Supplement to "Storage and processing in working memory: Assessing dual task performance and task prioritization across the adult lifespan"

Stephen Rhodes, Agnieszka J. Jaroslawska, Jason M. Doherty, Clement Belletier, Moshe Naveh-Benjamin, Nelson Cowan, Valerie Camos, Pierre Barrouillet, and Robert H. Logie

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Contents

1 Participant Information Split By Site

Table 1: Participant characteristics (means and standard deviations in parenthesis) for the life-span experiments split into four age-groups. 1 = 18-30, 2 = 31-43, 3 = 44-56, 4 = 57-70, 5 = 70+. YoE = years of education, VC = WASI vocabulary, MR = WASI matrix reasoning.

	UK					US				
	1	2	3	4	5	1	2	3	4	5
N	17	17	16	17	17	16	16	16	16	16
female	6	10	12	11	6	8	11	9	10	10
age	23.12 (3.50)	36.71 (3.62)	50.50 (3.63)	63.29 (2.89)	74.35 (3.33)	23.38 (3.65)	35.06 (2.91)	49.75 (3.51)	64.00 (4.23)	75.12 (2.68)
YoE	15.88 (1.90)	17.65 (4.83)	16.75 (2.44)	17.12 (3.97)	15.03 (3.97)	16.09 (2.70)	20.12 (5.00)	17.00 (3.12)	17.69 (2.30)	16.28 (2.71)
VC (T)	49.53 (4.50)	55.88 (5.23)	56.12 (5.21)	62.00 (9.44)	61.71 (6.78)	60.44 (8.15)	57.06 (11.43)	60.31 (7.69)	59.31 (9.18)	56.00 (9.54)
VC (raw)	37.59 (3.16)	42.76 (2.99)	43.00 (3.39)	45.53 (5.54)	44.76 (3.85)	43.44 (4.08)	42.62 (6.92)	45.31 (3.55)	43.94 (5.48)	40.56 (5.80)
MR (T)	58.18 (11.70)	55.12 (6.67)	55.00 (8.36)	56.06 (8.52)	62.12 (7.65)	55.25 (6.04)	55.31 (10.54)	55.12 (4.92)	59.44 (9.45)	58.44 (6.96)
MR (raw)	23.29 (3.79)	22.29 (2.64)	20.81 (3.56)	20.00 (3.74)	20.24 (3.42)	23.00 (1.90)	23.25 (2.24)	21.38 (2.53)	21.12 (4.30)	18.38 (3.38)
MoCA	28.47 (1.28)	27.59 (1.80)	27.56 (1.93)	27.29 (2.57)	26.82 (1.85)	29.00 (1.15)	27.69 (1.74)	28.56 (1.26)	27.56 (1.82)	26.19 (2.10)

2 Letter Identification Errors

Figure 1 presents the frequency of errors when they were made more than once (given that each letter was seen/ heard twice by each participant). Clearly participants confused ‘s’ for ‘f’ at a disproportionate rate in the auditory condition. Figure 2 presents the errors split into 5 age groups. Older adults were more likely to confuse ‘s’ for ‘f’.

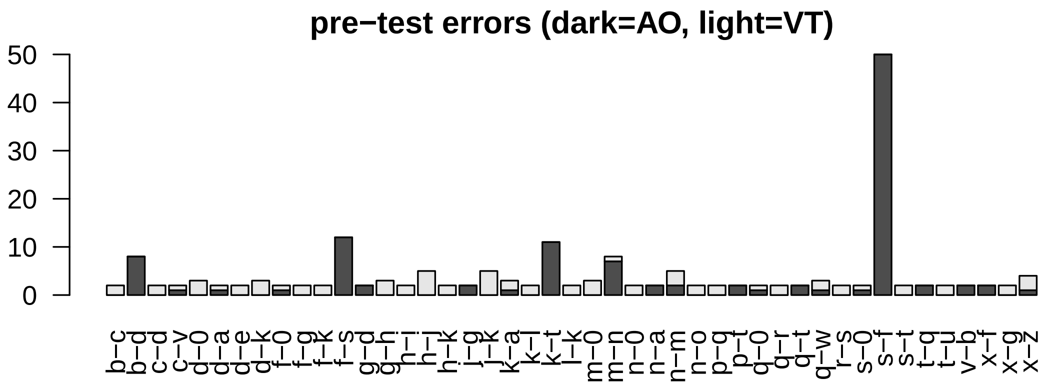

Figure 1: Frequency of errors on the pre-test phase presented in the form of ‘stimulus-response’. Only pairs for which the error rate exceeds 1 are presented to simplify plot.

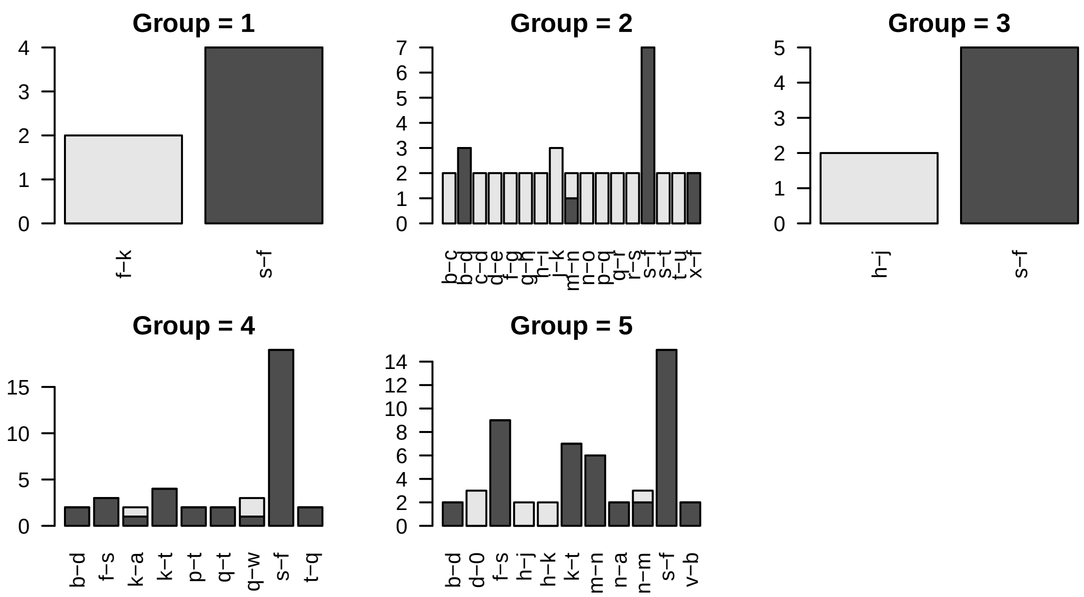

Figure 2: Frequency of errors on the pre-test phase presented in the form of ‘stimulus-response’ split by age group. Only pairs for which the error rate exceeds 1 are presented.

3 Span - Full Model Results

In the next sections we present the full model results and the steps taken in producing the simplified models presented in the main manuscript. The difference in BIC (Schwarz, 1978) was used in deciding between a model including a particular effect versus one excluding it. As a guide to interpreting these values, Raftery (1995, Table 6) suggests that a BIC difference (ΔBIC) of 0–2 be considered *weak*, 2–6 *positive*, 6–10 *strong*, and > 10 *very strong*.

3.1 Memory Span

Table 2: Full model for the analysis of memory span

Parameter	β	Std. Err	t
(Intercept)	6.020	0.111	54.281
Site (UK vs US)	0.031	0.111	0.279
Format (VT vs AO)	0.014	0.056	0.251
z(Age)	-0.488	0.071	-6.846
$z(\text{Age})^2$	-0.009	0.086	-0.106
Site × Format	-0.037	0.056	-0.653
Site × z(Age)	0.128	0.071	1.789
Format × z(Age)	0.004	0.036	0.123
Site × $z(\text{Age})^2$	-0.018	0.086	-0.208
Format × $z(\text{Age})^2$	-0.032	0.043	-0.738
Site × Format × z(Age)	0.028	0.036	0.766
Site × Format × $z(\text{Age})^2$	0.030	0.043	0.703

The full model from the analysis of memory span is presented in Table 2. The first step in reducing the model to the one presented in the main manuscript was to remove the Site × Format × non-linear age term interaction. The BIC difference suggested that the 3-way interaction should be removed ($\Delta\text{BIC} = 9.74$). Throughout, a positive BIC difference favors removal of an effect whereas a negative difference favors retention.

With the non-linear interaction removed we then attempted to remove the linear three-way interaction; the BIC comparison also favored removal ($\Delta\text{BIC} = 10.1$). We next removed the two-way interactions involving the non-linear age term (ΔBICs: age^2 × Format = 9.69, age^2 × Site = 8.83 and then each of the three remaining two-way interactions (ΔBICs: Format $\times$ age = 10.6, Site $\times$ age = 10.6, Site $\times$ Format = 10.6). This left us with only the main effects to consider. The non-linear age effect could be removed (ΔBIC = 8.84). Finally, the linear effect of age was retained as it BIC comparison was negative (ΔBIC = -32.05), whereas the main effects of Format (ΔBIC = 10.37) and Site (ΔBIC = 9.21) were both omitted.

3.2 Processing Span

Table 3: Full model for the analysis of processing span

Parameter	β	Std. Err	t
(Intercept)	8.922	0.222	40.231
Site (UK vs US)	-0.107	0.222	-0.481
Session (1 vs 2)	-0.703	0.080	-8.798
z(Age)	-0.561	0.143	-3.937
$z(\text{Age})^2$	-0.073	0.171	-0.425
Site $\times$ Session	0.003	0.080	0.042
Site $\times$ z(Age)	0.228	0.143	1.602
Session $\times$ z(Age)	0.053	0.051	1.040
Site $\times$ $z(\text{Age})^2$	0.032	0.171	0.189
Session $\times$ $z(\text{Age})^2$	0.089	0.062	1.448
Site $\times$ Session $\times$ z(Age)	-0.000	0.051	-0.004
Site $\times$ Session $\times$ $z(\text{Age})^2$	0.046	0.062	0.745

The full model for the analysis of processing span is presented in Table 3. The simplification started by removing the three-way interaction including the non-linear age term (ΔBIC = 8.98) followed by the linear three-way interaction (ΔBIC = 9.91). The interactions between the age^2 term with Session (ΔBIC = 7.36), and with Site (ΔBIC = 7.45) were also removed. We then turned to the three two-way interactions which each favored removal (ΔBICs: Session $\times$ age = 9.06, Site $\times$ age = 5.32, Site $\times$ Session = 9.03).

For main effects the non-linear age term was removed firstly (ΔBIC = 7.26). Finally, the BIC comparison suggested that we retain both age (ΔBIC = -6.91) and session (ΔBIC = -94.77) in the final model, whereas site (ΔBIC = 7.6) could be removed.

4 Memory and Processing Accuracy - Full Model Results

4.1 Memory Accuracy

Table 4 presents the full model for the analysis of memory accuracy, which was reduced to the model presented in the manuscript. The first thing removed from this model was the three-way, age^2 by condition by Format interaction (ΔBIC = 45.91) followed by the three-way interaction involving the linear age term (ΔBIC = 43.42). Next we turned to the two-way interactions including the non-linear age term and both could be removed (ΔBICs: Format $\times$ age^2 = 9.39, Condition $\times$ age^2 = 41.53). For the remaining two-way interactions the BIC comparison favored retaining the condition $\times$ age interaction (ΔBIC = -22.96) and the condition $\times$ format interaction (ΔBIC = -6.63). The format by age interaction, on the other hand, could be removed (ΔBIC = 8.52).

As the interactions retained in the model contained condition, format, and the linear age term we next only went on to consider removing the non-linear age effect. The BIC comparison favored its removal (ΔBIC = 9.63), which gave the final model presented in the main manuscript.

Table 4: Full model for the analysis of memory accuracy

Parameter	β	Std. Err	z
(Intercept)	0.754	0.054	13.886
c1. pure vs 90	-0.566	0.041	-13.833
c2. 90 vs 70	0.001	0.038	0.022
c3. 70 vs 50	-0.092	0.038	-2.426
c4. 50 vs 30	-0.137	0.037	-3.656
c5. 30 vs 10	-0.049	0.037	-1.330
Format (VT vs AO)	0.061	0.011	5.490
z(Age)	-0.131	0.035	-3.735
z(Age)^2	0.008	0.042	0.191
c1 $\times$ Format	-0.036	0.041	-0.878
c2 $\times$ Format	0.022	0.038	0.587
c3 $\times$ Format	-0.053	0.038	-1.399
c4 $\times$ Format	-0.067	0.037	-1.791
c5 $\times$ Format	-0.035	0.037	-0.936
c1 $\times$ z(Age)	-0.187	0.027	-6.950
c2 $\times$ z(Age)	-0.000	0.025	-0.005
c3 $\times$ z(Age)	0.003	0.025	0.112
c4 $\times$ z(Age)	0.008	0.024	0.342
c5 $\times$ z(Age)	0.058	0.024	2.393
Format $\times$ z(Age)	0.009	0.007	1.279
c1 $\times$ z(Age)^2	-0.022	0.032	-0.701
c2 $\times$ z(Age)^2	-0.047	0.030	-1.570
c3 $\times$ z(Age)^2	0.055	0.030	1.848
c4 $\times$ z(Age)^2	0.011	0.029	0.359
c5 $\times$ z(Age)^2	-0.025	0.029	-0.855
Format $\times$ z(Age)^2	0.005	0.009	0.537
c1 $\times$ Format $\times$ z(Age)	-0.050	0.027	-1.872
c2 $\times$ Format $\times$ z(Age)	-0.001	0.025	-0.021
c3 $\times$ Format $\times$ z(Age)	0.025	0.025	1.013
c4 $\times$ Format $\times$ z(Age)	-0.003	0.024	-0.132
c5 $\times$ Format $\times$ z(Age)	0.008	0.024	0.347
c1 $\times$ Format $\times$ z(Age)^2	-0.012	0.032	-0.380
c2 $\times$ Format $\times$ z(Age)^2	-0.012	0.030	-0.415
c3 $\times$ Format $\times$ z(Age)^2	0.014	0.030	0.472
c4 $\times$ Format $\times$ z(Age)^2	0.027	0.029	0.914
c5 $\times$ Format $\times$ z(Age)^2	-0.011	0.029	-0.376

4.2 Processing Accuracy

The results of the full, saturated model fit to processing accuracy are presented in Table 5. The first step was to remove the non-linear three-way interaction (ΔBIC = 38.09) followed by the linear one (ΔBIC = 29.79). Both of the non-linear two-way interactions were removed next (ΔBICs: Format $\times$ age^2 = 2.31, Condition $\times$ age^2 = 36.25). The only two-way interaction retained was between format and age, and in this case the BIC comparison was not particularly convincing (ΔBIC = -1.05). The condition $\times$ age (ΔBIC = 20.03) and condition $\times$ format (ΔBIC = 41.11) were both removed.

Finally, we turned to main effects. The non-linear effect of age could safely be removed (ΔBIC = 9.57). As the linear age effect and format were involved in a higher order interaction we did not consider removing these main effects. The BIC strongly favored retaining the main effect of condition in the final model (ΔBIC = -455.21).

Table 5: Full model for the analysis of processing accuracy

Parameter	β	Std. Err	z
(Intercept)	1.546	0.046	33.926
c1. pure vs 90	-0.083	0.039	-2.109
c2. 90 vs 70	0.015	0.039	0.386
c3. 70 vs 50	-0.051	0.039	-1.322
c4. 50 vs 30	-0.179	0.037	-4.772
c5. 30 vs 10	-0.071	0.036	-1.969
Format (VT vs AO)	0.053	0.011	4.797
z(Age)	-0.058	0.029	-1.962
z(Age)^2	-0.008	0.035	-0.233
c1 × Format	0.042	0.039	1.073
c2 × Format	0.078	0.039	1.999
c3 × Format	-0.070	0.039	-1.816
c4 × Format	0.044	0.037	1.174
c5 × Format	0.016	0.036	0.450
c1 × z(Age)	-0.105	0.026	-4.044
c2 × z(Age)	0.032	0.025	1.289
c3 × z(Age)	0.029	0.025	1.155
c4 × z(Age)	-0.078	0.024	-3.211
c5 × z(Age)	0.034	0.023	1.487
Format × z(Age)	-0.024	0.007	-3.314
c1 × z(Age)^2	-0.040	0.031	-1.308
c2 × z(Age)^2	-0.013	0.030	-0.449
c3 × z(Age)^2	0.022	0.030	0.743
c4 × z(Age)^2	-0.010	0.029	-0.328
c5 × z(Age)^2	-0.057	0.028	-2.044
Format × z(Age)^2	-0.021	0.009	-2.508
c1 × Format × z(Age)	0.059	0.026	2.294
c2 × Format × z(Age)	-0.055	0.025	-2.200
c3 × Format × z(Age)	-0.010	0.025	-0.392
c4 × Format × z(Age)	-0.038	0.024	-1.544
c5 × Format × z(Age)	0.023	0.023	1.003
c1 × Format × z(Age)^2	-0.018	0.031	-0.587
c2 × Format × z(Age)^2	-0.059	0.030	-1.981
c3 × Format × z(Age)^2	0.027	0.030	0.919
c4 × Format × z(Age)^2	0.003	0.029	0.099
c5 × Format × z(Age)^2	-0.026	0.028	-0.924

5 Memory and Processing Accuracy - An Alternative Model

The 'backwards difference' coding scheme used for the priority factor in the main analyses presented in the manuscript made particular sense as it allowed us to compare conditions with successively less emphasis placed on a given task. As such, a disproportionately large first comparison, between the single task condition and the dual task condition with 90 points assigned to the task, relative to the remaining contrasts would reasonably indicate a concurrence cost. Importantly, this coding scheme did not place constraints on the function relating accuracy to priority condition. This seemed reasonable given no strong reason to assume a particular function *a priori*.

Nevertheless, alternative models may be informative here. In particular we can conceive of one model which more parsimoniously splits the 'concurrence cost' from changes in performance related to the priority manipulation, the 'prioritization cost'. Specifically, this model contains a dummy coded variable, 'dual task', that is coded 0 for the single task condition and 1 otherwise (i.e. all condition where both tasks were performed at once). A second variable, 'emphasis away', quantifies the extent to which the allocation of points in a given condition placed emphasis away from the given task. Formally it is $(100 - M)/100$ where M is the number of points allocated to the task in question. Consequently, this variable ranged from 0 to 0.9, where 0 is the single task condition (in which all 100 points were given to the task in question). This model, then, assumes a linear change in the log odds of a correct task response with change in the number of points allocated to the particular task. The more positive the coefficient, the greater the prioritization cost between adjacent conditions. The inclusion of the dummy coded 'dual task' variable allows for performance in the dual task conditions to be disproportionately lower as implied by a concurrence cost irrespective of priority. Otherwise, the details of this alternative model and the manner in which it was simplified are the same as those used in the main manuscript. The final results for this alternative model are presented below for the memory and processing accuracy data.

5.1 Memory Accuracy

Table 6 presents the final alternative model results for the memory accuracy data. It clearly paints a similar picture to the analysis, using the unconstrained model, presented in the main manuscript. Both the dual task and emphasis away variables result in highly significant and large coefficients. The main effect of format is also

Table 6: Final results of alternative model for memory accuracy

Parameter	β	Std. Err	z
(Intercept)	1.091	0.036	30.082
Dual task	-0.263	0.013	-20.824
Emphasis away	-0.371	0.027	-13.720
Format (VT vs AO)	0.133	0.012	10.770
z(Age)	-0.077	0.036	-2.143
Emphasis away × Format	-0.162	0.023	-7.150
Dual task × z(Age)	-0.082	0.011	-7.674

present, with better accuracy in the VT condition relative to AO. The linear effect of age indicated that responses got less accurate with age and, crucially, there was also an interaction between this age term and the dual task variable. This interaction is consistent with the concurrence cost discussed in the manuscript. The emphasis away by age interaction was not retained in the model and was omitted by a fairly convincing BIC difference (ΔBIC = 7.72). This again is in line with their being no age difference in the size of prioritization costs. There was an interaction between emphasis away and format, suggesting a smaller prioritization cost for the AO condition which was also indicated in the main analysis.

Overall it is reassuring that this alternative model reaches the same conclusions as the less constrained, but *a priori* more appropriate, model presented in the main manuscript. Importantly, this model fits much better than the original model in terms of BIC (BIC_{main} = 62583.46, BIC_{alt} = 62501.93; ΔBIC = 81.52) suggesting that the linear assumption for the emphasis away variable is a reasonable one.

5.2 Processing Accuracy

In contrast to the memory results, for the processing data this alternative model did not fit as well as the original model presented in the main manuscript (BIC_{main} = 51772.81, BIC_{alt} = 51805.53; ΔBIC = -32.72). Therefore, the results of this final model, presented in Table 7, should be interpreted with that in mind.

The dual task variable in this analysis was not significant (although it appears in a higher order interaction, discussed below), whereas the priority variable (emphasis away) did yield a highly significant coefficient. This is consistent with overall there being no concurrence cost for the processing task but a clear prioritization cost. The dual task variable and the linear age term interacted such that older adults increas-

Table 7: Final results of alternative model for processing accuracy

Parameter	β	Std. Err	z
(Intercept)	1.732	0.031	56.237
Dual task	-0.005	0.012	-0.400
Emphasis away	-0.461	0.027	-17.132
Format (VT vs AO)	0.020	0.012	1.651
z(Age)	-0.031	0.031	-0.992
Emphasis away × Format	0.029	0.022	1.314
Dual task × z(Age)	-0.040	0.012	-3.253
Emphasis away × z(Age)	-0.003	0.027	-0.120
Format × z(Age)	0.006	0.012	0.497
Emphasis away × Format × z(Age)	-0.065	0.022	-2.953

ingly exhibited a concurrence cost (scaled effect size = -0.11). Finally, there was a highly unexpected three-way interaction between the emphasis away variable, format, and age such that the prioritization cost was more pronounced for increasingly older participants in the VT condition. However, this should be taken with a pinch of salt given that (1) the emphasis away by age interaction itself was not significant, suggesting that overall the prioritization cost did not differ as a function of age, (2) the effect size for this coefficient is small (scaled effect size = -0.18), and most importantly (3) this model did not provide as good a fit as the model presented in the main manuscript, most likely due to the assumption of linearity in the emphasis away variable. The original model did not enforce such a constraint, which could not be justified ahead of time, and its results should be preferred.

5.3 Evidence for concurrence costs

In the manuscript we suggest that the evidence for a concurrence cost for memory is clear whereas there is no evidence of such a cost in the processing data. To follow this up with the alternative model we examined the effect of omitting the dual task coefficient on the fit of the final models from Tables 6 and 7. For the memory data omitting this variable led to a large decrease in model fit relative to the model including this (ΔBIC = 435.6). This is strong evidence for the concurrence cost in the memory data. For the processing data this was not the case. Leaving out the main effect of dual task improved model fit (ΔBIC = -9.5). This supports the assertion that there is no concurrence cost in the processing data.

6 Analysis of Proportional Dual Task Costs

The analyses reported in the main manuscript are different from those often reported in dual task studies assessing age differences in working memory (e.g. Anderson, Bucks, Bayliss, & Della Sala, 2011; Logie, Cocchini, Della Sala, & Baddeley, 2004; Logie, Della Sala, MacPherson, & Cooper, 2007). Rather than look at raw accuracy these studies assess dual task costs as a proportion of single task performance; in other words, the difference between single and dual task accuracy is divided by single task accuracy. The rationale underlying analyses such as these is that it accounts for differences in single task performance between the groups, although the assumptions underlying this analysis are actually more complex (see Guttentag, 1989). Nevertheless, as our main analysis revealed main effects of age one may ask whether a more conventional analysis of proportional scores would produce the same result. Therefore, we conducted ANOVAs on proportional dual task costs for the memory and processing data with the factors of presentation-recall format (AO, VT), age group (18–30, 31–43, 44–56, 57–70, 71–81), and condition (M =10, 30, 50, 70, 90). In addition to F ratios and p values, we also report the default JZS Bayes' factors of Rouder, Morey, Speckman, and Province (2012) as estimated via the `BayesFactor R` package (Morey & Rouder, 2015). We used the default settings other then setting"whichModels" to "top" such that the Bayes factors reflect a comparison of a model omitting a given main effect or interaction to the full model including all main effects an interactions. The Bayes factors we report reflect the weight of evidence *in favor* of the effect in question (i.e. BF_{10}). Evidence against an effect is given by a Bayes factor less than 1 ($BF_{01} = 1/BF_{10}$).

The proportional dual task costs are presented in Figure 3. To summarize, these analyses largely confirm what the main analysis, and additional analyses above, reveals with regards to the effects of age on dual task performance. The models reported in the main manuscript should be favored for interpretation as they were conducted on trial level data (not aggregates) on an appropriate scale for accuracy data.

6.1 Memory Proportional Costs

The top two panels of Figure 3 show the proportional costs for the letter recall task. There were main effects of condition ($F(4,\ 636) = 17.07$, $p < 0.001$, $BF_{10} >$ 1000) and age group $F(4,\ 159) = 3.41$, $p = 0.01$, $BF_{10} = 2.25$) mirroring the main analysis presented in the manuscript. Crucially, this suggests that the increase in the memory concurrence cost was not due to the small age differences in single task

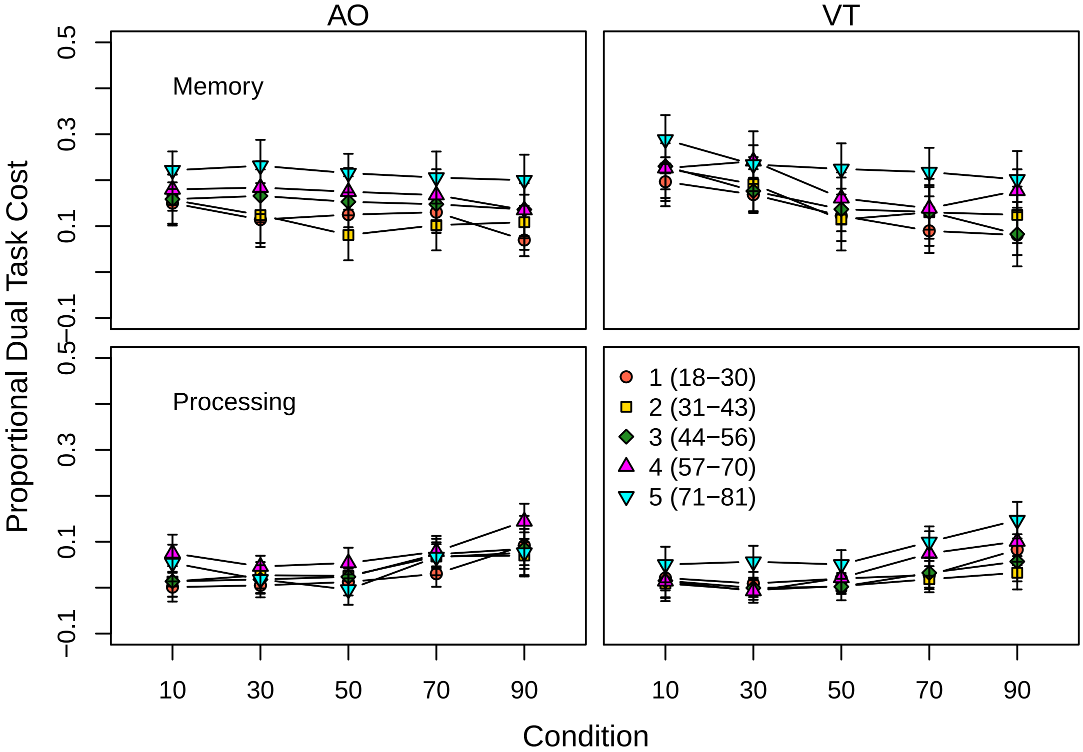

Figure 3: Proportional dual task costs ([single task - dual task]/ single task) for the memory and processing tasks. Error bars are 95% confidence intervals.

performance. There was no evidence in favor of a main effect of presentation-recall format ($F(1,\ 159) = 1.69$, $p = 0.20$, $BF_{10} = 1.28$).

Turning to interactions, in line with the main analysis, there was a significant interaction between condition and presentation-recall format, $F(4,\ 636) = 4.62$, $p < 0.01$, $BF_{10} = 0.35$ (note the small Bayes factor against this effect). There was no evidence (indeed Bayesian evidence against) interections between format and age ($F(4,\ 159) = 0.23$, $p = 0.92$, $BF_{10} = 0.007$), as well as age and condition ($F(4,\ 636) = 0.68$, $p = 0.81$, $BF_{10} = 4.08 \times 10^{-5}$) supporting the lack of age difference in the prioritization cost. Finally, the weight of evidence was against the three way interaction ($F(16,\ 636) = 0.62$, $p = 0.87$, $BF_{10} = 4.2 \times 10^{-4}$).

6.2 Processing Proportional Costs

The bottom two panels of Figure 3 show the proportional costs for the aritmetic processing task. In line with the main analysis there was no evidence of a main effect of age ($F(4,\ 159) = 1.99$, $p = 0.10$, $BF_{10} = 0.20$) but there was a clear effect of condition ($F(4,\ 636) = 32.44$, $p < 0.001$, $BF_{10} > 1000$). Further there was no clear main effect of presentation-recall format ($F(1,\ 159) = 1.39$, $p = 0.24$, $BF_{10} =$

0.42) which somewhat goes against the main analysis, but note the size of the Bayes factor.

There was an interaction between age and format, however, demonstrating the same pattern of a somewhat smaller age differences in the AO condition ($F(4, 159) = 3.17$, $p = 0.02$, $BF_{10} > 1000$), although it is worth reiterating that no overall age differences were found in processing performance. Age and condition clearly did not interact ($F(4, 636) = 0.91$, $p = 0.55$, $BF_{10} = 4.81 \times 10^{-4}$) and nor did condition and format ($F(4, 636) = 0.27$, $p = 0.90$, $BF_{10} = 0.002$). Finally, there was no evidence of a three way interaction ($F(16, 636) = 1.56$, $p = 0.07$, $BF_{10} = 0.003$).

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