), while others revealed no such effect (Park et al., 1989; Rankin et al.,
119 1984; Sauz on et al., 2006, 2016). These declines are likely due to the alteration of prefrontal
120 cortex (PFC) functioning during aging (Raz, 2000, 2005). Indeed, this brain area is known to
121 be critical for the implementation of organizational strategies as evidenced by neuroimaging

122 data (Blumenfeld & Ranganath, 2006; Kirchoff et al., 2014) as well as neuropsychological
123 and behavioral data showing lower mnemonic organizational processes in patients with
124 frontal lesions (Gershberg & Shimamura, 1995; Kramer et al., 2005; Rocchetta & Milner,
125 1993) or with lower frontal activities such as depressed patients (Taconnat et al., 2010).

126 The PFC underlies both cognitive control (e.g., Yuan & Raz, 2014) and working
127 memory (e.g., Barbey et al., 2013), suggesting that these two controlled processes play a key
128 role for the implementation of organizational strategies. Critically, age-related decline is
129 observed in cognitive control, also termed as executive functions (e.g., Ferguson et al., 2021;
130 Taconnat et al., 2022) as well as in working memory capacities (e.g., Fabiani et al., 2016;
131 Hasher & Zacks, 1988; Salthouse, 1994). Age-related decline in cognitive control and in
132 working memory could contribute to lower episodic memory performance in older adults
133 (e.g., Angel et al, 2011; Bouazzaoui et al., 2014; Taconnat et al., 2022 for research on the
134 relationships between executive functions and episodic memory, and for research on the
135 relationships between working memory and episodic memory, see Bender & Raz, 2012; Hara
136 & Naveh-Benjamin, 2015). Although cognitive control and working memory are often
137 associated and share a common underlying executive attention component (McCabe et al.,
138 2010; and see Guerrero et al., 2022, for a discussion on this point), they may not represent
139 the same capacities. Indeed, while both cognitive control and working memory are goal-
140 directed processes regulating information, only working memory comprises a storage
141 component to attain goals (Friedman et al., 2006; Friedman & Miyake, 2017; Miyake et al.,
142 2000; Miyake & Friedman, 2012). At the brain level, the mid-ventrolateral region of the PFC
143 cortex has been shown to support the organization of information retrieved from posterior
144 areas (semantic memory), whereas the mid-dorsolateral region supports the active
145 manipulation stored in working memory (Owen et al., 1999; 2005), suggesting that distinct
146 areas of the frontal lobes are differently implicated in cognitive control and working memory.

147 Importantly, recent behavioral research on individual differences has shown the three core
148 components of cognitive control (shifting, inhibition, updating; Miyake et al., 2000) are not
149 related to working memory capacity (Frischkorn et al., 2019; Frischkorn et al., 2022; Rey-
150 Mermet et al., 2019; but see also Draheim et al., 2021).

151 Semantic organization could be especially rooted in cognitive control processes
152 related to the retrieval of semantic knowledge (i.e., semantic categories) whereas subjective
153 organization could be associated to the integration and storage of information entering
154 working memory. For example, Tacconnat et al. (2009) showed that a decline in cognitive
155 control was associated with semantic organization impairments in older adults (see also
156 Tacconnat et al., 2010, for an experiment in depressive patients with low cognitive control).
157 Note that in their study, the authors did not explore the role of working memory in semantic
158 organization. Thus, the relations between cognitive control and semantic clustering found by
159 Tacconnat et al. (2009) does not preclude a relation between working memory and semantic
160 clustering. In another study, Kuhlman and Touron (2016) explored the link between semantic
161 organization and working memory. They asked participants to learn an organizable wordlist
162 without specific instruction about a possible organization of the words (i.e., spontaneous
163 semantic organization), or telling participants that the words belonged to a few semantic
164 categories and that using these categories could facilitate learning and word recall (i.e.,
165 instructed semantic organization). Their results showed that only the instructed semantic
166 organization condition was associated to working memory. It is possible that individuals
167 engage more effort during instructed semantic organization than spontaneous semantic
168 organization as they are aware of the best strategy to adopt in advance in order to facilitate
169 recall. Although hypothetical, this would explain why the former type of semantic
170 organization is associated to working memory but not the latter. However, in a recent study,
171 Cherry et al. (2021) found that semantic organization was associated to working memory

172 although the participants were not provided with clustering instructions. Thus, it is not clear
173 whether spontaneous semantic organization is closely associated to working memory or not.

174 No study has directly explored the cognitive mechanisms underlying subjective
175 organization. This strategy relates to subjectively forming new associations between
176 semantically unrelated items. This ability to create new associations in episodic memory,
177 necessary for subjective organization, could be closely linked to associative memory.
178 Associative memory involves binding unrelated items into a coherent memory episode.
179 According to the *Associative Deficit Hypothesis* (Chalfonte & Johnson, 1996; Naveh-
180 Benjamin, 2000), older adults have particular difficulties in encoding or retrieving the
181 associations among the components of memories, which would explain in part the age-
182 related decline in episodic memory. Reduced associative memory in older adults (e.g.,
183 Bender et al., 2010; Mitchell et al., 2000; Naveh-Benjamin, 2000) could be due to a deficit in
184 cognitive resources, such as attentional processes (Kilb & Naveh-Benjamin, 2007) or
185 working memory (Bender & Raz, 2012; Hara & Naveh-Benjamin, 2015). Though working
186 memory has not always been associated with episodic memory, in particular associative
187 memory (see Bartsch et al., 2019), there are nevertheless reasons to suspect that working
188 memory might be crucial for subjective organization as working memory contributes to
189 associative memory.

190 In the present study, we investigated semantic organization and subjective
191 organization with two free-recall memory tasks, and their relationship with cognitive control
192 and working memory measures in younger and older adults. Therefore, our general research
193 question was to examine whether cognitive control and working memory contribute
194 differently to organizational behaviors in episodic memory and whether their contributions
195 are subjected to age-related changes. The prerequisite, in order to achieve our objectives, will
196 be to first verify that the measures of working memory and cognitive control actually

197 measure two independent cognitive components. To answer these questions, we derived two
198 confirmatory (1 and 2) and three exploratory (3, 4 and 5) hypotheses, which are described
199 below. We first sought to replicate well-established findings with younger adults showing
200 better recall, semantic and subjective organization (e.g., Sauz on et al., 2006; Taconnat et al.,
201 2020; Hypothesis 1) as well as higher cognitive control and working memory performance
202 than older adults (e.g., Braver, 2008; Rhodes et al., 2019 ; Hypothesis 2). Then, we tested the
203 participants with six cognitive tests that are theoretically designed to tap either cognitive
204 control or working memory. This allowed us to statistically test that cognitive control and
205 working memory are two distinct controlled processes (Hypothesis 3). Based on this
206 dissociation, we predicted that semantic organization would be mainly underlined by
207 cognitive control, in accord with previous research (e.g., Taconnat et al., 2009), whereas
208 subjective organization would be mostly sustained by working memory consistent with
209 studies that showed that associative memory would be linked to working memory (e.g.,
210 Bender & Raz, 2012; Hara & Naveh-Benjamin, 2015; Hypothesis 4). This result would also
211 be in line with the findings of neuroimaging studies which reported that working memory
212 could contribute to episodic memory through its role in managing the relationships between
213 items. This would promote the strengthening of inter-item association, leading on to
214 improving episodic memory, in accord with the idea that associative memory is a major
215 component of episodic memory functioning (e.g., Chalfonte & Johnson, 1996; Naveh-
216 Benjamin, 2000). Finally, we predicted the contributions of cognitive control and working
217 memory to these organizational processes could be subjected to age-related differences
218 (Hypothesis 5).

219 **Method**

220 *Transparency and Openness*

221 The data, the analytic code (written in R) and the list of words used for the memory
222 tasks can be found on the Open Science Framework depository at
223 https://osf.io/sbqvp/?view_only=c97a3ff072594934861bc3110d4bc531

224 The study design, hypotheses and analytic plan were not preregistered.

225 *Participants*

226 Based on previous studies from our research group (e.g., Taconnat et al., 2009), a
227 total of 130 healthy French younger and older adults living in a medium-sized metropolitan
228 area (Tours, France) were recruited, to ensure having 65 participants per age group.

229 All older participants lived at home and were recruited from leisure clubs and the
230 Senior Citizens' University. The younger participants were recruited from leisure clubs and
231 through referrals by the older participants. In order to minimize a possible cohort effect and
232 because none of the older adults had a high level of education, none of the younger
233 participants were recruited from higher education institutions. Participants were all
234 volunteers and were individually interviewed to exclude those with a history of alcoholism,
235 undergoing treatment for psychiatric illness, or taking psychoactive medication. The older
236 adults were also screened on the Mini Mental State Examination (MMSE; Folstein et al.,
237 1975), with the cut-off threshold set at 27 points to minimize the risk of including people
238 with pre-clinical dementia. Participants were mostly Caucasian, although this information
239 was not systematically collected. This research was approved by the Ethic Committee of the
240 Department of Psychology from the University of Tours (Title: *Corrélats cognitifs des*
241 *stratégies de mémoire au cours du vieillissement*).

242 No power analysis was run prior to data collection. Nevertheless, we conducted an *a*
243 *posteriori* sensitive power analysis to interpret near significance effects (see Discussion).

244 From the total sample, three participants (two younger adults and one older adult)
245 were excluded because they were on medications, two other older adults whose scores at the

246 MMSE were below 27 points were removed from the sample as well as an additional two
 247 older adults whose recall scores did not allow the computation of organizational scores as
 248 these scores were too low. Therefore, the final sample consisted of 123 participants with 63
 249 younger adults (aged from 20 to 34 years-old; 33 women) and 60 older adults (aged from 60
 250 to 80 years-old; 35 women). As reported in Table 1, the two groups were matched on their
 251 performances on the Mill-Hill vocabulary test (Raven, 2000), number of years of formal
 252 education, self-reported health score (measured by using a five-point scale from 0 (bad
 253 health) to 5 (very good health) and depression and anxiety scores on the HADS (Hospital
 254 Anxiety and Depression Scale; (Zigmond & Snaith, 1983).

255

256 Table 1: Demographic characteristics of each age group.

	Younger (n= 63)	Older (n= 60)	t (121)
Age	25.82 (3.49)	71.5 (3.94)	67.95 ***
Educational level	12.62 (1.83)	11.92 (2.83)	1.63 (p=.107)
Vocabulary	25.31 (3.32)	26.36 (3.42)	1.72 (p=.087)
Subjective Health	3.82 (.90)	3.88 (.88)	.36 (p = .720)
Depression	5.98 (2.53)	6.30 (2.82)	.65 (p=.515)
Anxiety	6.38 (2.70)	5.48 (3.16)	1.69 (p=.093)

257 Note: *** = $p < .001$

258

259 *Materials and procedure*

260 The experiment was conducted in two sessions, 3 to 5 days apart depending on the
 261 participants' availability, and no participant dropped out of the study. During the first
 262 session, participants were screened and interviewed. They performed one of the episodic
 263 memory tasks (list of organizable words or list of non-organizable words) and about half of
 264 the battery of the cognitive tests. During the second session, they completed the other
 265 episodic memory task and the remaining tests from the cognitive test battery. The episodic
 266 memory tasks and cognitive tests were counter-balanced across participants.

267

268 *Episodic memory tasks*269 *Organizable words-based episodic memory task and semantic organization*

270 Participants were shown once a categorized 20-word list (five categories of four

271 words, see Tacconnat et al., 2020). The words were arranged and presented in pseudo-random

272 order so that two words from the same category were never presented sequentially.

273 Participants were not informed about the possible structuring of lists. The words for the five

274 categories were selected from a table (Marchal & Nicolas, 2003) which was constructed from

275 category classes generated by young and older adults. The categories were matched with

276 respect to word length, word frequency (Brulex database, (Content et al., 1990) and typicality

277 of semantic category, similar for both younger and older adults. The words were 5-8 letters

278 long, with 2-3 syllables, and were all concrete nouns. The stimuli were presented on a

279 computer screen, for five seconds each. After the list presentation, participants performed a

280 letter comparison task (XO) for 45 seconds. This task served as an interference task to

281 prevent the recency effect. After the XO task, the participants were asked to say as many

282 words as they could recall, and the recalled words were recorded by the experimenter. In this

283 way, any difficulty in writing was avoided, particularly in older adults. The participants were

284 asked to recall the list three times without re-learning it, with 30 seconds between each

285 repetition, with the aim of evaluating the evolution or stability of memory and clustering

286 across time. At the end of encoding and recall, participants relaxed for a few minutes before

287 taking the remaining tests.

288 The *Adjusted Ratio Clustering* score (ARC) developed by (Roenker et al., 1971) was

289 used as a measure of semantic organization at recall. A score of 0 indicates chance clustering

290 and a score of 1 refers to perfect clustering. It is computed according to the following

291 formula:

292
$$ARC = \frac{R - E(R)}{\max R - E(R)}$$

293 “...where R is the total number of category repetitions, $\max R$ is the maximum possible
 294 number of category repetitions, and $E(R)$ is the expected (chance) number of category
 295 repetitions” (Roenker et al., 1971, p. 46).

296 This adjusts for the differences in total number of items recalled which is important
 297 considering that young adults are likely to recall more words than older participants. Thus,
 298 ARC scores are relatively independent of the recall score, inasmuch as a low score at recall
 299 may lead to a high ARC score if the few words are recalled in an organized fashion.

300 *Non-organizable words based episodic memory task and subjective organization*

301 Participants were shown once a non-categorizable 20-word list comparable to the
 302 organizable list with respect to word length and word frequency (Brulex data base, Content et
 303 al., 1990, and see Taconnat et al., 2020 for the use of the same list). The same procedure as
 304 the organizable words-based episodic memory task was used in respect of the time of
 305 presentation of the items, the interference task, and the three free-recall tasks with an interval
 306 of 30 seconds between each.

307 The Pairwise Frequency scores (PF): Subjective clustering across free-recall trials
 308 (Anderson & Watts, 2013 ; Sternberg & Tulving, 1977) were calculated according to the
 309 following formula:

310
$$PF = O(ITR) - E(ITR)$$

311 where $O(ITR)$ corresponds to the number of item pairs recalled commune to two successive
 312 trials whatever the order of recall of these two items, $E(ITR)$ is the expected value of the
 313 number of intertrial repetitions and is calculated as follows:

314
$$E(ITR) = \frac{c(c-1)}{hk}$$

315

316 where with c corresponding to the number of items recalled both to trial t and trial $t+1$, h
317 corresponding to the total number of words recalled, at trail t , and k corresponding to the
318 number of total words recalls at trial $t+1$. According to this formula, the higher the index, the
319 better the organization.

320 The coding of the ARC and PF scores was done by one of the authors, and thus was
321 not blind to the experimental conditions.

322 *Cognitive Assessment*

323 Six cognitive test scores were selected, designed specifically to evaluate different
324 cognitive control and working memory processes. These tests have been chosen as they are
325 classically used by the one hand to assess cognitive control, requiring cognitive control but
326 not storage in memory, and by the other hand, target working memory, because they
327 necessitate both storage and manipulation of the information to be processed.

328 *Cognitive control*

329 *Wisconsin Card Sorting Test (WCST; Heaton et al., 1993)*. This test assesses general
330 cognitive control and was administered and scored according to the standard procedure using
331 a pack of 64 cards. The specific measure retained here was the number of perseverative
332 errors, which are those most affected by age and the most representative of cognitive control
333 (Miyake et al., 2000). Perseveration reflects difficulty in adaptively discontinuing a prepotent
334 response or use of a previously reinforced strategy when its use is no longer beneficial. A
335 high score on this test reflects low performance.

336 *Stroop Color-Word Test (SCWT; (Stroop, 1935)*. Two sub-tests of the standard
337 SCWT assessing inhibition were used: the color sub-test in which participants have to name
338 the color of crosses (XXX), and the color-word interference sub-test in which they have to
339 name the color of color-words while ignoring the printed word. In each sub-test, participants
340 were required to name colors aloud as quickly as possible for 45 seconds, and the number of

341 correct responses was recorded. Taking the crosses condition as the baseline, scores were
 342 transformed into proportion scores for each participant as follows:

$$343 \quad \frac{(\textit{ColourNaming score}) - (\textit{ColourWordInterference score})}{\textit{ColourNaming score}}$$

344 *Trail Making Test (TMT; Reitan, 1958)*. The TMT, which assesses shifting, includes
 345 two parts: A and B. In part A, the participants have to connect digits in ascending order. In
 346 part B, the participants have to alternately connect letters in alphabetical order and digits in
 347 ascending order (e.g., 1A2B3C, etc.). Performance was measured by the time necessary to
 348 complete each part of the task. A flexibility score was calculated by applying the following
 349 formula:

$$350 \quad \frac{(\textit{Completion time for part B}) - (\textit{Completion time for part A})}{\textit{Completion time for part A}}$$

351 *Working memory*

352 *N-back task* (Kirchner, 1958, Leon-Dominguez et al., 2015). In this task, the
 353 participant views 30 letters (consonants) displayed on a computer screen, one at a time. From
 354 the third letter, participants had to make decisions (“same” or “different”) about the stimulus
 355 they saw “2-back” as each new stimulus was presented. Participants were requested to give
 356 their answer verbally, and the experimenter recorded the answers. The score was the number
 357 of correct answers.

358 *The Backward Digit Span* (Hilbert et al., 2015 ; Wechsler, 2008; Yoshimura et al.,
 359 2021). Testing procedure for the Digit Span task was followed according to the standard
 360 administration from the Weschler Adult Intelligence Scale (WAIS), that is, strings of digits
 361 are read to subjects at a rate of 1 per second and the subject is asked to repeat them orally in
 362 the correct sequence (either forward or backward order). The number of digits in each string
 363 increases from 2 to 8. The test is stopped when the participant consecutively fails two trials.

364 Total score corresponded to the maximum number of digits the participant was able to repeat
 365 correctly.

366 *The Alpha Span Test* (Craik et al., 2018). In this task, 14 lists of common one-syllable
 367 words were used. The lists varied in length from 2 to 8 words, and there were two lists of the
 368 same length. Presentation started with the list length of two words and increased to one word
 369 unless participants failed on both lists of the same length. On each trial, the participant's task
 370 was to rearrange the words mentally and recall them orally in alphabetical order. The score
 371 was the number of items recalled as a member of a correctly recalled adjacent pair.

372 *Data analyses*

373 Data were analyzed using R version 4.1.0 (Team R Core, 2021). We first analyzed
 374 age-related differences on recall (number of words) and ARC and PF using Linear Mixed
 375 Model (LMM; Hypothesis 1). First of all, on recall, we fit a LMM with age group (younger
 376 adults, older adults) as a between-subjects factor, memory task (organizable, non-
 377 organizable) and trial number (1, 2, 3) as within-subject factors and Participants as a random
 378 factor. This model was fit with the *lme4* and *afex* packages (Bates et al., 2015; Singmann et
 379 al., 2020). We then examined the effects of age group and memory task on semantic
 380 organization using the variable ARC as dependent variable. As this variable comprises scores
 381 from 0 and 1 and included 0 and/or 1, this was not suitable to be fit using a GLMM with a
 382 Binomial distribution. As such, we used a Beta Regression (Ferrari & Cribari-Neto, 2010)
 383 and to account for 0 and 1 values, we applied the following transformation:

$$384 \quad \frac{(y(n-1))+0.5}{n}$$

385 where n is the sample size (Smithson & Verkuilen, 2006)

386 This Beta Regression was fit using the *betareg* package (Cribari-Neto & Zeileis,
 387 2010). Following this analysis, we examined the effects of age group and inter-trial (first trial
 388 to second trial or 1-2 inter-trial — second trial to third trial or 2-3 inter-trial) – but not trial

389 number as for ARC, given that PF needs at least two trials to be computed – as between-
390 subjects and within-subject factors and Participant as random factor on subjective
391 organization (PF) using another LMM. For all the analyses described above, the package
392 *emmeans* (Lenth, 2020) was used to perform the pairwise comparisons with Tukey
393 adjustments when there were multiplicity issues.

394 Age-related differences on the different cognitive tests (cognitive control and working
395 memory) were analyzed using t-tests (Hypothesis 2).

396 We then conducted a Structural Equation Modelling (SEM) analysis using the
397 package *lavaan* (Rosseel, 2012) to examine whether the cognitive tests were representative
398 of cognitive control and working memory (Hypothesis 3). To do so, we fit and compared two
399 SEM models where all cognitive tests (observed variables) accounted for one latent variable
400 (model 1) and where the WCST, SCWT and TMT loaded onto one latent variable (cognitive
401 control) and the N-Back test, Digit Span and Alpha Span loaded onto another latent variable
402 (working memory; model 2). From this analysis, we then took the best model to test how the
403 latent variable(s) was/were predicted of recall in both memory tasks (organizable, non-
404 organizable), semantic organization (ARC) and subjective organization (PF) using a third
405 SEM model (Hypothesis 4). The fit of the different models was assessed using the
406 comparative fit index (CFI) and the Akaike Information Criterion (AIC). The CFI has a value
407 ranging from 0 to 1 that indicates the proportion of improvement in the overall fit of the
408 hypothesized model relative to a null model in which all covariances between variables are
409 zero and this value should be ideally around or greater than .95 (Bentler, 1990 ; Hu &
410 Bentler, 1999).

411 Finally, we performed multiple linear regressions on the *average scores* of ARC and
412 PF with the cognitive control index and the working memory index as continuous factors and
413 age group as a categorical factor to explore to what extent these indices predicted the use of

414 these two organizational behaviors and whether there were age-related differences
 415 (Hypothesis 5). To this aim, we fit two models with these three main factors (cognitive
 416 control index, working memory index and age group) as well as the two two-way interactions
 417 of interest, which were between cognitive control index and age group and working memory
 418 index and age group. We fit the regression models with the z -scores of the cognitive control
 419 and working memory indices as they provided less collinearity issues than the latent factor
 420 scores, which was checked with the function *VIF* from the *regclass* package. For these
 421 regression models, we were interested in the main effects of age group, cognitive control
 422 index, working memory index and the two two-way interactions between cognitive control
 423 index and age group, and working memory index and age group.

424 **Results**

425 *Hypothesis 1: Age-related effects on recall*

426 The analyses revealed main effects of age group, $\chi^2 = 63.73$, $df = 1$, $p < .001$, memory
 427 task, $\chi^2 = 285.30$, $df = 1$, $p < .001$, and trial number, $\chi^2 = 10.54$, $df = 2$, $p = .005$, on recall.

428 Younger adults recalled more words than older adults ($M_{\text{younger adults}} = 10.30$ vs. $M_{\text{older adults}} =$
 429 7.10) and recall was higher in the organizable words memory task than in the non-
 430 organizable words memory task ($M_{\text{organizable words}} = 10.21$ vs. $M_{\text{non-organizable words}} = 7.21$).

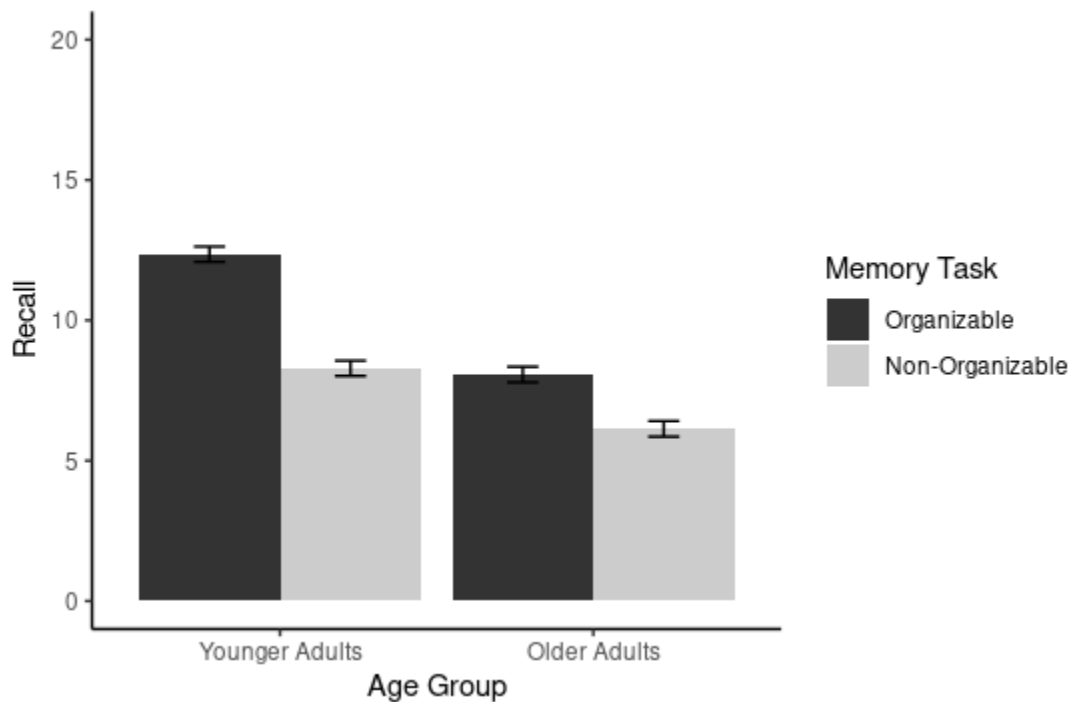
431 Regarding the effect of trial number, participants had a higher recall performance in the first
 432 trial than in the two next trials ($M_{\text{first trial}} = 9.07$ vs. $M_{\text{second trial}} = 8.56$ vs. $M_{\text{third trial}} = 8.50$; $ps <$
 433 .023), and no difference was observed between the second and third trials, $p = .954$.

434 These effects were qualified by a significant two-way interaction between age group
 435 and memory task, $\chi^2 = 44.18$, $df = 1$, $p < .001$, revealing that younger and older adults
 436 recalled more words in the words organizable memory task than in the words non-
 437 organizable memory task (younger adults: $M_{\text{organizable words}} = 12.35$ vs. $M_{\text{non-organizable words}} =$
 438 8.29; older adults: $M_{\text{organizable words}} = 8.07$ vs. $M_{\text{non-organizable words}} = 6.13$; $ps < .001$), the

439 difference was more pronounced for younger adults than for older adults as evidenced by t-
 440 ratios (18.33 vs. 8.51). Moreover, in both memory tasks, younger adults recalled more words
 441 than older adults, $ps < .001$, but this was especially the case for the organizable memory task
 442 (Figure 1).

443 No other interactions were significant, $ps > .061$.

444



445

446 Figure 1. Recall as a function of age group and memory task. Both younger and older adults
 447 recalled more words in the words organizable memory task than in the words non-
 448 organizable memory task, although this was more pronounced for younger adults.

449

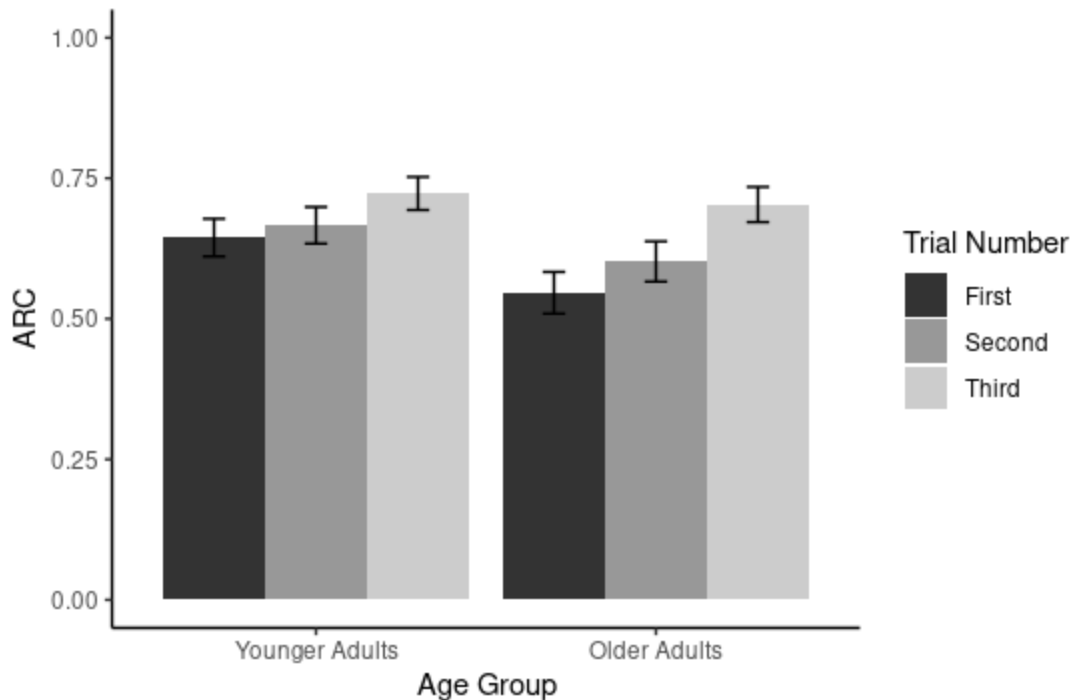
450 *Hypothesis 1: Age-related effects on ARC*

451 On semantic organization (ARC), there were main effects of both age group, $\chi^2 =$
 452 4.68, $df = 1$, $p = .030$, and trial number, $\chi^2 = 12.88$, $df = 2$, $p < .001$, indicating that younger
 453 adults had slightly higher semantic organization than older adults ($M_{\text{younger adults}} = .68$ vs.

454 $M_{\text{older adults}} = .62$), and semantic organization was not significantly different from the first to
 455 the second, but was significant from the second to the third trial ($M_{\text{first trial}} = .60$ vs. $M_{\text{second trial}}$
 456 $= .63$ vs. $M_{\text{third trial}} = .71$; $p = .502$ and $p = .036$; Figure 2).

457 The interaction between age group and trial number was not significant, $p = .563$.

458



459 Figure 2. ARC as function of age group and trial number. Semantic organization was slightly
 460 higher for younger adults than older adults and was only significantly higher from the second
 461 to the third trial.

462

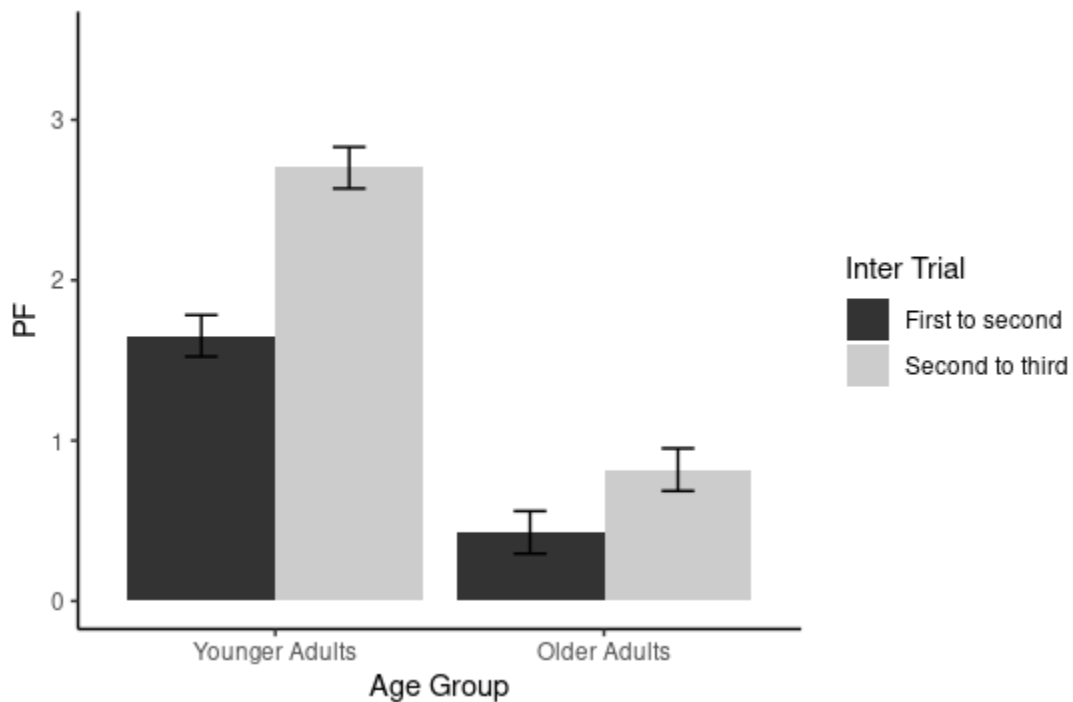
463 *Hypothesis 1: Age-related effects on PF*

464 On subjective organization (PF), there were main effects of age group, $\chi^2 = 73.87$, df
 465 $= 1$, $p < .001$, and inter trial, $\chi^2 = 43.13$, $df = 1$, $p < .001$, indicating that younger adults had
 466 higher subjective organization than older adults ($M_{\text{younger adults}} = 2.17$ vs. $M_{\text{older adults}} = .62$), and
 467 subjective organization was higher in the 2-3 inter trial than in the 1-2 inter-trial ($M_{1-2 \text{ inter-trial}}$
 468 $= 1.04$ vs. $M_{2-3 \text{ inter-trial}} = 1.76$). However, the significant two-way interaction between age

469 group and inter trial, $\chi^2 = 10.32$, $df = 1$, $p = .001$, indicated that subjective organization
 470 increased more between inter trial 1-2 and inter trial 2-3 in younger adults than in older
 471 adults (younger adults: $M_{1-2 \text{ inter-trial}} = 1.65$ vs. $M_{2-3 \text{ inter-trial}} = 2.70$; $p < .001$; older adults: (M_{1-2}
 472 $\text{inter-trial} = .42$ vs. $M_{2-3 \text{ inter-trial}} = .82$; $p = .007$; Figure 3).

473

474



475 Figure 3. PF score as a function of age group and inter-trial. Both age groups showed higher
 476 subjective organization in the second to third inter-trial than in the first to second inter-trial,
 477 but this was more pronounced for younger adults than older adults.

478

479 *Hypothesis 2: Age-related effects on the cognitive tests*

480 As shown in Table 2, the effect of age group was significant on all the cognitive control
 481 and working memory measures, which is in accord with the classical pattern of cognitive aging.

482

COGNITIVE CONTROL AND WORKING MEMORY IN MEMORY ORGANIZATION

483 Table 2. Comparisons between means (and SD) scores of cognitive control (Perseverative
 484 errors for the WCST; the Inhibition Index for the SCWT; the Flexibility Index for the TMT)
 485 and working memory (Correct Answers for the N-Back; Number of Digits Correctly Recalled
 486 for the Digit Span backward; Total of Items Recalled for the Alpha span) measures in younger
 487 and older adults.

	Younger (n=63)	Older (n=60)	t (121)
Cognitive control			
WCST	8,92 (3,97)	22,36 (16,56)	6,12***
SCWT	0,47 (0,11)	0,60 (0,12)	6,36***
TMT	30,71 (11,12)	74,18(61,09)	5,43***
Working Memory			
N-Back	7,71 (1,49)	5,00 (1,16)	11,31***
Digit Span backward	7,95 (2,14)	5,65 (1,29)	7,28***
Alpha span	7,79 (1,36)	4,85 (1,34)	12,11***

488 Note: WCST: Wisconsin Card Sorting Test; SCWT Stroop Color-Word Test; TMT: Trail
 489 Making Test; *** = $p < .001$

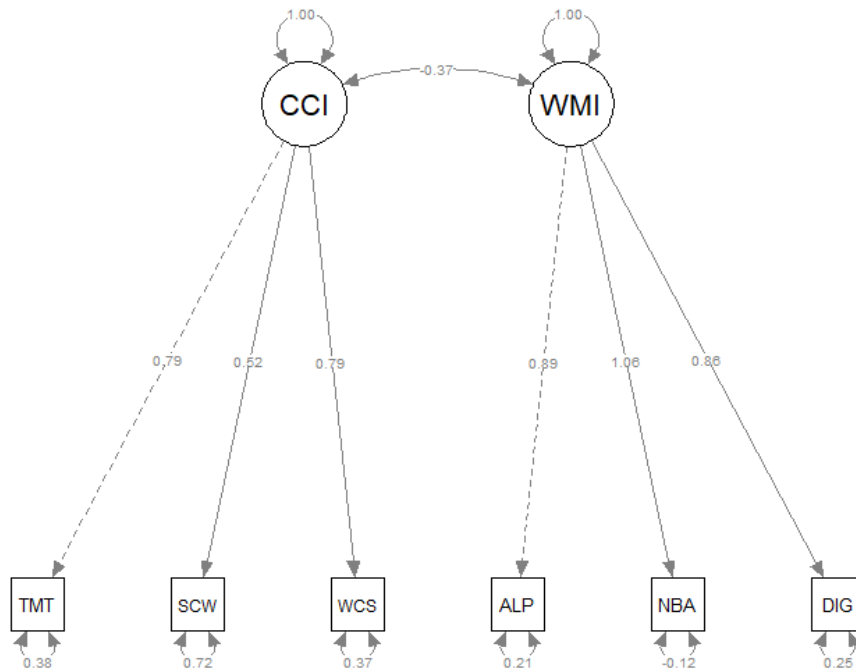
490

491 *Hypotheses 3 and 4: Structural Equation Modelling analyses*

492 The model fit indices for Model 1 (all variables loading to a single factor) indicate a
 493 poor fit to the data: CFI = .855, RMSEA = .300 and SRMR = .197. We therefore ran Model 2
 494 (WCST, SWT and TMT loading onto one cognitive control variable and N-Back test, Digit
 495 Span and Alpha Span loading onto another working-memory variable), which showed a
 496 better fit to the data (Model 1: AIC = 1552.5, $\chi^2 = 108.404$; Model 2: AIC = 1476.8, $\chi^2 =$
 497 30.609), $\chi^2 = 77.796$, $p < .001$, with better fit indices (Model 2: CFI = .967, RMSEA = .152
 498 and SRMR = .110) and indicated that WCST, SWT and TMT significantly contributed to the

499 cognitive control latent variable ($ps < .001$) whereas the N-Back, Digit Span and Alpha Span
 500 contributed significantly to the working memory latent variable ($ps < .001$; see Figure 4).

501



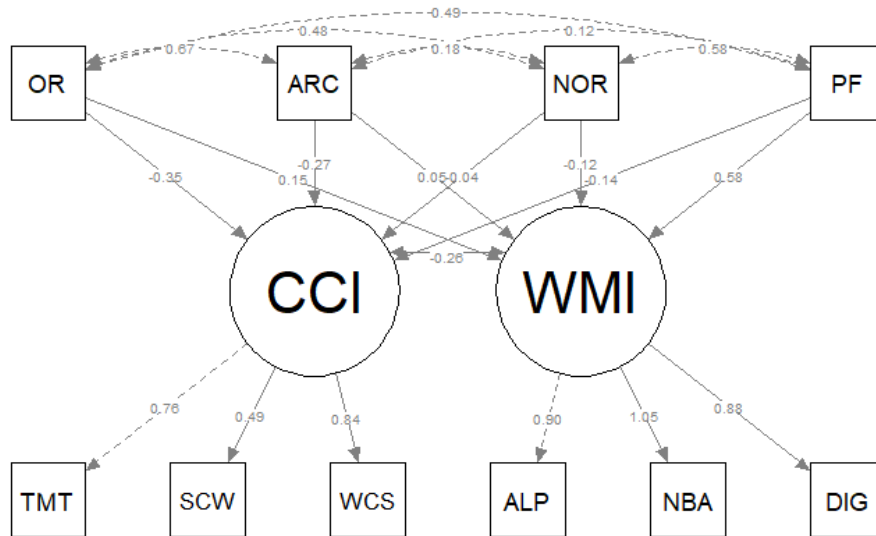
502

503 Figure 4. Plot of the SEM model comprising one cognitive control latent index variable
 504 (CCI) and another working memory index latent variable (WMI). The dashed line indicates
 505 that the loading factors were fixed at a scale of 1.

506

507 Based on Model 2, we fit another SEM model (Model 3) where we added the
 508 regressions factors of organizable recall, ARC, non-organizable recall and PF to the cognitive
 509 control and working memory latent variables. In this model (CFI = .927, RMSEA = .144 and
 510 SRMR = .080), organizable recall and ARC were predicted by cognitive control, $z = -2.47$, p
 511 = .014 and $z = -2.26$, $p = .024$, respectively, but not by working memory, $ps > .095$. Finally,
 512 working memory predicted only PF, $z = 6.82$, $p < .001$, but not other regression factors $ps >$
 513 .080 (Figure 5).

514



515

516 Figure 5. Plot of the SEM model comprising one cognitive control index latent variable
 517 (CCI) and another working memory index latent variable (WMI) and the four regression
 518 factors organizable recall (OR), ARC, non-organizable recall (NOR) and PF. The dashed line
 519 indicates that the loading factors were fixed at a scale of 1.

520

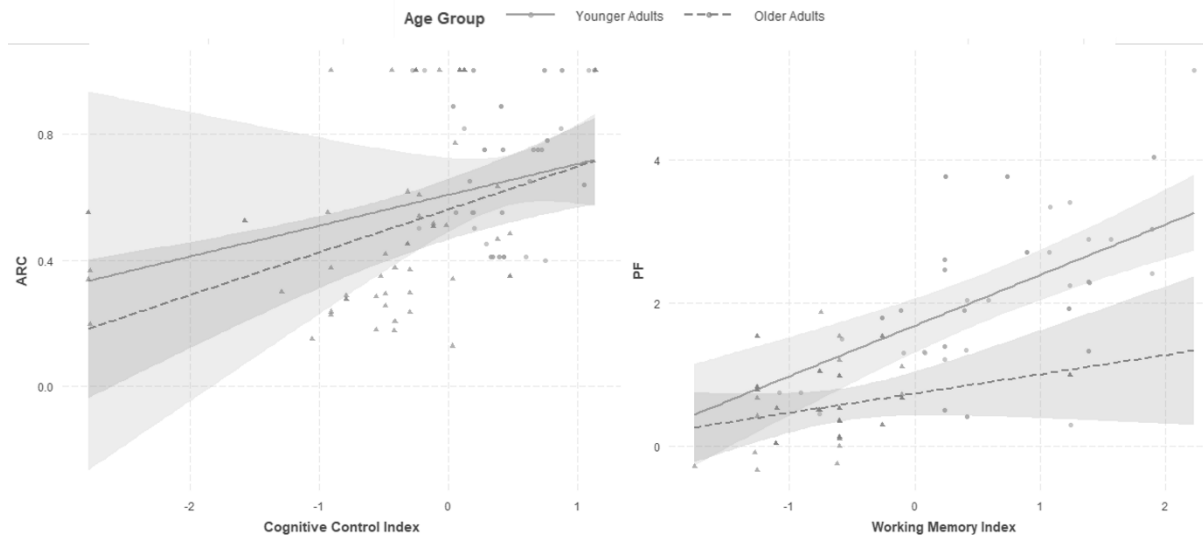
521 *Hypothesis 5: Regression analyses on semantic and subjective organization*

522 Cognitive control and working memory indices explained a significant proportion of
 523 variance in semantic organization (ARC) scores, $R^2 = .18$, $F(5, 117) = 5.41$, $p < .001$. the
 524 model revealed a significant main effect of cognitive control index, $F(1,117) = 13.61$, $p =$
 525 $.003$, partial $\eta^2 = .17$, but no other main effects, $ps > .694$, and no significant interactions, ps
 526 $> .083$. Overall, the higher their cognitive control abilities, the more participants engaged in
 527 semantic organization (ARC), (Figure 6, left panel).

528

529

530



531

532 Figure 6. ARC as a function of age group and the cognitive control index (left) and of age
 533 group and working memory index (right). ARC was associated with higher cognitive control
 534 indices for all participants, and PF tended to be more associated with the working memory
 535 index for all participants.

536

537 Cognitive control and working memory indices explained a significant proportion of
 538 variance in subjective organization (PF scores), $R^2 = .57$, $F(5, 117) = 30.91$, $p < .001$. The
 539 model yielded significant main effects of age group, $F(1,117) = 21.30$, $p < .001$, partial η^2
 540 = .15, and working memory index $F(1,117) = 27.60$, $p < .001$, partial $\eta^2 = .44$, but not of
 541 cognitive control index, $p = .327$. This indicated that younger adults ($M = 1.69$) had a higher
 542 use of subjective organization than older adults ($M = .74$) and the use of this strategy in both
 543 age groups was positively associated with higher working memory indices. No interactions
 544 were significant, $ps > .054$.

545 **Discussion**

546 In the present study, we investigated how two organizational strategies (semantic and
 547 subjective organization) were underlined by different controlled systems (cognitive control

548 and working memory) and to what extent these relations were subjected to potential age-related
549 effects.

550 To begin with, in line with our general predictions, we replicated many previous
551 findings with younger adults recalling more words than older adults in the two wordlists
552 (organizable and non-organizable, Hypothesis 1; e.g., Nyberg, 2017; Oswald et al., 2020;
553 Rhodes et al., 2019) and the former outperforming the latter in all cognitive control and
554 working memory measures (Hypothesis 2; e.g., Braver, 2008; Rhodes et al., 2019). Regarding
555 task-related findings, consistent with the literature, we found that participants recalled more
556 words from the organizable wordlist than from the non-organizable wordlist regardless of their
557 age (Bäckman & Wahlin, 1995; Herlitz & Viitanen, 1991; Sauz on et al., 2006; Stuss et al.,
558 1996), and there was an overall decrease in recall performance from the first trial to the two
559 next trials (Taconnat et al., 2020).

560 Regarding organizational behaviors (Hypothesis 1), we observed that younger adults
561 showed both higher semantic and subjective organization than older adults, though with some
562 differences. Indeed, the difference between the two age groups for subjective organization (PF
563 score) was important as already shown in previous studies (e.g., Davis et al., 2013; Hultsch,
564 1974; Kausler, 1994; Light, 1991; Sauz on et al., 2006; Stuss et al., 1996; Taconnat et al.,
565 2020; Witte et al., 1990, 1993). Conversely, although the difference between younger and older
566 adults for semantic organization (ARC score) was also significant for the Beta regression
567 analysis, it failed to reach significant for the regression analysis. This was likely since three
568 different ARC scores were inserted in the Beta regression analysis whereas an average of the
569 three different ARC scores was included in the regression analysis. Therefore, these results
570 contributed to the literature with some studies reporting that older adults do use semantic
571 organization spontaneously during recall as much as younger adults (e.g., Bäckman & Wahlin,
572 1995; Burack & Lachman, 1996; Kahana & Wingfield, 2000; Kuhlmann & Touron, 2016; Park

573 et al., 1989; Rankin et al., 1984; Sauz on et al., 2006; Tacconnat et al., 2020), while other studies
574 indicate a significant age-related impairment in the use of this mnemonic strategy (e.g.,
575 Denney, 1974; Howard et al., 1981; Tacconnat et al., 2009; West & Thorn, 2001; Zivian &
576 Darjes, 1983). Nonetheless, our findings suggest that there seems to be more impairment in
577 subjective organization than in semantic organization with aging.

578 Moving on to our main research question, namely regarding the contributions of
579 cognitive control and working memory to different organizational mnemonic strategies and
580 whether it is subjected to age-related differences, the prerequisite for answering this question
581 was that the different cognitive tests evaluating the controlled processes were divided into two
582 factors, one corresponding to cognitive control and the other to working memory. The idea that
583 working memory and cognitive control correspond to distinct processes was based on work
584 using brain-imaging methods (e.g., Owen et al., 1999; 2005) and recent research on individual
585 differences (e.g., Frischkorn et al., 2019; Frischkorn et al., 2022; Rey-Mermet et al., 2019). In
586 link with these previous findings, the SEM analyses revealed that a model yielding two distinct
587 latent factors, respectively one for cognitive control (based on the SWCT, WSCT, TMT, which
588 are tasks that do not include a short-term storage component) and another for working memory
589 (N-Back, Backward Digit Span, Alpha Span tests, which are tasks that include a short term
590 storage component), was better than a single latent factor model (Hypothesis 3). This result
591 supports the fact that these two controlled processes are underpinned by different brain regions.
592 Importantly, based on this dissociation and consistent with our Hypothesis 4, we reported that
593 overall, the cognitive control latent factor predicted semantic organization and the
594 corresponding recall from the organizable wordlist whereas the working memory latent factor
595 sustained subjective organization but was not associated with any recall measures.

596 These results were confirmed and refined in our regression analyses examining the
597 contribution of cognitive control and working memory to semantic and subjective organization

598 depending on age group. Indeed, in line with the prediction of our Hypothesis 4, our regression
599 analyses revealed that cognitive control was a significant predictor of semantic organization
600 and working memory a significant predictor of subjective organization for both younger and
601 older adults. As such, contrary to what was expected with our Hypothesis 5, we did not find
602 evidence for age-related changes in these two associations as interactions were not significant.
603 However, to better interpret these non-significant interactions, we conducted a sensitive power
604 analysis with G*Power (Faul et al., 2007), setting an alpha power of .80, a total sample size
605 equal to 124 and a number of predictors equal to 5 (three main effects and two interactions).
606 This analysis indicated that with this sample, our design would have been able to detect
607 significant effects with a minimum effect size of $f^2 = .11$ or partial $\eta^2 = .10$. As the effect size
608 of these two interactions were below these minimum effect sizes the design could have
609 detected (partial $\eta^2 = .03$), this indicated that the test of these interactions is not informative
610 with our sample size (Lakens, 2022).

611 However, it is important to note that our results are not consistent with a recent study
612 showing that semantic organization and working memory are related (Cherry et al., 2021). But,
613 this study used another measure of clustering than the ARC score, which was the number of
614 categories among correctly recalled items. As such, the latter measure is heavily dependent on
615 recall performance and might explain the difference between this study and ours. Future
616 investigations should look at how different measures of clustering behaviors are similar or
617 different in order to ensure appropriate comparisons between studies.

618 To conclude, we investigated for the first time in a single study the age-related
619 respective contribution of cognitive control and working memory processes to two
620 organizational behaviors, semantic and subjective organization, in episodic memory. In line
621 with previous studies, we showed that older adults engaged less semantic organization than
622 younger adults, with a strong reliance on cognitive control capacities in both age groups. While

623 younger adults used more subjective organization than older adults and this strategy was
624 underlined by working memory capacity in both age groups. These results shed new lights on
625 our understanding on how two controlled processes differently contribute to organizational
626 behaviors in episodic memory.

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