Supplementary Material to Manuscript

Early Selection versus Late Correction: Age-Related Differences in Controlling Working Memory Contents

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Contralateral and Ipsilateral Waveforms

Supplementary Figure 1 shows the contralateral and ipsilateral waveforms time locked to the onset of the memory array. As can be seen, the presentation of the memory array elicits distinct P1 and N1 components between 100 and 200 ms (both at contralateral and ipsilateral sites) followed by two relative negativities at contralateral sites: a transient one between 200 and 300 ms, i.e., the N2pc, and another, more sustained one that lasts until the end of the retention interval, i.e., the contralateral delay activity (CDA). As in the study by Jost, Bryck, Vogel, and Mayr (2011) we analyzed the amplitude modulation of the CDA to investigate whether distractors are encoded in working memory (WM). In addition, we also investigated the N1 and the N2pc as these are regarded to reflect initial perceptual and attentional processes.
Supplementary Figure 1. Contralateral and ipsilateral waveforms time locked to the onset of the memory array. Negative voltage is plotted upward.

**N1**

The posterior N1 reflects early perceptual processing of visual stimuli. In the present study the posterior N1 was present both at contralateral and ipsilateral electrodes (see Supplementary Figure 1) and therefore not obvious in the contralateral minus ipsilateral difference waves. This is not surprising, because the same number of objects is presented in
the two hemifields. In our studies, we sometimes observe a small negative peak also in the
difference waves. This, however rather stems from latency differences between contralateral
and ipsilateral electrodes than from differences in the maximum amplitude per se.

As can be seen in Supplementary Figure 2, the N1 emerged as a distinct ERP
component whose maximum amplitude (i.e., between 180 and 200 ms) differed between the
conditions. To analyze these differences, amplitudes were extracted for time windows of 20
ms centered around the grand average peak of each condition. Note that the N1 in set size 1
condition of the elderly seems to consist of a series of smaller components between 150 and
300 ms. This was also evident in individual waveforms. The extracted time window for this
condition covered the first local peak (at 222 ms) within the N1 time range.

Supplementary Figure 2. Posterior N1 measured at a cluster of three electrodes contralateral to the
attended hemifield (O1/O2, PO3/PO4, PO7/PO8).

As described in the main text and as evident from the figure above, the amplitude
pattern differed for younger and older adults. Young adults showed an amplitude increase for
the distractor compared to the no-distractor conditions. Older adults also showed a distractor
effect, but, in addition, an amplitude increase with set size. Importantly, these specific
patterns in each age group also held for subgroups of low and high WM capacity (see
Supplementary Figure 3). Both groups of older participants not only showed an amplitude increase with distractor presence, but also with set size (all interactions with capacity were not significant, \( ps > .484 \)). Moreover, this set-size effect was not present in younger adults, neither for high capacity nor for low capacity individuals.

Supplementary Figure 3. N1 and N2pc effects in subgroups, i.e., low working memory capacity versus high working memory capacity. The age-group specific effects even hold for the subgroups.

**Contralateral Activities: the N2pc and the CDA**

**Rationale for computing difference waves.** Both N2pc and CDA are contralateral negativities that are obtained by computing the difference between contralateral and ipsilateral posterior activity. The rationale for this approach is based on the primarily contralateral organization of the visual system and is as follows: In the task design, the participant is presented with a bilateral display with equal amounts of stimuli in each hemifield. The
participant is asked to attend to and remember the stimuli in only one of these hemifields. Thus, task-general activity such as perceptual response will be equivalent for each hemisphere, but the process of interest (i.e., maintenance) will be reflected in activity contralateral to the attended hemifield. Consequently, computing the difference wave contralateral-minus-ipsilateral allows isolating activity that is specific to maintenance.

For both components, we computed the difference waves for seven posterior electrode pairs (O1/O2, PO7/PO8, PO3/PO4, P7/P8, P5/P6, P3/P4, P1/P2). Similar positions were used in previous CDA studies (see e.g., Vogel, McCollough, & Machizawa, 2005; Jost et al., 2011).

**Topographies.** Supplementary Figure 4 depicts the topographical distributions of the N2pc and the CDA separately for younger and older adults. Although the topographies slightly differed between the components (see also McCollough, Machizawa, & Vogel, 2007) and the age groups, each of the seven electrodes that were considered in the analyses showed a contralateral-ipsilateral difference both in the N2pc and in the CDA time range. This holds for both young and old adults albeit generally larger effects for younger adults.

![Topographies](image)

*Supplementary Figure 4. Topographies of the N2pc and the CDA separately for younger and older adults exemplarily for the set size 3 condition. For the N2pc, amplitudes were extracted from a 25-ms time window in which the N2pc was largest in each group. For the CDA, the time window between 500 and 1000 ms was chosen.*
In both groups the N2pc was largest at electrode pair PO7/PO8 (which is typical for the N2pc, see e.g., Luck, 2014). Moreover, in both groups the difference was smaller at medial than at lateral electrodes and smallest at P1/P2. The only obvious difference between the age groups was that the elderly show a less steep “anterior-posterior gradient”, i.e., differences at parietal electrodes were almost as large as the difference at occipital electrodes.

The amplitude of the CDA was largest at lateral parietal electrodes and smaller at medial electrodes (O1/O2, P1/P2). This largely holds for both groups, although these differences are less pronounced in the group of the elderly.

N2pc

Additional Analyses. Both young and older adults exhibit clear contralateral-ipsilateral differences between 200 and 300 ms – the N2pc – indicating that shifting attention to the relevant side was successful. In addition to the analysis reported in the manuscript, we also ran separate analyses for the 25-ms time windows. Since the time course of the N2pc slightly differed between the groups, these analyses were run separately for younger and older adults, i.e., for the younger adults between 175 and 300 ms and for the older adults between 200 and 350 ms. As will be shown below, these analyses provided similar findings as the maximum-amplitude analysis reported in the manuscript.

For younger adults, the N2pc amplitude responded to the number of presented targets. The N2pc started somewhat later for the set size 3 than for set size 1 condition, but reached a larger amplitude maximum (see Figure 2C in the manuscript). The early latency and the later amplitude differences were significant in the time windows between 175 and 225 ms and between 250 and 300 ms, respectively, with t(24)-values varying between -2.52 (p = .019, d = -0.38) and 5.05 (p < .001, d = 0.98). Most importantly, young adults also showed a distractor effect. The amplitude was larger for the two distractor conditions than for the no-distractor conditions. Importantly, this also held when the distractor condition with one target and two
distractors was compared with the set size 3 condition having the same total number of items. This difference was significant between 175 and 250 ms with \( t(24) \)-values between -3.81 (\( p = .001, d = -0.49 \)) and -6.72 (\( p < .001, d = -0.91 \)). Note there was no further increase for the distractor condition with three targets and two distractors which presumably reflects an often observed stable plateau at around three to four items (for review, see Anderson, Vogel, & Awh, 2014).

Older adults showed a smaller set-size effect than younger adults, but of the same pattern, i.e., with a later onset but larger amplitude for the set size 3 than for the set size 1 condition. However, only the amplitude differences between 300 and 350 ms reached significance, \( t(23) \) values 2.61 (\( p = .016, d = 0.41 \)) and 4.05 (\( p < .001, d = 0.67 \)). However, in contrast to younger adults, older adults did not show a distractor effect. The maximum amplitudes of the distractor conditions were even a bit smaller than that of the set size 3 condition. There was only a slight difference in early time windows between 200 and 250 ms indicating that the N2pc started earlier in the set size 1 + distractors condition, \( t(23) \) values -4.19 (\( p < .001, d = -0.57 \)) and -2.94 (\( p = .007, d = -0.37 \)).

Note that the pattern was similar when for the N2pc analysis more typical electrodes (i.e., PO7/PO8) were used. Importantly the lack of a distractor effect in older adults held for all of the seven electrode pairs that were included in the analysis.

**Functional Significance.** Apart from distractor processing, older and younger adults behave the same, with increasing amplitude for the set size 3 compared to the set size 1 condition. Across a wide variety of tasks (such as visual search, multiple object tracking, and subitizing) the N2pc has been found to increase with set size reaching a stable plateau around three items. Moreover, the shape of this N2pc amplitude by set size function turned out to be a robust predictor of performance in each of these tasks. This common empirical pattern has been taken as evidence that the N2pc reflects item individuation and selection (for review, see Anderson et al., 2014; Mazza & Caramazza, 2015). Thus, the N2pc in our study presumably
reflects initial item selection before the information is stored in WM (which is reflected by the CDA).

The increased amplitude in the distractor conditions for younger adults might reflect increasing requirements for item individuation and selection when distractors were presented. However, this interpretation is difficult to reconcile with the observation that distractors did not have the same effect in older adults. The distractor conditions even elicited numerically smaller amplitudes than the set size 3 condition. It is implausible to assume that older adults’ target selection is not hampered by distractors or that distractors have been already fully suppressed at this point (the filtering delay in the subsequent CDA speaks against this). The amplitude increase with distractors, thus, presumably means something different than target selection difficulty.

Luck and Hillyard (1994) originally hypothesized that the N2pc reflects the suppression of distractors surrounding the attended object (see also Eimer, 1996; Luck, Girelli, McDermott, & Ford, 1997). Although there is evidence against this notion (e.g., Hickey, McDonald, & Theeuwes, 2006), the present findings of larger amplitudes in the distractor conditions could be related to distractor suppression – in terms of “selection for suppression”. We observed a similar pattern in a study in which the target discriminating dimension was color, i.e., targets and distractors differed in color (unpublished data). The distractor effect in the N2pc, thus, does not seem to be specific to the distractor types used here. However, it also needs to be noted that previous studies using a similar filtering paradigm focused on the CDA but by and large neglected N2pc effects, often because of an overlap of the two components (see e.g. Jost et al., 2011; Vogel et al., 2005, but see Störmer, Li, Heekeren, & Lindenberger, 2013). Evidence, thus, is rare.

Although it is not entirely clear, which mechanism is reflected by the N2pc modulation in general and in the present study in particular (and the N2pc might even reflect multiple processes), the important finding here is, that the distractor modulation observed for
the younger adults was not just reduced in older adults, but even not present. This qualitatively different pattern is in accordance with the findings from the N1. All in all, younger adults exhibited stronger distractor sensitivity in both components and they also reached maximum filtering efficiency earlier than the older adults (as shown by means of the CDA). These findings indicate qualitatively different processing between the age groups throughout the processing stream, which is in line with the assumption of distinct mechanisms to control the contents of WM. Moreover, the observed pattern within the N2pc remained specific to the age groups when subgroups were formed on the basis of WM capacity (see Supplementary Figure 3). Especially, the distractor effect held for both low capacity and high capacity young adults, but was absent for older adults both with high and low capacity. ANOVAs revealed that all interactions with WM capacity were not significant (for superordinate ANOVAs including age as factor, $F$s < 1.1; for ANOVAs separated for the age groups, $F$s < 1).

**CDA and Set Size**

As in many previous studies (e.g., Jost et al., 2011; Vogel & Machizawa, 2004) the amplitude of the CDA increased with set size (see Figure 3A in the manuscript). This was the case for both older and younger adults. To analyze the time course of this set-size effect, ANOVAs were run for 25-ms-time windows between 350 and 1100 ms including the repeated measures factor set size (1 vs. 3, both without distractors) and the between-subject factor age. This revealed a significant main effect set size between 350 and 1100 ms. The $F(1, 47)$ values ranged from 10.44 ($p = .002, \eta_p^2 = .18$) to 100.97 ($p < .001, \eta_p^2 = .68$). The main effect age, i.e., larger amplitudes for younger than for older adults, was significant in time windows 375-550 ms, 600-850 ms, and 950-1025 ms, with $F(1, 47)$ values ranging from 4.04 ($p = .05, \eta_p^2 = .08$) to 11.78 ($p = .001, \eta_p^2 = .20$). The interaction Age $\times$ Set Size was not significant.
The amplitude increase of the CDA usually reaches an asymptotic limit with WM capacity which is at around 3 items (see Vogel & Machizawa, 2004). This can also be observed in our results. As can be seen in Figure 3A of the manuscript, no further amplitude increase was present for the set size 3 + distractors condition (see also Jost et al., 2011). As a consequence, in the around-capacity range, the CDA is not sensitive for differentiating between storing targets and storing distractors. However, that distractors were unnecessarily stored in the set size 3 + distractors condition became obvious in the behavioral data.

An aspect of the data that cannot be easily accomplished for is the absence of a larger contralateral activity in the conditions with one target. This might suggest that older adults are not able to attend to the indicated hemifield and/or to suppress processing the irrelevant hemifield. However, occurrence of clear N2pc components in all conditions is evidence against this. The N2pc as another contralateral negativity that precedes the CDA suggests that attention already had been oriented to one side but might have not been maintained throughout the retention interval. Moreover, lateralization in the set size 1 condition often is relatively weak, leading to small CDA amplitudes (e.g., Jost et al., 2011; Störmer et al., 2013). Although we do not have an explanation for the fact that amplitudes here are even below zero, we do not think that it is problematic for our findings. Filtering scores have been calculated with the set size 3 condition that did produce robust lateralization. Moreover, the same pattern of a delay in filtering was observed in the study by Jost et al. (2011), in which all conditions elicited typical CDAs. Thus, it is unlikely that older adults’ delay in filtering observed in the present study is linked to missing lateralization.

References


