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Distraction by unintentional recognition:

Neurocognitive mechanisms and modulations by ageing.

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A thesis submitted for the degree of Master of Science by Research

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July 2018

Word count 12,554

Student number: 15909291

Declaration

I declare that the work presented in this thesis is my own carried out under the normal terms of supervision. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

John A. Allen
July 2018

1. Acknowledgements

2. Abstract

Previous research has suggested that aging is associated with increased distractibility and impaired intentional retrieval processes. I investigated potential age differences in the effect of unintentional recognition of to-be-ignored distractor images on intentional recognition decisions to targets words, and the brain processes that are associated with unintentional versus intentional recognition. This research involved comparing old (60-76) and young (18-24) adults' performance and brain activity during a Memory Stroop task, analysing behavioural data (accuracy and reaction times), event-related potentials (ERPs) and induced and evoked EEG oscillations in the theta and alpha bands. At the behavioural level, the older group exhibited the expected poorer intentional recognition memory for targets, but the biasing effect of unintentional distractor recognition on target decisions was very similar across age groups. In the ERP domain, the older group showed much reduced or absent ERP effects related to 'familiarity' and 'recollection' that were strongly expressed in the younger group. Furthermore, the older group showed a reversal of typical old/new ERP effects for targets, suggesting that they engaged a qualitatively different neurocognitive process during intentional recognition. This effect may reflect a compensatory mechanism that is used as part of an adaptive strategy to address age-related declines in the brain processes used by young adults to solve the task. However, broadly similar patterns of old/new differences in theta and alpha power were found across both age groups for both intentional target recognition and unintentional distractor recognition. Overall, the results show novel evidence of how the neural correlates of recognition memory are affected by aging and intentionality, and suggest that future research should employ both ERP and oscillation analysis of EEG data to better understand neurocognitive aging.

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6. Introduction

Healthy aging causes significant changes to the human brain and certain cognitive functions. One such change is that older adults show a reduced ability to selectively attend to task-relevant stimuli while ignoring distractions (de Fockert, Ramchurn, van Velzen, Bergström, & Bunce, 2009). Distractibility can be problematic in many situations, including during episodic memory retrieval when intentional recognition judgements to target stimuli can be biased unintentional recognition of distracting information in the same environment (Ste-Marie & Jacoby, 1993). Indeed, older adults have been shown to be more susceptible to distraction-induced recognition biases than younger adults (Anderson, Jacoby, Thomas, & Balota, 2011). Recent ERP research investigated the neural mechanisms that underlie such biases in young adults, and found that intentional and unintentional recognition were associated with dissociable neurocognitive retrieval processes that seem to interact to produce biases in recognition judgements (Bergström, Williams, Bhula, & Sharma, 2016). However, it is not known how these neurocognitive processes are modulated by healthy aging, and how they contribute to the increased behavioural biases observed in older age. The current thesis investigated these issues in the first electrophysiological study of unintentional and intentional recognition in both healthy young and older adults.

Brain volume decreases by around 5% every decade from age 40 onwards, with atrophication accelerating from age 70, accompanied by a reduction in cerebral blood flow (Peters, 2006). Brain volume reduction and the reduction in the number of neurons is markedly greater in some regions than others, such as in the prefrontal cortex (PFC;Raz, Rodrigue, & Haacke, 2007). The PFC is closely involved in mediating executive (or "cognitive control") functions (Baddeley, 1997) a set of cognitive abilities that enable us to intentionally control otherwise automatic behaviours and mental processes across different

domains (e.g. perception, memory, language, etc.). For example, executive control functions enable us to keep goal-relevant information in working memory while ignoring distractions, to override automatic urges, to flexibly switch between different tasks or mental states, and to continuously monitor a situation. Since executive functions are mediated by the PFC, these functions are likely to be particularly affected by brain changes that result from normal aging (West, 1996). Consistent with this view, older adults show a reduced ability to selectively attend to task-relevant stimuli while ignoring distractions (de Fockert et al., 2009) and also show additional processing of distractors both at a perceptual level (Biss, Ngo, Hasher, Campbell, & Rowe, 2013) and at a conceptual level (Amer & Hasher, 2014) that is not seen in younger adults.

In addition to executive functions, another common finding is that episodic memory deteriorates notably with age, even in healthy individuals (Light, 1991; Nyberg, Lövdén, Riklund, Lindenberger, & Bäckman, 2012). In line with the "frontal lobe" hypothesis of ageing outlined above (West, 1996), the particular memory abilities that seem to be most affected by age are those that rely on executive functions, such as strategic retrieval processes, which includes memory search and monitoring processes (Morcom, 2016). Interestingly, recent research has shown that the increased susceptibility to distraction that occurs with old age can also affect episodic memory retrieval. Anderson, Jacoby, Thomas, & Balota, (2011) found in their "Memory Stroop" paradigm that participants' ability to correctly identify which target words that had been previously seen (old), or not seen (new) in a recognition task can be affected by concurrently displayed old or new distractor images. That is, participants were more likely to respond that a target word was old if the distractor image was also old than if the distractor was new. This might suggest that either that they misattributed unintentional distractor recognition to targets or that novelty (lack of familiarity) in the new distractors countered recognition of the

10

familiar target. Furthermore, this effect was more likely in participants aged over 60 when compared to a young adult group, suggesting that older people are particularly biased by unintentional recognition of distracting information in their environment due to impaired executive functions.

6.1. ERP correlates of intentional and unintentional recognition

The dual-process model of recognition memory proposed that recognition memory can be dissociated into two independent mechanisms: familiarity and recollection (Mandler, 1980; Yonelinas & Jacoby, 2012). Accordingly, familiarity is a feeling that a stimulus has been previously encountered and is a relatively automatic and unintentional process that happens rapidly and without retrieval of any accompanying context. In contrast, recollection is a slower, more deliberate, intentional process, which involves the retrieval of contextual details from a previous episodic event. Much research has supported this model (Curran, 1999; Rugg et al., 1998; Tsivilis, Otten, & Rugg, 2001) and has identified neural correlates of the two processes. In Event-Related Potentials (ERPs), 'familiarity' is expressed as an early mid-frontal positivity in the 300-500ms post-stimulus period for previously seen ("old") stimuli compared with new stimuli (referred to as the 'FN400' old/new effect). Recollection is correlated with greater left parietal positivity in ERPs for old compared to new items, with an onset around 500ms and a duration of 200-400ms, that is commonly referred to as the 'left parietal old/new effect' (Rugg & Curran, 2007). The dual process model predicts that unintentional recognition of distractors should primarily involve familiarity rather than recollection, because the former is a more automatic process than the latter. Consistent with this prediction, a recent study (Bergström, Williams, Bhula, & Sharma, 2016) found a specific link between a large ERP FN400 'familiarity' effect for distractors and behavioural recognition biases in the "Memory Stroop" paradigm

(Anderson et al., 2011), whereas the ERP left parietal 'recollection' effect was only associated with intentional target recognition.

These neural correlates of familiarity and recollection have been less widely researched in older adults compared to young, and the available evidence is less consistent. Considering familiarity, Friedman et al. (2011) found some consistency in the early mid-frontal ERPs of both older and younger adults. Wegesin et al. (2002) also found early (300-600ms) old/new differences for both groups, although the effect was more right-sided and had a later onset in the older group. However, often early ERP correlates for familiarity are reduced in older age groups (Friedman, 2013; Pitarque et al., 2016; Wang, de Chastelaine, Minton, & Rugg, 2012; for fMRI evidence see also; Duarte, Henson, & Graham, 2008)

Regarding recollection, older adults often fail to exhibit the classic left-parietal old/new ERP effect commonly found in younger adults (Bergström et al., 2016; Rugg & Curran, 2007) and instead often display different ERP patterns in the same scalp area and time window. Some studies have found reduced ERP old/new effects (Ally, Simons, McKeever, Peers, & Budson, 2008; Friedman et al., 2011; Sebastián, Reales, & Ballesteros, 2011; Wang et al., 2012) and others have even found reversed effects (Li, Morcom, & Rugg, 2004). Thus, whereas the effect of aging on the ERP correlate of familiarity is rather inconsistent, there is typically a more consistent reduction (or even reversal) of the ERP correlate of recollection in older compared to younger adults, consistent with theoretical models that suggest that aging primarily affects intentional processes that contribute to recollection, while leaving automatic familiarity intact (Koen & Yonelinas, 2014).

In addition to the typical old/new positive differences described above, episodic recognition is also often associated with a later posterior negativity (LPN) that has a sustained time-course (Donaldson & Rugg, 1998; Friedman, Cycowicz, & Bersick, 2005; Mecklinger, Rosburg, & Johansson, 2016). This ERP effect is more negative going for previously seen items and typically onsets before a response is made, often overlapping with parietal old/new effects (Duarte, Ranganath, Trujillo, & Knight, 2006), and continues and peaks afterwards. The LPN appears to reflect late stage memory processes, such as retrieval monitoring in situations of conflict (See Mecklinger et al., 2016 for a review). In the Memory Stroop paradigm, Bergström et al. (2016) also found an LPN effect for previously seen distractors, which they interpreted as related to post-retrieval or response monitoring that was elicited by unintentionally recognised distractors. That is, they argued that their young participants engaged monitoring processes to try to overcome response biases induced by distractor recognition.

Interestingly, late, sustained old/new negativities that resemble the LPN are often seen in older adults during episodic retrieval. However Mecklinger et al. (2016) observes that, in older adults, the late negativity found is often found over a wider area and is less focused over the posterior regions as typically observed in younger adults. Therefore, Mecklinger et al. suggest that the late negativity in older adults is unlikely to reflect the same ERP components as the LPN in young participants. Instead, late ERP negativities in older people may be caused by compensatory cognitive restructuring in older adults, or differences in retrieval strategies between young and old (Cabeza, Anderson, Locantore, & McIntosh, 2002; Craik & Rose, 2012; Friedman, 2013; Morcom & Johnson, 2015). Interestingly, it has been proposed (Dulas & Duarte, 2011) that overlapping components in older adults may be responsible for observed reductions of the classic old/new ERP effects described above. That is, the positive ERP components associated with familiarity and

recollection might be masked by LPN-like negativities that occur at the same time but have opposing polarities and therefore "cancel out" at the scalp (Luck, 2014) To investigate this issue, James et al. (2016) carried out additional filtering targeted at removing sustained lower frequency components and subsequently also found typical old/new differences in the 250-500ms time-frame. Their results were thus consistent with the view that aging often spares automatic memory processes such as familiarity (Koen & Jonelinas, 2014), but suggests that these processes are not always detected with standard ERP methods.

6.2. Brain oscillations and episodic retrieval

Rhythmic neural activity - brain oscillations - are generated by the synchronised firing of groups of neurons and the frequencies of these oscillations are recognised as a central mechanism underlying memory (Hanslmayr & Staudigl, 2014). Decomposition of raw EEG signals using mathematical techniques such as Fourier Transforms have revealed that these different frequencies typically cluster into specific frequency bands where activity in that band tends to show similar functional properties. EEG oscillations therefore are most commonly separated into Delta (0-4Hz), Theta (4-8Hz), Alpha (8-12Hz), Beta (12-30Hz) and Gamma (>30Hz) bands (Sauseng & Klimesch, 2008). It is common to make a distinction between induced oscillations - EEG potentials generated by non-automatic higher-order processes that may or may not be time-locked to stimulus onset versus more automatic evoked potentials which are tightly time-locked and therefore contribute to ERPs (David, Kilner, & Friston, 2006).

Oscillation analysis is a complementary technique to ERPs as it offers a number of methodological advantages in certain situations. In the first instance, variability in the temporal onset of evoked potentials ('latency jitter') can have a detrimental impact on

derived ERPs typically by causing a flattening of the estimated signal (Kok, 2001). As latency jitter in neurocognitive processes is a characteristic that is more widely encountered in older adults (Saville et al., 2011; Schmiedt-Fehr & Basar-Eroglu, 2011) it is not unreasonable to expect age-related differences in ERPs between groups for this reason (independent of other possible causes). Measuring induced oscillations thus enables researchers to better capture neural effects that have a degree of temporal variability. Furthermore, since the raw EEG signals themselves represent the summation of multiple concurrent but dissociated brain processes (as discussed above), decomposing the data into non-overlapping frequency bands may provide a helpful first step in dissociating different neurocognitive processes that may be associated with different frequency bands.

Recent research has investigated the possible roles of each frequency band in episodic memory, in terms of event-related synchronization and desynchronisation of individual bands across different brain regions (Hanslmayr, Staresina, & Bowman, 2016). Considering memory retrieval in general, decreases in synchronised activity (power) in both the alpha and beta bands (i.e. neural desynchronisation) have been shown to correlate with memory retrieval (Hanslmayr, Staudigl, & Fellner, 2012). With regards to familiarity, alpha power decreases with a wide scalp distribution have been found between 400-600ms in haptic recognition memory, which was also modulated by age (Sebastián et al., 2011), and an association between familiarity and the gamma band has also been suggested (Gruber, Tsivilis, Giabbiconi, & Müller, 2008). However, there is also evidence linking theta synchronisation with familiarity (Klimesch, Doppelmayr, Yonelinas, et al., 2001) so the evidence on this issue is rather unclear. In contrast, many studies have found that recollection correlates with an increase in synchronised theta band activity (i.e. increased theta power) in younger adults, that typically has a left parietal distribution and thus may

be related (but separable) from the left parietal old/new ERP effect (Gruber et al., 2008; Jacobs, Hwang, Curran, & Kahana, 2006; Strunk, James, Arndt, & Duarte, 2017).

Despite the substantial amount of research into EEG oscillations and memory in young adults, there is much less research on age related differences in brain oscillations related to memory, however reliable old/new effects in theta were found in both younger and older adult groups in a haptic recognition memory task (Sebastián et al., 2011). A recent study (Strunk et al., 2017) investigating EEG oscillations in source memory found similar theta power increases in young and old groups, and interpreted this to mean that similar amounts of information were recollected by both groups. Thus, there is some evidence from the literature that older and younger adults can show rather similar recognition-related EEG oscillation effects, even though their ERP effects are often markedly different.

6.3. Summary and aims

This study investigated behavioural, ERP and oscillation measures of distractor-induced recognition biases. Two groups, one of younger and the other of older adults completed a Memory Stroop paradigm whilst having their EEG recorded, and I analysed their behavioural responses, ERPs, and theta/alpha oscillations.

I aimed to replicate the behavioural findings that older adults were more susceptible to intentional recognition biases caused by unintentional recognition of distractors in the "Memory Stroop" task (Anderson et al., 2011) and to examine how the ERP correlates of familiarity (FN400), recollection (late parietal), and post-retrieval monitoring (LPN) for targets and distractors were affected by ageing, by comparing an older groups' performance with existing findings from a younger cohort (Bergström et al., 2016).

Finally, I undertook a time-frequency decomposition of the raw EEG signals to investigate possible links between alpha and theta power and intentional versus unintentional recognition memory, and to explore whether these oscillatory effects differed between older and younger adults.

6.4. Predictions

6.4.1. Behavioural predictions

First, I expected to replicate Anderson et al.'s (2011) previous findings that hit rates (correctly recognising a previously seen target word as 'old') were reduced in the older adults in line with their well-reported decline in episodic memory (Nyberg et al., 2012). However, previous research had not placed older adults under working memory load conditions in this paradigm, so I also expected to possibly find a larger reduction of hits in the older adults due to this additional challenge. I expected to find correct rejections (correctly detecting a previously unseen target word as 'new') to be similar for both groups, in line with Anderson et al. (2011) who found that age primarily reduced hits and not correct rejections. I also expected slower response times (RTs) in the older compared to younger group, in common with Anderson et al. (2011) and the literature on ageing research.

Most importantly, I expected to replicate previous findings (Anderson et al., 2011) that the congruency of target and the distractor (e.g. congruent: both OLD or both NEW; or incongruent: one OLD, one NEW) affected the participant's accuracy so that congruent trials were more accurate than incongruent trials, both in terms of hits and correct rejections. I also expected that this bias may be increased in magnitude in the older adult group due to their known problems with enhanced distractibility (Weeks & Hasher, 2014).

6.4.2. ERP predictions

ERP findings in this Memory Stroop paradigm with younger adults (Bergström et al., 2016) found significantly more positive midfrontal early ERP amplitudes (FN400) for both the old target words and old distractor images than their corresponding new conditions, which was interpreted to index a rapid and automatic familiarity process that occurs regardless of whether recognition in intentional or unintentional. Given the relatively well preserved automatic memory in older adults (e.g. Angel et al., 2013) I expected a similar effect in the old group, possibly even enhanced for the old distractor images due to older adults' increased difficulty in selectively attending to target information in the face of distraction, which could cause them to experience more unintentional recognition of distractors. Because previous research has suggested that recollection is impaired in older age (e.g. Koen & Yonelinas, 2014), this led me to expect that the older group would show a reduction in the late parietal ERP positivity previously found for old compared with new targets in younger adults (Bergström et al., 2016), that is widely associated with conscious recollection.

Bergström et al. found an LPN effect (Mecklinger et al., 2016) for previously seen distractors, which they interpreted as related to post-retrieval or response monitoring that was elicited by unintentionally recognised distractors. This LPN effect could arguably be decreased in the older group due to the expected poorer strategic memory processes in this group (Morcom, 2016), however the increased likelihood that the older group would recognise the distractors may instead lead to a stronger LPN effect in this group, if their need for response monitoring was enhanced. Finally, I also expected that the older group may show additional changes to neural components due to compensatory cognitive restructuring in older adults (Cabeza, 2002; Friedman, 2013; Morcom & Johnson, 2015).

6.4.3. Oscillations predictions

I expected to find increased theta power (Gruber et al., 2008) and a decrease in alpha power (Hanslmayr et al., 2012) as a function of intentional target recognition for the younger group, with similar but perhaps weaker effects in the older group due to their well reported impairment in recollection processing. Alternatively, if some changes in ERP effects in older adults (e.g. Li et al., 2004) are due to jitter of evoked responses and/or component overlap, then perhaps their oscillation effects will turn out to be more similar to the younger adult group than their ERPs (e.g. Strunk et al., 2017). Since EEG oscillations associated with unintentional recognition has not previously been investigated, I had no firm predictions for how theta and alpha would covary with recognition of distractors. Instead, I simply aimed to explore whether these oscillation effects were different when compared to intentional target recognition, and when compared across young and old groups.

7. Method

7.1. Participants

Two groups, each of 24 right-handed adults participated in this experiment (Younger group: $M_{age} = 21$; range = 18-24; 8 males, 16 females. Older group: $M_{age} = 66$; range = 60-76; 11 males, 13 females). Participants were all neurologically healthy, right-handed native English speakers and took part either as part of course requirements (younger group, first reported as Experiment 1 in Bergström et al., 2016) or as unpaid volunteers from the local community (older group). The older group were all socially active and in relatively good health and pre-screened using the MMSE (or Folstein test; Folstein, Folstein, & McHugh, 1975). A threshold of 26/30 was set for inclusion: no participants failed and the group average score was 29.4. The average number of years of full-time education for older group was 16.5 years (range 12 to 22 years). This data was not explicitly collected for the younger adult group however given that they were all university students it is likely that their group average was very similar. All reported normal or corrected-to-normal vision and provided informed consent prior to taking part. The experiment was approved by the Research Ethics Committee of the University of Kent.

7.2. Materials

Experiment stimuli were comprised of 272 words and 272 colour photographs. The words were all taken from the ANEW database (Bradley & Lang, 1999) with valence ratings ranging rating between 3.8 and 7.6 (9 point scale). All words contained between four and eight characters and either one or two syllables. The photographs were selected so that half were rated neutral and half negative valence, however as valence had no impact upon ERPs or behaviour all analyses were reported with this factor collapsed. The majority came from the IAPS database (9 point scale – ratings between 1.51 and 6.62; (Lang, Bradley, &

Cuthbert, 2008) with the remainder coming from the GAPED database (100 point scale –

ratings between 1.35 and 45.7; Dan-Glauser & Scherer, 2011). Sixteen words and 16

photographs (of balanced valence) were used for a practice phase with the remainder being

used in the actual experiment. The assignment of stimuli was fully counterbalanced across

the experimental conditions.

7.3. Experimental design and procedure

The experiment was identical to Experiment 1 in Bergström et al. (2016), which itself was

based on a novel "Memory Stroop" paradigm developed by Anderson et al. (2011), with

the only exception that older adults were only required to complete eight out of the 10

study-test blocks that had been completed by the young group (in order to avoid fatigue

due to an overly long session). To avoid confounds when comparing the results from the

groups, I then extracted data from the first eight blocks in the young group to use as a

comparison. The experimental tasks were implemented in E-Prime and displayed on a 20"

colour monitor operating with a resolution of 1024x768 pixels. All participants' responses

were given using the buttons 1-4 on a conventional QWERTY keyboard, and response

hand was counterbalanced across participants and maintained consistent through all tasks.

Before commencing the main experiment, participants were given verbal

instructions for the whole experiment, then they were required to carry out a short practice

block. This practice phase was repeated if participant performance was too low. Phase 1

was a study phase containing 32 trials (16 words and 16 images (photographs)) in which

individual stimuli were presented randomly intermixed. Each trial commenced with a

500ms fixation cross which was followed by the stimulus for 3000ms. Whilst there is

evidence that non-varying fixation periods can lead to temporal expectancy which can

become evident in the corresponding evoked potentials (Min et al., 2008), my subsequent analyses all focused on group comparisons and so any such affects can reasonably be expected to be consistent and so for consistency with the previous experiment with younger adults the pre-stimulus fixation period was kept constant. During the time the stimulus was on screen participants were required to enter a rating score of 1 to 4 for each individual stimulus indicating how 'pleasant' they found it to be, with higher number indicating a higher degree of pleasantness. These ratings were done to ensure deep encoding of all stimuli and to standardise encoding processing mode between individuals.
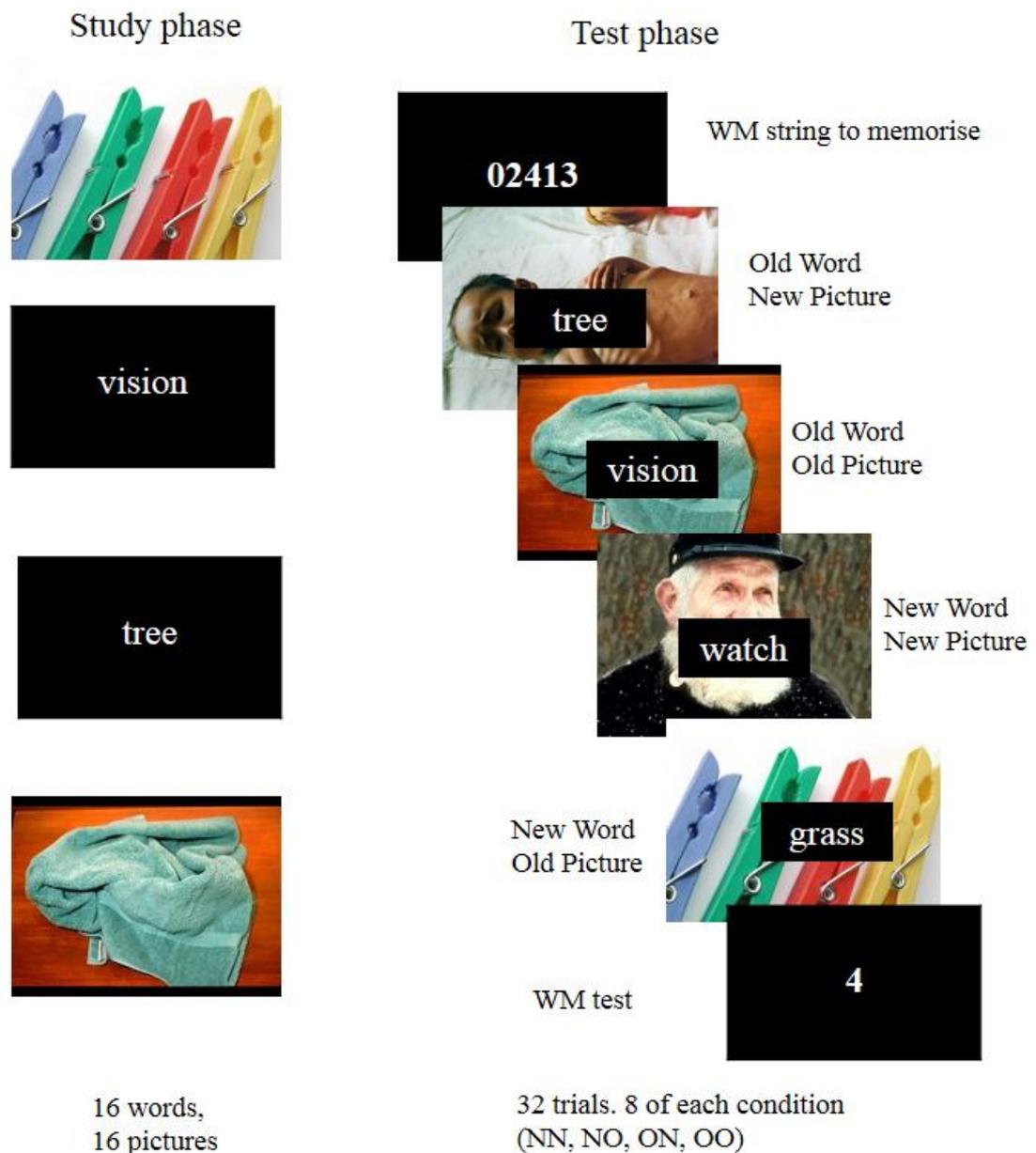
Figure 7.1 Schematic of the Memory Stroop task. Study phase: participants rated a series of words and images for 'pleasantness' on a scale of 1 to 4. Test phase: participants judged whether or not the central target word was previously seen (old or new), while ignoring distractor images. The test phase was interspersed with a WM load task (see method for details; text font not to scale).

A new WM string to memorise displayed prior to fixation pseudo-randomly once every 3-6 trials : 3000ms.

Fixation: 500ms.

Word/picture stimuli: upto 3000ms, display cleared upon old/new judgement response.

Number prompt, shown once every 3-6 trials. Participant has up to 3000ms in which to respond with the digit from the original string that followed this digit.(in this case '4')

Figure 7.2 Timeline of test phase.

Phase 2 comprised of two interspersed tasks. The primary recognition task included 32 trials, which commenced with the presentation of a fixation cross for 500ms followed by the simultaneous presentation of a background 'distractor' image overlaid with target word, both presented for 3000ms. Participants were instructed to consider only the target word stimulus and to: press '1' if they judged that the word had been presented previously in the study phase or '2' if they judged it to be a new word (i.e. not previously presented in the study phase) and also to reply as quickly as possible, whilst maintaining accuracy. The word-image combinations were arranged in one of four possible conditions (a new word with either a new or old image or an old word with either a new or an old image), with eight word-image pairs for each condition being presented in a randomly intermixed order. Any late responses given after the stimuli pair had been cleared from the screen were removed from the analysis.

Previous research has shown that the effect of incongruent distractors is increased when participants' attention is divided (Ste-Marie & Jacoby, 1993), therefore participants were required to additionally perform a working memory task simultaneously with the main task. This secondary task required the participant to maintain a sequence of four digits (drawn from 1234 and always starting with the digit 0) in working memory using a covert rehearsal technique which has been shown to increase distractor effects (de Fockert, Rees, Frith, Christopher, & Lavie, 2001). Such a number string was displayed for 3 seconds and then followed by between four to six of the previously described target word recognition trials. Subsequently a single digit was displayed for 3 seconds, during which time the participant was required to press the appropriate key to indicate the digit had that followed the probe digit in the original string. For example, given the string '02143' as in Figure 7.1, if prompted with a '1' the correct participant response would be to press the '4' key. To help ensure that participants were engaged in this WM task, they were given immediate on-screen feedback (correct/incorrect) after their response. Subsequently a new five-digit string was presented for the participant to remember during the next sequence of trials and when later prompted with a single digit, they needed to respond according to the most recent number string they had seen. Importantly, during the pre-experiment briefing participants were instructed that (i) both the target word and the number string tasks were equally important; (ii) the number string always started with the digit 0 (iii) they should sub-vocally rehearse the number string when it appeared and continue to do this whilst they performed the subsequent target word trials. The researcher continued to monitor performance of the number string task and if the running total accuracy was below 60% then the participant was gently reminded at the next inter-block rest of the instructions (however they were not informed of their score).

The third and final component of each experiment block was a 'distractor recognition test' that included four trials where the participant was shown an individual image (presented for 3000ms following a 500ms fixation cross) and asked to judge whether or not they had seen it in the previous study phase (pressing 1 for 'previously seen' ('old') and 2 for 'new'). The rationale for this test was to make sure that participants paid equal attention to memorise the images as well as the words in the first (study) phase (knowing that this would be tested). Participants were permitted short rest breaks at the end of each study-test block.

Behavioural data analysis focused on recognition performance (accuracy and RTs) from the primary recognition test. For each DV, an ANOVA with the factors Group (Older/Younger adults), target Word (Old/New) and distractor Image (Old/New) was conducted and these were followed up with 2-way ANOVA's or two-tailed t-tests as appropriate.

7.4. EEG recording and pre-processing

EEG was recorded continuously during the test phase using an actiCAP (Brain Products Gmbh) with 64 electrodes at 500Hz and with a 0.05-70Hz bandwidth filter. Electrode locations were positioned in accordance with the extended 10-20 system with FCz as the electrical reference electrode. Before EEG data acquisition, the impedance at each electrode was reduced to under 25 KOhms (required threshold for these types of active electrodes) and signal quality was visually monitored throughout the experiment. In addition, electrooculography (EOG) was recorded at two sites - lower-left VEOG and right side HEOG.

Offline processing of the recorded EEG data was carried out using EEGLAB (Delorme & Makeig, 2004). Each participant's data were processed independently as follows. Initially all signals (apart from HEOG & VEOG) were re-referenced to the average value of the two mastoid electrodes and then the test phase data was segmented into 3500ms epochs (this included a 500ms pre-stimulus period). These epochs were baseline corrected to the average amplitude between -200-0ms pre-stimulus. Any excessively noisy channels were removed (and interpolated later on post-ICA) and any individual trial epochs that contained extreme noise (e.g. excessive muscle activity) were removed. Each participant's concatenated data were then individually submitted to Infomax ICA (using EEGLAB's *runica* method with the 'extended' option set) after which the data was cleaned by the visual identification and removal of noise components that were deemed to represent eye movements (blink & saccade), muscle activity or bad electrodes. Identification was done by studying a combination of activity power spectrum plots, component scalp maps, and the time course of the component activity across all trials. The components identified for removal were then removed from the original data by back-projection of the remaining components to generate the cleaned data signals. The data was then filtered (30Hz low pass) and re-baselined again against the mean of the 200ms period preceding stimulus. Any channels that had been removed previously were then interpolated. The cleaned and filtered trial data were visually assessed and any trials that retained noticeable artefacts were removed. Altogether these steps lead to an average of 7.4% of trials being excluded (ranging from 6.6% to 8.1% across the four conditions – see Appendix A). Because the young group had more EEG trials than the old group (due to completing 10 blocks rather than eight), I then randomly paired each young participant with an old participant and matched the trials across each condition. For example, if the old participant had 60 trials and the young participant had 72 in a particular condition, I

deleted the last 12 trials in the young participant's data. This matching process ensured

identical EEG trial numbers per condition across the two groups.

Table 7.1 Average, maximum and minimum number of epochs used to generate each participants ERPs per condition (same for both groups).

	Mean	Maximum	Minimum
Old Word Old Image	59	63	44
Old Word New Image	59	64	46
New Word Old Image	58	64	41
New Word New Image	58	64	46

Next, the pre-processed and cleaned EEG data were further analysed in two ways.

First, ERPs were generated for the four conditions by averaging together the raw EEG

across epochs for each condition and participant separately. Second, the raw single-trial

EEG data was also processed using EEGLAB's time-frequency (TF) decomposition

function (*newtimef*), which uses Morlet wavelets (Percival & Walden, 1993) to extract

event-related spectral perturbations (ERSP), which is a measure of oscillatory power over

time as elicited by an event, in comparison to a baseline period. This function was applied

to the single trial data and subsequently averaged to estimate the average ERSP for each

condition, which means that it captured both evoked and induced oscillations. ERSP was

estimated for two non-overlapping frequency bands (theta: 4-7Hz (incl.); alpha:8-11Hz

(incl.)) with wavelets centred at equal 1Hz intervals and the number of wavelet cycles

increasing slightly from lower frequencies to higher (in order to optimise the trade-off

between temporal versus frequency resolution), ranging from 3 cycles at 4Hz to 4.125 at

11Hz. In order to ensure that the prestimulus period was sufficiently long for reliably

estimating the baseline power of lower frequencies, I mirrored each 500ms pre-stimulus

segment and concatenated it to the beginning of each epoch (see e.g. Vogelsang, Gruber,

Bergström, Ranganath, & Simons, 2017), thus resulting in a 1000ms prestimulus period for

time-frequency decomposition. To avoid edge effects (distortions at the beginning and end

of the time-window being analysed), the decomposition process involves removal of some data points at the start and at the end of each epoch ERSP resulting in the -1000ms to +3000ms time window being truncated down to -582ms to +2580ms. As a result, the ERSP was estimated in relation to the average power during a baseline period between -582ms to -375ms pre-stimulus. This baseline period was chosen so that it would fall before the time point where post-stimulus activity might "bleed" into the pre-stimulus period due to the low temporal resolution of the lower frequency wavelets (a 3-cycle 4Hz wavelet centred at time zero actually extends -375ms into the pre-stimulus time-window), to ensure the baseline was not biased by stimulus-elicited activity.

7.5. EEG statistical analysis

For both ERPs and EEG oscillations, I initially conducted targeted analyses focusing only on the time-windows and electrode locations where the ERP correlates of familiarity and recollection are typically expressed. Thus, following Bergström et al. (2016) and a large body of literature (e.g. Rugg & Curran, 2007), I extracted mean ERP amplitudes from the mid-frontal Fz electrode between 300-500ms to measure the FN400 old/new effect and from the left parietal P3 electrode between 500-800ms to measure the left parietal old/new effect. These mean amplitudes were analysed with ANOVAs (with the factors Group (Older/Younger adults), target Word (Old/New) and distractor Image (Old/New)), and significant ANOVA effects were followed up with two-tailed *t*-tests. As appropriate, to test how familiarity-related and recollection-related ERP effects would be modulated by aging based on our a-priori hypotheses. I also analysed mean power of recognition-related theta and alpha EEG oscillations at the same time-windows and locations and using the same analysis procedure (ANOVA and *t*-tests),in order to determine whether they were modulated in a similar way to the ERP effects or not.

Analysing EEG data only from specific time intervals at a few, specific electrode sites risks missing effects in other time windows and at other scalp locations, both of which might reasonably be expected given other evidence for increased temporal jitter and also for brain compensatory effects in older adults (see introduction). Furthermore there is little literature relating to the location and timing of memory-related oscillation effects in older adults. To provide a more comprehensive account, non-rotated Task Partial Least Square (Task-PLS) analyses of the whole spatio-temporal data were conducted the both on the ERPs and on the derived oscillation data. Task PLS is a multivariate correlational technique that analyses the cross-block covariance between a matrix of the spatio-temporal EEG/ERP data and *a priori* orthogonal contrast vectors that relate to the experiments hypotheses (in this case: old vs. new words; old vs. new images; young vs. old group, and their interaction terms – see Appendix A for specific details) to conduct inferential analyses of the relationship between the experimental design and the resultant brain activity without focusing on specific time points or electrode sites. The technique uses permutation testing (randomisation without replacement) to repeatedly calculate the sums of squares of the cross-block covariance between the spatio-temporal data and the design contrasts with conditions randomly shuffled, to determine the probability of obtaining the observed covariance (or larger covariance) under the null hypothesis. To estimate where and when effects reliably occur, it also computes "electrode saliences" for each contrast, which show the time point and electrodes that most strongly show the effect. It then estimates the confidence intervals of these saliences by bootstrap resampling (sampling with replacement) from the original sample and recalculating the electrode saliences for each bootstrap sample. If the ratio of the observed salience to its bootstrap standard error is greater than 1.96 it can be considered reliable as this ratio is roughly equivalent to a z-

score if the distribution is Gaussian. For detailed descriptions of PLS, see Krishnan,

Williams, McIntosh, & Abdi, (2011)

The PLS analysis was conducted on each dataset using PLSGUI, a Matlab toolbox

(McIntosh & Lobaugh, 2004) that is freely available from www.rotman-baycrest.on.ca. For

these analyses, 7500 permutations (resampling without replacement) were used to test the

covariance of the contrasts with the spatiotemporal EEG data and 500 bootstraps

(resampling with replacement) were used to determine the confidence intervals on the

electrode saliences.

8. Results

8.1. Behaviour

Both groups exhibited high accuracy in the WM task, although the old group performed somewhat lower, but not significantly so (Younger adults (YA): $M = 0.84$, $SD = 0.10$; Older adults (OA): $M = 0.79$, $SD = 0.11$; $t(46)=1.55$, $p=.13$). One participant in each group scored lower than two standard deviations below the mean (WM accuracy = 0.57 and 0.55 respectively for the younger and older group) however excluding these did not affect any of the inferential results for the target recognition task and so all participants were included in all analyses.

Table 8.1 summarises the accuracy and responses times on the target recognition task for both the younger and the older groups for, separated into the four conditions.

Table 8.1 Mean proportion accurate responses and reaction times (ms) for target recognition in both groups.

	Younger adults		Older adults	
	Mean Accuracy (SD)	Mean RT (SD)	Mean Accuracy (SD)	Mean RT (SD)
Old Word Old Image	.94(.07)	1220(206)	.86(.12)	1454(244)
Old Word New Image	.90(.08)	1174(191)	.83(.12)	1419(218)
New Word Old Image	.90(.11)	1291(201)	.89(.08)	1496(193)
New Word New Image	.93(.07)	1253(222)	.91(.08)	1456(220)

8.1.1. Behaviour - Accuracy

A 2x2x2 mixed ANOVA was carried out on the accuracy data (within subjects factors: Target Word old/new status and Distractor Image old/new status; between subjects factor: Age). This revealed a main effect of Age, with lower accuracy in the old than the young group ($F(1,46)=4.66$, $p=.04$). There was however a trend for an interaction between Age and Target Word old/new status ($F(1,46)=3.56$, $p=.066$, $np^2=.072$), which was driven by

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lower hit rates for older adults (M=.85 SD=.12) compared to younger adults (M=.92, SD=.07; t(37.5)=2.65, p=.01 Cohen's d=.55), but no significant difference between groups in correct rejection rates for new words (t(46)=1.55, p=.13).

Importantly, there was also a significant effect on accuracy based on the congruency of the stimuli with reduced accuracy for trials with incongruent stimuli (old word & new image or new word and old image) compared with congruent stimuli (old/old or new/new; Interaction between Target Word old/new status and Distractor Image old/new status: F(1,47)=14.97, p<.001, np^2=.242). However, there was no group interaction with this congruency effect (Three-way interaction: F(1,46)=0.15, p=.70, np^2=.003) and no other significant effects (Word: F(1,46)=2.35, p=.132, np^2=.049; Image: F(1,46)=0.923, p=.342, np^2=.02; Image x Age: F(1,46)=0.004, p=.949, np^2<.0001). To follow up on the significant congruency interaction, paired samples t-tests were performed to compare the effect of old vs. new distractors separately for hits and correct rejections, collapsed across age groups. Hits were significantly more likely with old than new distractors (t(47)=3.38, p=.001, Cohen's d=.31) whereas correct rejections were significantly more likely with new than old distractors (t(47)=2.61, p=.012, Cohen's d=.25).

8.1.2. Behaviour – Reaction times

A 2x2x2 mixed ANOVA of the same design was similarly carried out for reaction times (in ms). This elicited significant main effects for Age, Word (old/new) and Image (old/new), as follows. Older adults were significantly slower overall (M=1454, SD=188) than younger adults (M=1235, SD=197; F(1,46)=15.5, p<.001 np^2=.252). Responses for Old Words were significantly faster (M=1317, SD=242) than responses for New Words (M=1372, SD=225; F(1,46)=5.82, p=.02, np^2=.112). Trials with a previously seen distractor image elicited significantly slower responses (M=1365, SD=224) than trials with new distractor images (M=1323, SD=222; F(1,46)=19.66, p<.001, np^2=.299). There were no significant interactions between any of the factors, including no congruency bias as found for the accuracy data (Word x Age: F(1,46)=0.802, p=.375, np^2=.017; Image x Age: F(1,46)=0.001, p=.979, np^2<.001; Word x Image: F(1,46)=0.044, p=.835, np^2=.001; Word x Image x Age: F(1,46)=0.524, p=.473, np^2<.011).

In sum, the behavioural analysis highlighted the following key findings. There was an overall congruency bias for target recognition accuracy with greater accuracy for trials where the old/new status of target word and distractor image were the same, which is consistent with previous findings (Anderson et al., 2011; Bergström et al., 2016). There was however no significant difference in this congruency bias between the old and young groups, as had been found previously (Anderson et al., 2011). Neither group showed a congruency bias for reaction times, but there was evidence of both lower hit rates and generally slower responses in the old group. Thus, whereas the older group showed impaired performance in terms of target recognition accuracy and speed, the influence of unintentional distractor recognition was very similar across age.

8.2. ERPs

Grand-average ERPs were derived for each group for the mid frontal (Fz) and the left

parietal (P3) sites. See Figure 8.1 for ERP plots showing the four conditions and Figure 8.2

for scalp topography plots showing the old/new differences for both target words and
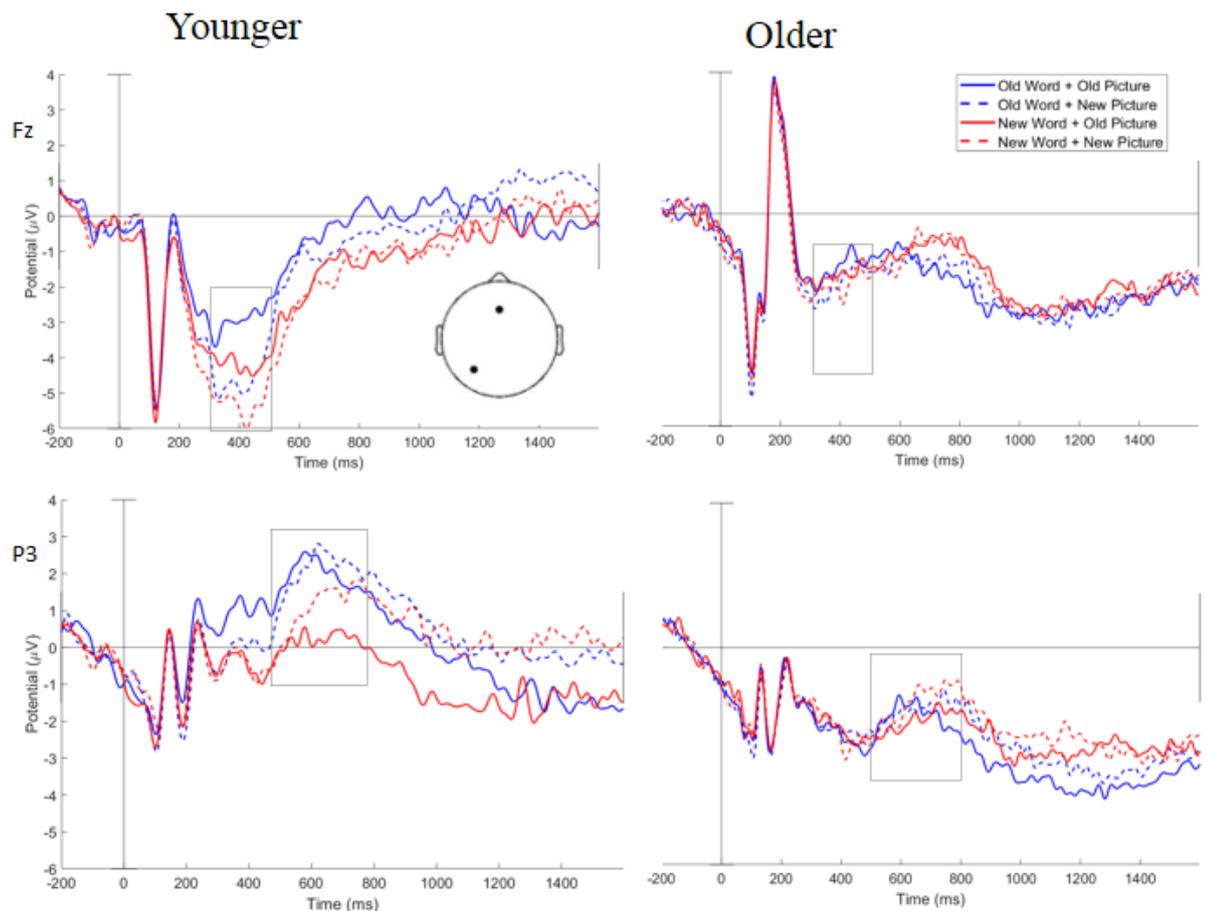
distractor images.

Figure 8.1 Grand-average ERPs for older and younger adults at mid-frontal (top) and left-parietal (bottom) locations for the four conditions. Boxes in the upper panel highlight the 300–500ms time-window used to analyse the FN400 old/new effect at Fz, and boxes in the lower panel highlight the 500-800ms time-window used to analyse the left parietal old/new effect at P3.
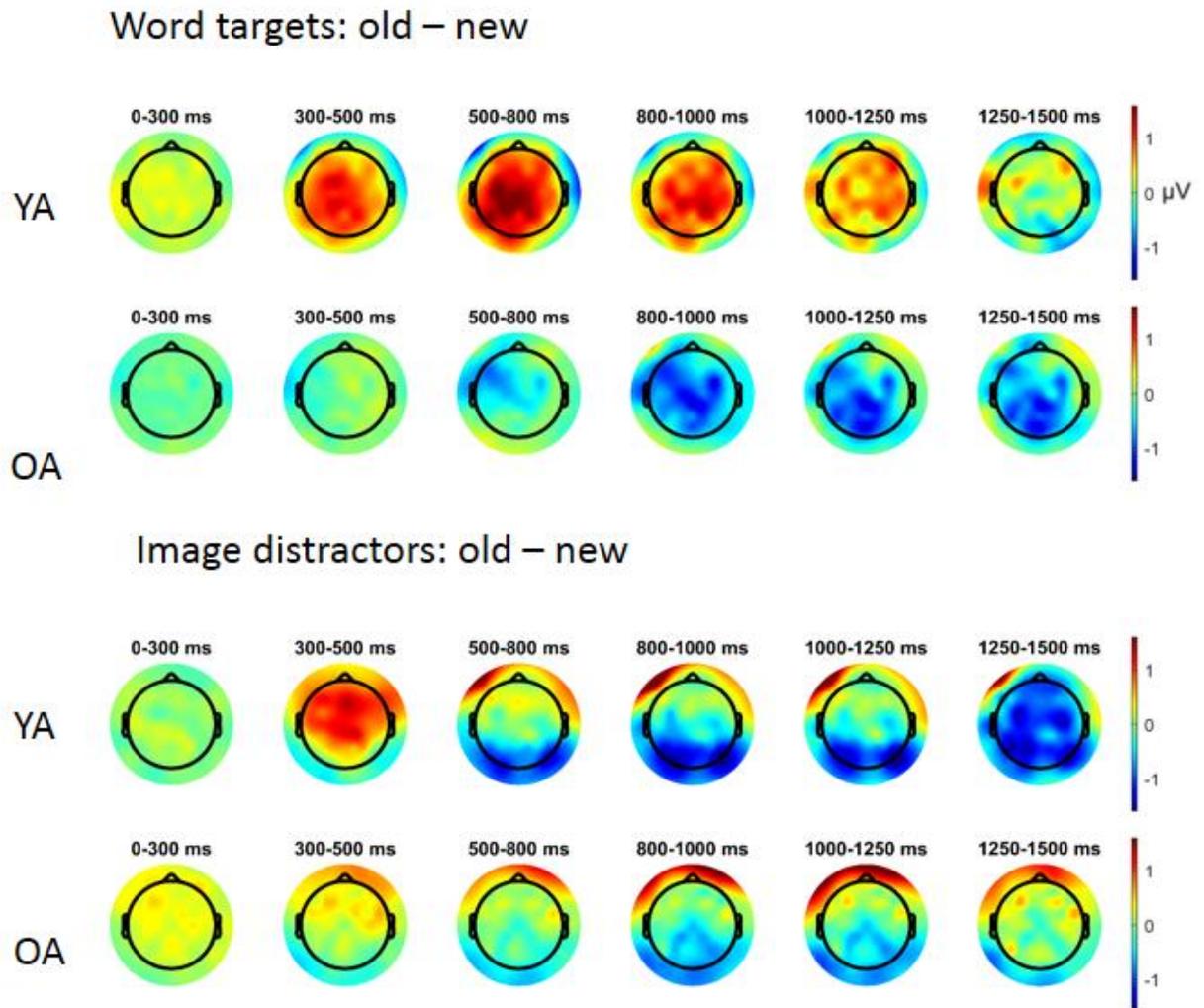
Figure 8.2 Scalp topographies of old-new effects for target Words and distractor Images for younger (YA) and older (OA) groups. Whilst the younger group elicited the anticipated early FN400 and later parietal old/new effects, these were not strongly expressed in the older group, who instead showed a centro-parietal negativity for old compared to new targets.

8.2.3. ERPs - Targeted analysis

8.2.3.1. FN400 old/new effects

A 2x2x2 mixed ANOVA was conducted on mean ERP amplitudes at Fz between 300-500ms with the same factors as the behavioural analysis (within factors: Target Word old/new status and Distractor Image old/new status; between factor: Age). This analysis

revealed significant FN400 modulations dependent on whether both target Words ($F(1,46)=6.83$, $p=.012$, $np^2=.129$) and distractor Images ($F(1,46)=43.91$, $p<.001$, $np^2=.488$) had been previously seen, however there was a highly significant interaction for Image old/new status with Age Image x Age: $F(1,46)=14.56$, $p<.001$, $np^2=.24$) and a trend to interaction between Word and Age ((Word x Age: $F(1,46)=4.03$, $p=.051$, $np^2=.081$). No other interactions were significant (Word x Image: $F(1,46)=0.970$, $p=.330$, $np^2=.021$; Word x Image x Age: $F(1,46)=0.189$, $p=.666$, $np^2=.004$). Follow up paired t-tests within each group revealed that for target Words, positive FN400 ERPs for old compared to new Words was only evident in the younger group ($t(23)=2.64$, $p=.014$, Cohen's $d=.19$) with no FN400 differences between old and new Words in the older group ($t(23)=0.624$, $p=.539$). However, the old Images elicited significantly more positive FN400s than new Images in both younger ($t(23)=6.68$, $p<.001$, Cohen's $d=.28$) and older participants, albeit the difference was smaller in the latter group ($t(23)=2.25$, $p=.034$, Cohen's $d=.13$).

8.2.3.2. Parietal old/new effects

For the left parietal site, mean ERP amplitudes between 500-800ms were submitted to another 2x2x2 mixed measures ANOVA (same factors as in previous sections). This analysis revealed significant old/new memory main effects for Target Words ($F(1,46)=11.34$, $p=.002$, $np^2=.198$) and also an interaction between Age and Word old/new status (($F(1,46)=12.21$, $p=.001$, $np^2=.21$), which was caused by the typical parietal old/new difference for target Words being present only in the young group ($t(23)=4.29$, $p<.001$, Cohen's $d=.28$) with no difference found in the older group ($t(23)=0.106$, $p=.917$).

There was also a main effect of Image ($F(1,46)=7.10$, $p=.011$, $np^2=.134$) that was in the opposite direction to typical old/new effects, but this effect did not significantly interact with Age ($F(1,46)=0.632$, $p=.431$, $np^2=.014$). That is, old Images elicited significantly more *negative* parietal ERPs in this time-window than new Images in both young and old adults (see Fig 8.2). There was no other significant effects (Word and Image ($F(1,46)=2.56$, $p=.117$, $np^2=.053$; Word x Image x Age ($F(1,46)=0.279$, $p=.60$, $np^2=.006$).

8.2.4. ERPs split by performance in older group

To further investigate the somewhat surprising lack of FN400 and left parietal old/new ERP effects in the older group, the older group was split into two, equally sized sub-groups based on their overall recognition accuracy scores collapsed across all conditions. The purpose of this analysis was to understand whether the small old/new differences were simply due to the older groups' on-average poorer target recognition memory, or due to other factors. The mean accuracy for the two older groups (high and low) was 93.5% and 81.2% and this compared with an average accuracy of 91.7% for the whole younger group. Thus the younger group and the high scoring older group had comparable mean accuracy. Due to the small groups sizes (N=12) no statistical analyses were undertaken for the two sub-groups however visual inspection of Figure **8.3** (grand-average ERPs) and Figure 8.4 (scalp topographies) indicate that it was not the case that the higher performing older adults showed preserved FN400 and left parietal old/new effects. Instead, the main difference between the groups seemed to be a larger centroparietal negativity for old compared to new target words in the low performing sub-group (although as this effect was not confirmed statistically it should be interpreted with caution).
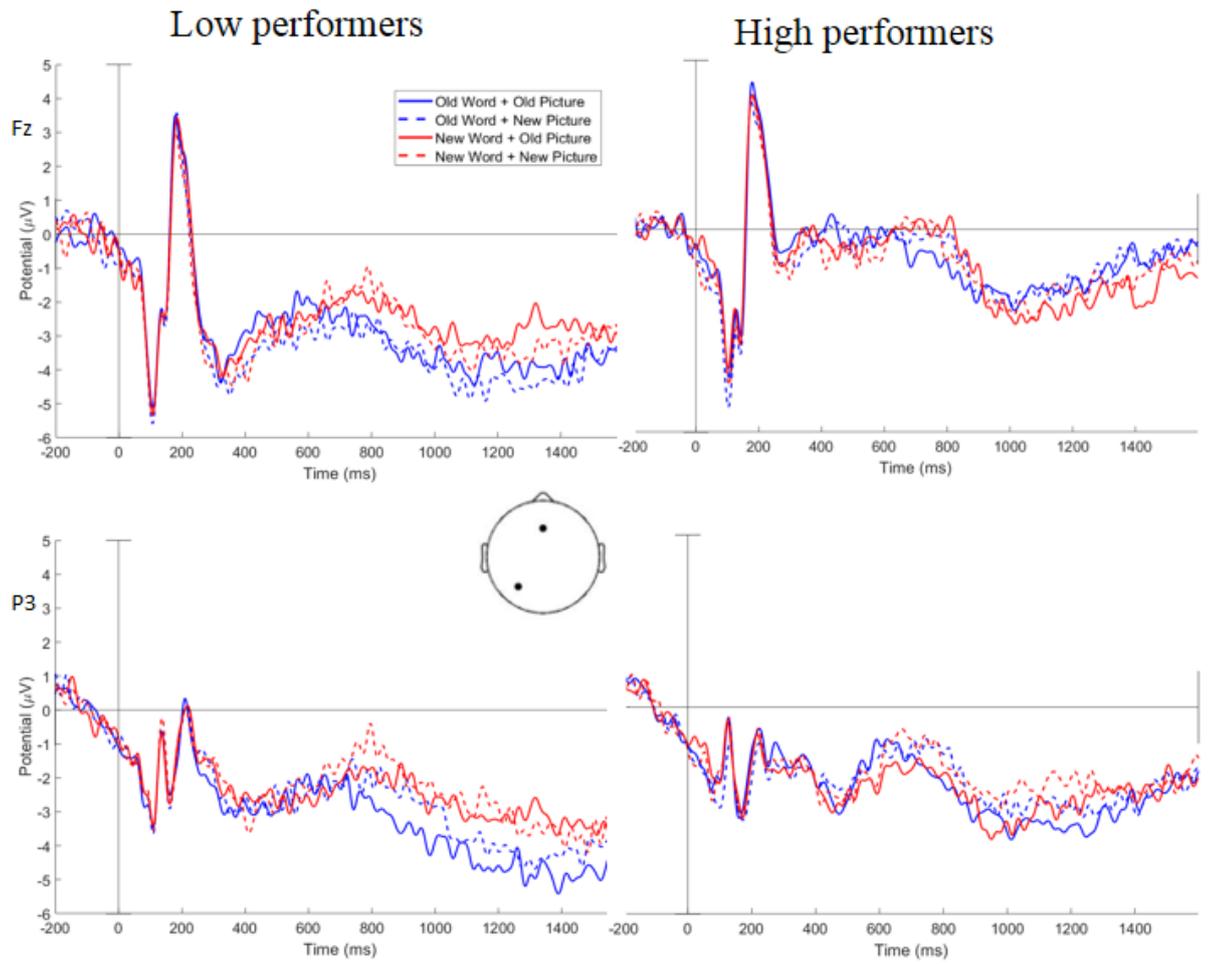
Figure 8.3. **Grand average ERPs for higher and lower performing older adults at mid-frontal (top) and left-parietal (bottom) locations for the four conditions.**
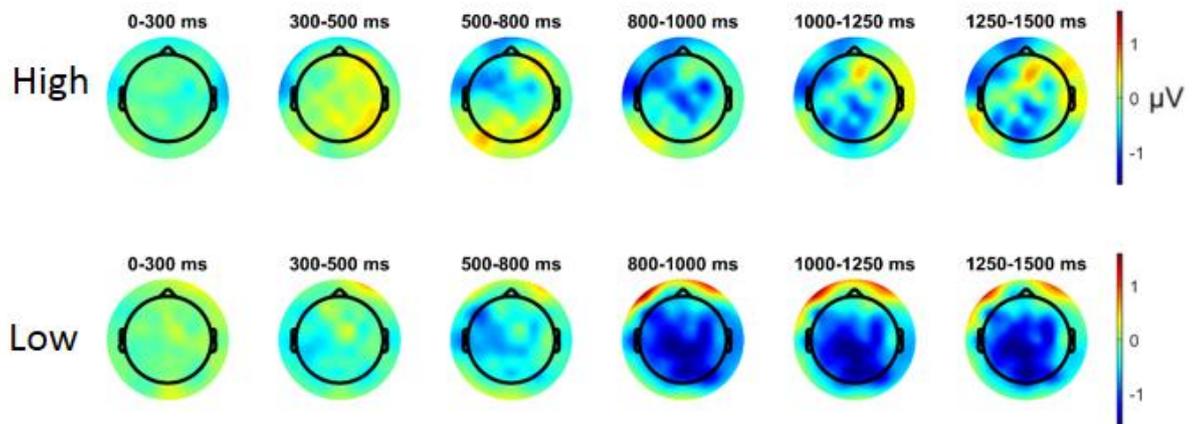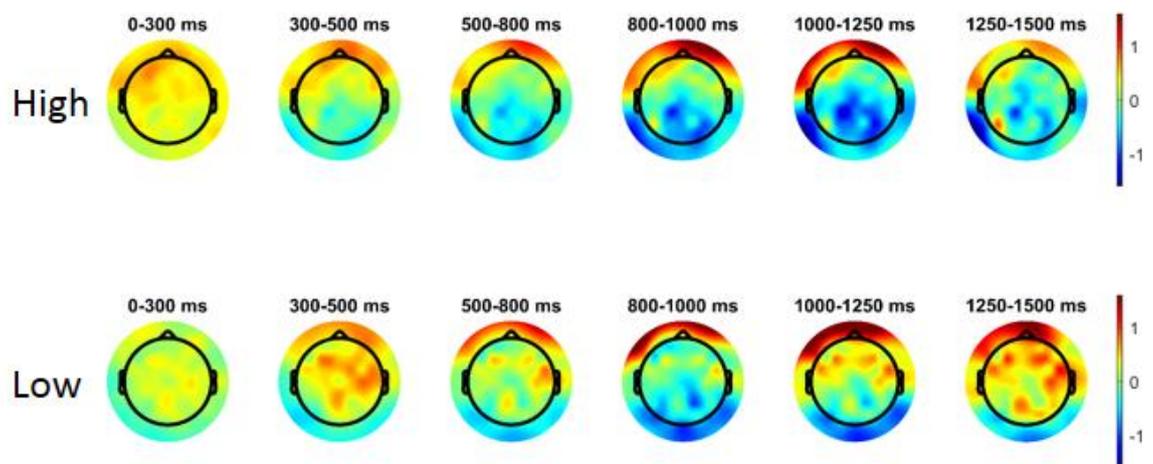
Figure 8.4 Scalp topographies of old-new effects for target Words and distractor Images for high performing and low performing older adults. Neither group clearly showed the canonical FN400 and left parietal old/new effects

8.2.5. ERPs - PLS whole head analysis

Next, I conducted a data-driven non-rotated Task PLS analysis of the ERP data in order to investigate ERP effects that may have been missed by the targeted focal analysis. This analysis was carried out on all scalp channels (excluding EOG channels) and over a time window from 0 to 1500ms (comparable to Bergström et al., 2016). The first analysis was carried out with the full factorial structure as used in the previous sections (within factors: Target Word old/new status and Distractor Image old/new status; between factor: Age; see Figure 11.1 and Figure 11.2 in Appendix A for details of the contrast matrices used for the PLS analyses). This analysis revealed a highly significant main effect of Group, and significant main effects were also found for both target Words and distractor Images as well as a highly significant interaction between target Word and Group (see Table 8.2). Subsequent non-rotated PLS analyses with the Word and Image factors within each group found significant main effects within both old and young groups for both Target Word and for Distractor Image old/new status (Table 8.2). However, inspecting the scalp distributions of these effects (see Figure 8.5 for the electrode salience to bootstrapped standard error ratios for old/new contrasts) showed that the Word x Group interaction in the full factorial analysis was caused by *opposite* going old/new differences for Target Words in the young compared to old group. That is, while the young group showed sustained ERP positivities for old compared to new Word Targets, the old group showed sustained ERP negativities with a later onset (see also Fig. 8.2). Both groups showed a similar pattern of ERPs for old compared to new distractor Images, with and early fronto-central positivity followed by a later posterior negativity, although these effects were somewhat weaker in the older group.

Table 8.2 Significance values of the contrasts in the whole-head PLS analysis of the ERPs. Percentage cross-block covariance accounted for in parentheses. (Significant results highlighted in bold).

	Word	Image	W x I	Group	W x G	I x G	W x I x G
Combined	**.046** **(2%)**	**.001** **(4%)**	.106	**<.001** **(86%)**	**<.001** **(5%)**	.12	.849
YA	**.001** **(43%)**	**.006** **(38%)**	.163	-	-	-	-
OA	**.001** **(49%)**	**.025** **(37%)**	.754	-	-	-	-
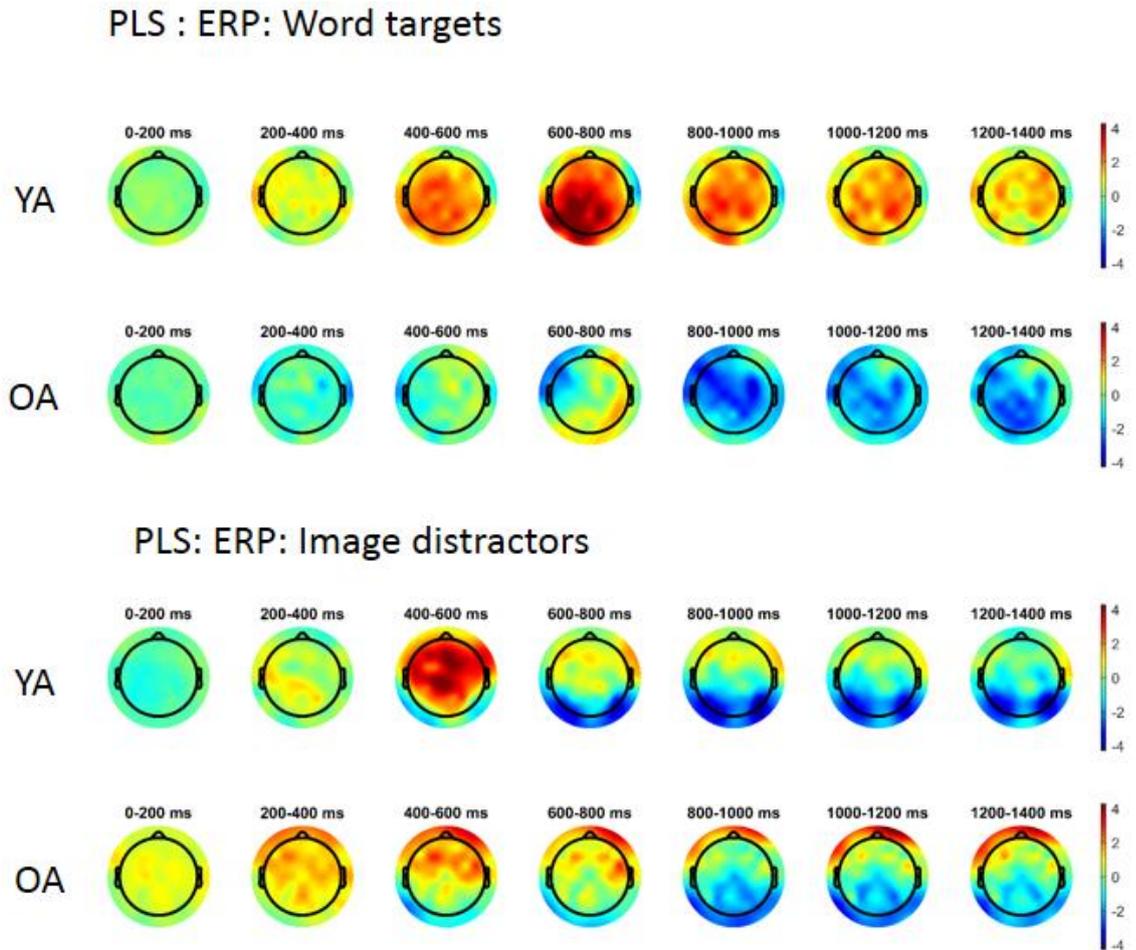
Figure 8.5 Scalp topographies of electrode saliences to bootstrapped standard error ratios for old/new contrasts in the whole-head PLS analysis on ERPs. These plots show the reliability of old/new effects for target Words (upper) and distractor Images (lower) separately for younger (YA) and older (OA) groups. The bootstrap ratios are approximately equivalent to z scores; values > 1.96 indicate electrodes and time points that reliably show more positive ERP amplitude for old than new items, and values < −1.96 indicate electrodes and time points that reliably show more negative ERP amplitude for old than new items

Time-frequency analysis

Figure 8.6 and Figure 8.7 show the estimated ERSP old/new differences at two sample electrodes (Fz and P3), with alpha and theta bands highlighted. These plots illustrate similarities between the older and younger groups in oscillatory old/new differences, in that both groups seemed to show enhanced alpha and theta power for old compared to new words, whereas old images elicited enhanced theta power but reduced alpha power. Figures

8.8 and 8.9 shows the average time-course of mean alpha and theta ERSP changes

respectively, for all four conditions.
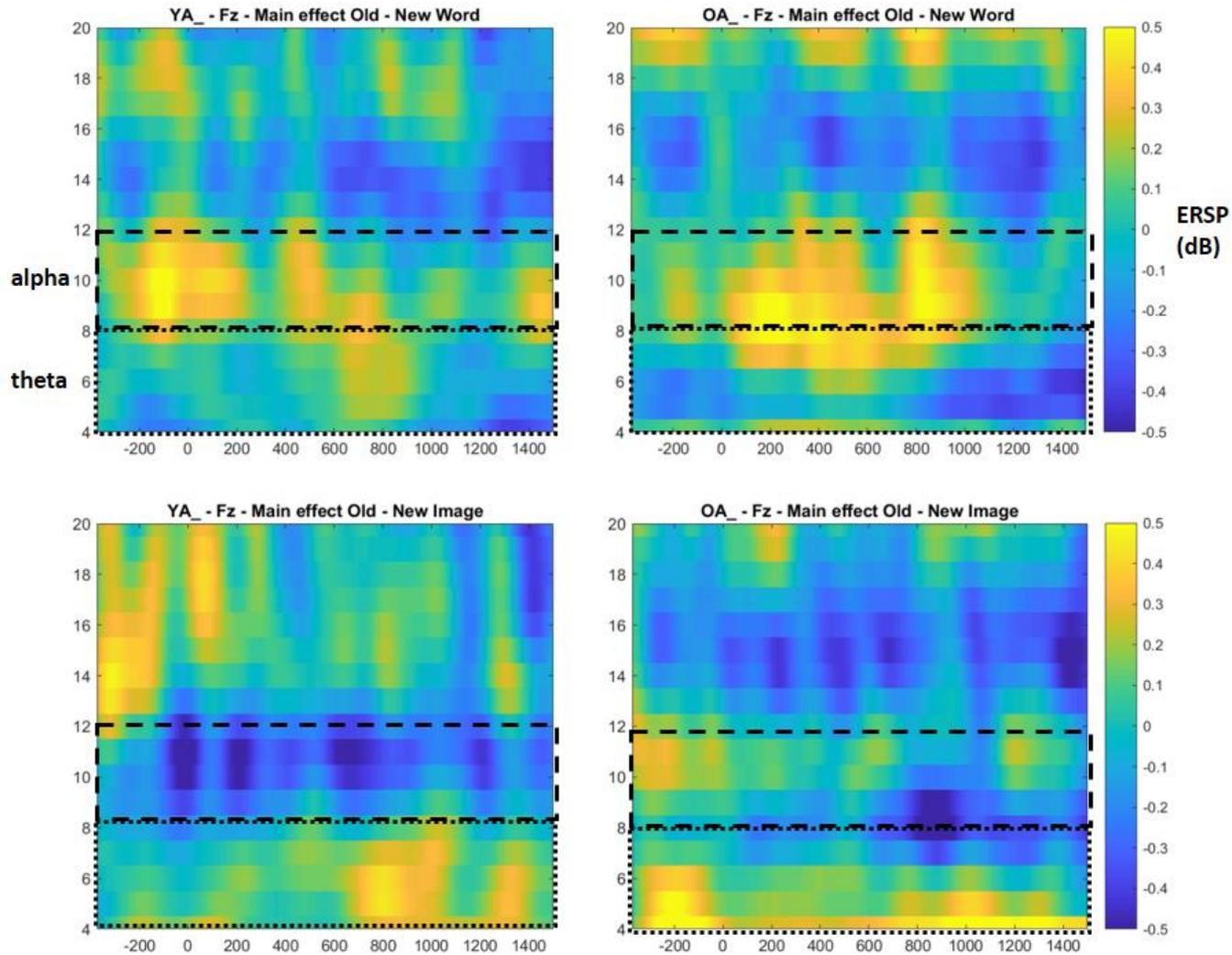
Figure 8.6 ERSP plots at the mid-frontal electrode (Fz) showing old-new effects for Words (upper) and Images (lower) for the younger (YA: left) and older (OA: right) groups. The horizontal axis represent time in milliseconds with zero indicating stimulus onset. The vertical axis indicates the frequency (in Hz) of the decomposed signal. For the colour scale, yellow indicates positive differences where the old word or image elicited greater power than the new one, with blue indicating the reverse pattern.
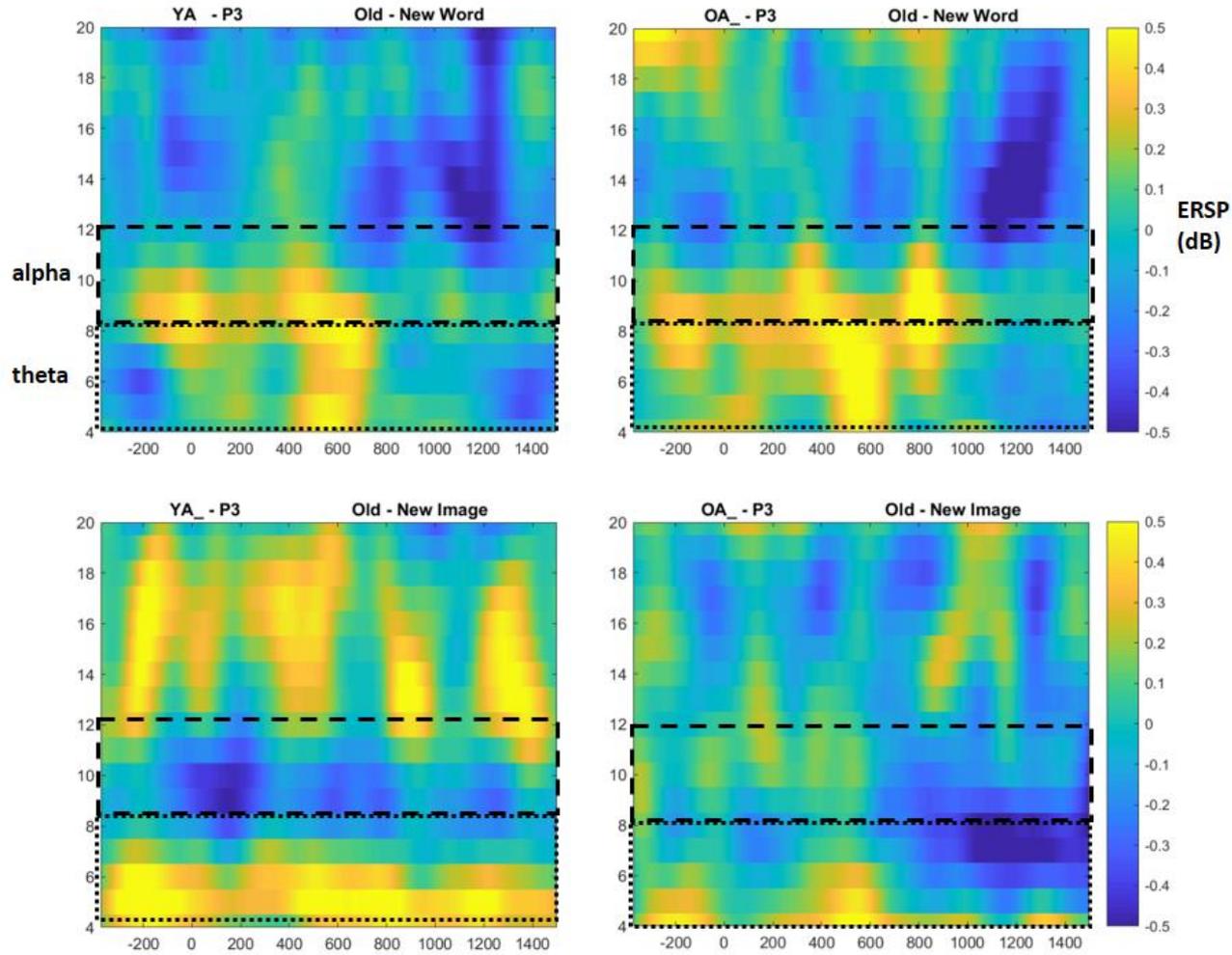
Figure 8.7 ERSP plots at the left parietal electrode (P3) showing old-new effects for Words (upper) and Images (lower) for the younger (YA: left) and older (OA: right) groups. The horizontal axis represent time in milliseconds with zero indicating stimulus onset. The vertical axis indicates the frequency (in Hz) of the decomposed signal. For the colour scale, yellow indicates positive differences where the old word or image elicited greater power than the new one, with blue indicating the reverse pattern.
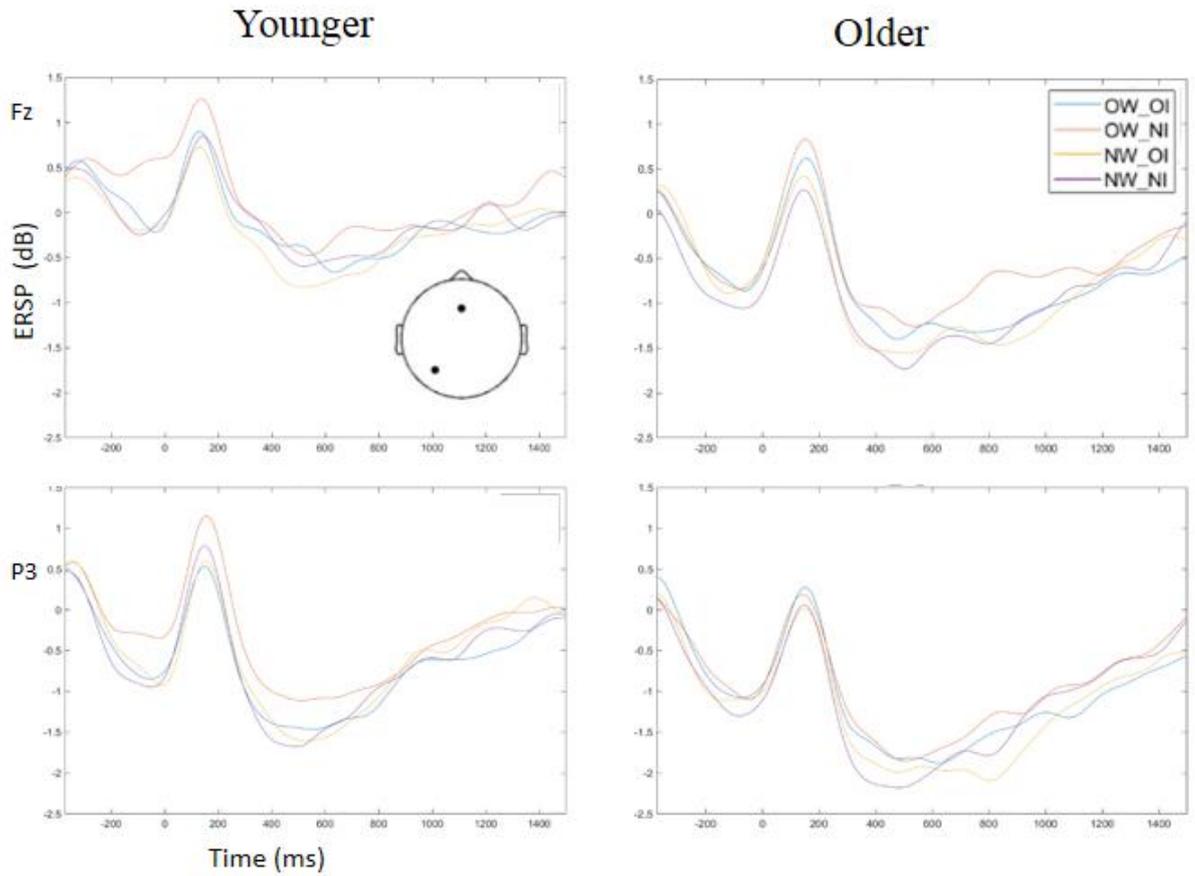
Figure 8.8 Mean alpha power at mid-frontal (Fz, top) and left-parietal (P3, bottom) electrodes for younger (left) and older (right) groups. ERPS has been averaged across the alpha frequency band (8-11 Hz).
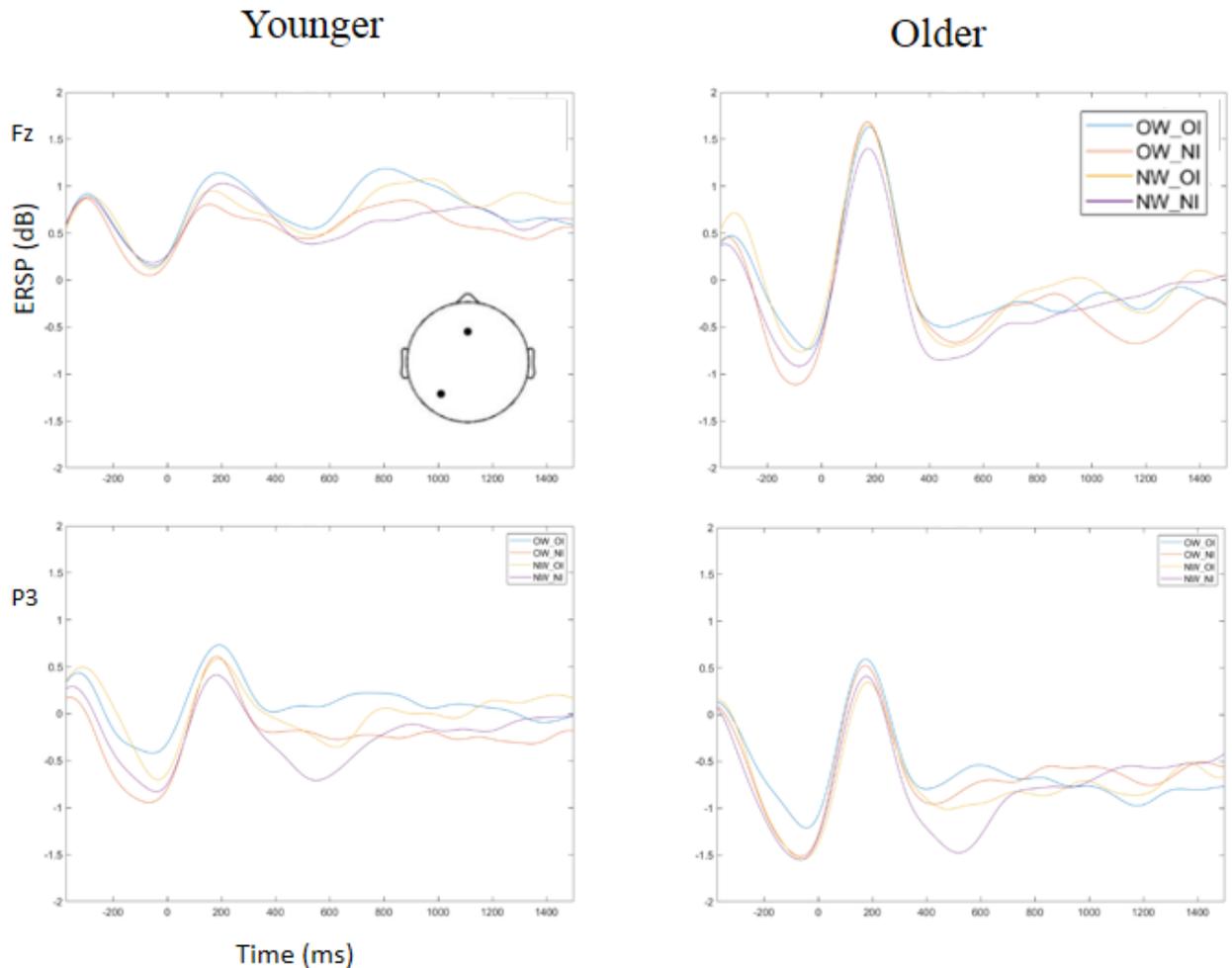
Figure 8.9 Mean theta power at mid-frontal (Fz, top) and left-parietal (P3, bottom) electrodes for younger (left) and older (right) groups. ERPS has been averaged across the theta frequency band (4-7 Hz).

8.2.6. Targeted analysis

The derived time-frequency power data was first analysed by calculating mean ERSP values for the theta and alpha frequency bands for the same time windows and locations as for the targeted ERP analysis.

8.2.6.3. Mid-frontal (Fz) alpha and theta oscillations between 300-500ms

Two 2x2x2 mixed ANOVAs (within factors: Target Word old/new status and Distractor Image old/new status; between factor: Age Group) were carried out on the mean theta and

alpha power values separately, at the Fz electrode in the 300ms-500ms post stimulus time window (associated with familiarity in ERPs). This analysis revealed a main effect in alpha power for Word (see Table 8.3 for a full summary of the statistical results). All conditions saw a reduction from baseline in alpha power however this drop was greater for previously unseen target Words than it was for previously seen ones (New: $M = -0.96$; Old: $M = -0.69$) with patterns being similar in both the younger and the older groups. There were no further significant effects or trends for alpha nor were there any significant findings for theta in this time window.

Figure 8.6 is an ERSP plot showing the old-new differences in alpha and theta power across the full duration of the grand-averaged epoch at electrode Fz and illustrates the relatively higher alpha power for intentional word recognition.

Table 8.3 ANOVA results for ERSP effects in theta and alpha bands at Fz electrode between 300-500ms.

Effect	Frequency (theta/alpha)	Statistics
W	theta	$F(1,46)=0.70$, $p=0.407$, $\eta p^2=0.015$
WxG	theta	$F(1,46)=0.69$, $p=0.412$, $\eta p^2=0.015$
I	theta	$F(1,46)=0.97$, $p=0.329$, $\eta p^2=0.021$
IxG	theta	$F(1,46)=0.08$, $p=0.773$, $\eta p^2=0.002$
WxI	theta	$F(1,46)=0.01$, $p=0.933$, $\eta p^2<0.001$
WxIxG	theta	$F(1,46)=0.54$, $p=0.470$, $\eta p^2=0.012$
W	**alpha**	$\boldsymbol{F(1,46)=5.86, p=0.019, \eta p^2=0.113^*}$
WxG	alpha	$F(1,46)=0.66$, $p=0.422$, $\eta p^2=0.014$
I	alpha	$F(1,46)=1.43$, $p=0.239$, $\eta p^2=0.030$
IxG	alpha	$F(1,46)=0.33$, $p=0.567$, $\eta p^2=0.007$
WxI	alpha	$F(1,46)=0.01$, $p=0.929$, $\eta p^2<0.001$
WxIxG	alpha	$F(1,46)=0.89$, $p=0.349$, $\eta p^2=0.019$

W=Word, I=Image, G=Group, *p<0.05, **p<0.001

Table 8.4 ANOVA results for ERSP effects in theta and alpha bands at P3 electrode between 500-800ms

Source	Frequency (theta/alpha)	Statistics
W	**theta**	$\boldsymbol{F(1,46)=9.44, p=0.004, \eta p^2=0.17}$******
WxG	theta	$F(1,46)=0.01, p=0.934, \eta p^2<0.001$
I	**theta**	$\boldsymbol{F(1,46)=5.52, p=0.023, \eta p^2=0.107}$*****
IxG	theta	$F(1,46)=0.80, p=0.375, \eta p^2=0.17$
WxI	theta	$F(1,46)<0.01, p=0.974, \eta p^2<0.001$
WxIxG	theta	$F(1,46)=0.16, p=0.688, \eta p^2=0.004$
W	alpha	$F(1,46)=3.85, p=0.056, \eta p^2=0.077$
WxG	alpha	$F(1,46)=0.04, p=0.842, \eta p^2=0.001$
I	alpha	$F(1,46)=1.50, p=0.228, \eta p^2=0.031$
IxG	alpha	$F(1,46)=0.17, p=0.679, \eta p^2=0.004$
WxI	alpha	$F(1,46)=0.56, p=0.459, \eta p^2=0.012$
WxIxG	alpha	$F(1,46)=0.26, p=0.616, \eta p^2=0.006$

W=Word, I=Image, G=Group, *p<0.05, **p<0.001

8.2.6.4. 500ms to 800ms

Corresponding similar analyses (whose results are summarised in Table 8.4 targeting the P3 electrode in the 500ms-800ms time window (where an old/new difference is associated with recollection in ERPs) revealed strong main effects for Word in theta power. All conditions saw a reduction from baseline in theta power however this drop was greater for previously unseen target Words than it was for previously seen ones (New: M = -0.68; Old M = -0.35) with patterns being similar in both the younger and the older groups. This time window also saw a significant effect of Image in theta power however this effect appears to have been primarily driven by the younger group (older group: M=0.159, SD=0.894, $t(23)$=-.87, p=.394; younger group: M=0.354, SD=0.586, $t(23)$=-2.96, p=.007, Cohen's d=.258), although note that the interaction with Group was not significant. All conditions saw a reduction from baseline in theta power however this drop was greater for previously unseen target Images than it was for previously seen ones (New: M = -0.65; Old M = -0.39). There was also a trend for higher alpha power for old Words with no group

interaction. There were no other significant effects nor trends for alpha or theta in this time window. Figure 8.8 and Figure 8.9 together illustrate these effects.

8.2.7. Time-frequency - PLS whole head analysis

Next, I conducted non-rotated Task PLS analyses of the oscillation data on all scalp channels (excluding EOG channels) and over a time window of -374ms to 1500ms. This time window was chosen since a wavelet with 3 cycles at 4Hz extends -375ms into the pre-stimulus period when centred at stimulus onset, and thus the pre-stimulus period from -375ms to 0ms could potentially be influenced by post-stimulus brain responses ("temporal bleeding"). Thus, by including the full spatiotemporal EEG data this analysis provided a comprehensive assessment of global patterns of alpha and theta changes associated with intentional and unintentional recognition in the two groups. The first two analyses were full factorial PLS analyses for theta and alpha bands (i.e. including all three factors: Target Word old/new status; Distractor Image old/new status; Age young vs. old). As can be seen in Table 8.5, these analyses revealed significant main effects of Group in both alpha and theta bands, and significant or near-significant main effects of Word old/new and Image old/new status, but no interactions between Group and the other factors. Thus, these initial analyses indicated that both old and young groups showed relatively similar oscillatory effects in alpha and theta bands (in contrast to in the ERP domain).

Table 8.5 Significance values of the contrasts in the whole-head PLS analysis for ERSP in the theta and alpha frequency bands. Percentage cross-block covariance accounted for in parentheses. Significant and near significant results highlighted in bold.

				ERSP			
	Word	Image	Group	W x I	W x G	I x G	W x I x G
Theta	**.058 (4%)**	**.046 (5%)**	**<.001 (83%)**	.849	.266	.296	.826
Alpha	**.018 (7%)**	**.064 (5%)**	**.031 (74%)**	.417	.133	.528	.694

To further investigate how the effects of Target Word and Distractor Image recognition were expressed in theta and alpha ERSP for the two groups separately, I next conducted further PLS analyses that tested the Word and Image factors separately for the younger and the older groups. Since these factors did not interact with Group in the full factorial analysis reported above, I wanted to verify whether they were indeed similar in both groups. Table 8.5 shows the results of the permutation analyses that determines which contrasts are significantly expressed in the EEG data, and Figures 8.10 and 8.11 show when and where these contrasts are reliably expressed in the spatiotemporal data (as determined by the ratio of the electrode saliences to their bootstrapped standard error).

Table 8.6 Significance values of the contrasts in the whole-head PLS analysis for ERSP in theta and alpha bands, split by Group. Significant and near significant results highlighted in bold.

			ERSP			
	Word		Image		W x I	
	Old	Young	Old	Young	Old	Young
Theta	0.147	0.1	**0.022 (51%)**	0.461	0.751	0.838
Alpha	**0.026 (52%)**	0.119	0.193	.166	0.709	0.407

As can be seen in Table 8.6, the results of the permutation analyses were less clear due to a reduction in statistical power when participants were split into two groups. Nevertheless, the results indicate that there were no substantial differences between the groups, bar the effect of image old/new status on theta ERSP, which was somewhat stronger in the older group, and the effect of Word old/new status on alpha ERSP, which was also somewhat stronger in the older group. Thus, there was no evidence for reduced old/new differences in alpha and theta ERSP older age, since the majority of effects were similar between groups or stronger in the old than the young group. Figure 8.9 illustrates the topographic distributions of the electrode salience to bootstrapped standard error ratios in alpha ERSP for both target Words and distractor Images, separately for the two groups. These highlight the somewhat similar positive old/new differences for target Words in both groups, however with some differences in the distributions and with the older group exhibiting more widespread and longer lasting effects (consistent with a stronger effect in the permutation test in the older group (0-1200ms cf a shorter period 0-800ms in the younger group)). In contrast, both groups showed an alpha power reduction for old compared to new distractor Images, which again had an earlier timecourse in the younger group and quite different topographies across groups.
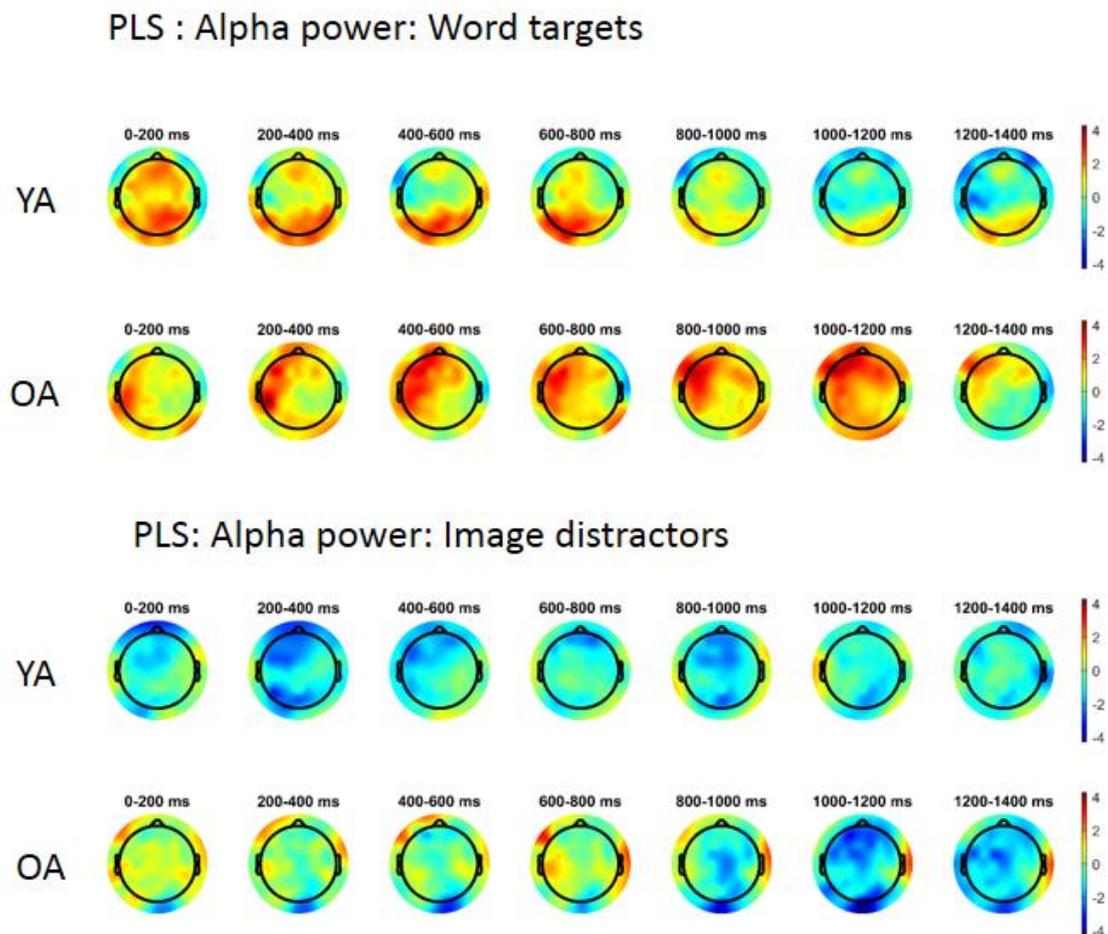
Figure 8.9. Scalp topographies of electrode saliences to bootstrapped standard error ratios for old/new contrasts in the whole-head PLS analysis on ERSP in the alpha band. These plots show the reliability of old/new effects for target Words (upper) and distractor Images (lower) separately for younger (YA) and older (OA) groups. The bootstrap ratios are approximately equivalent to z scores; values > 1.96 indicate electrodes and time points that reliably show more positive ERSP amplitudes (i.e. event-related synchronisation) for old than new items, and values < -1.96 indicate electrodes and time points that reliably show more negative ERSP amplitudes (i.e. event-related de-synchronisation) for old than new items.

Figure 8.10 illustrates the topographic distributions of the electrode salience to

bootstrapped standard error ratios in theta ERSP for both target Words and distractor

Images, separately for the two groups. These show that both groups had similar positive

old/new differences for target Words (particularly in the left-sided posterior region during

53

the 200ms-1000ms period), and also for distractor Images. However, similarly to the

effects in the alpha band, the older group again exhibited more diffuse topographies for

old/new differences.
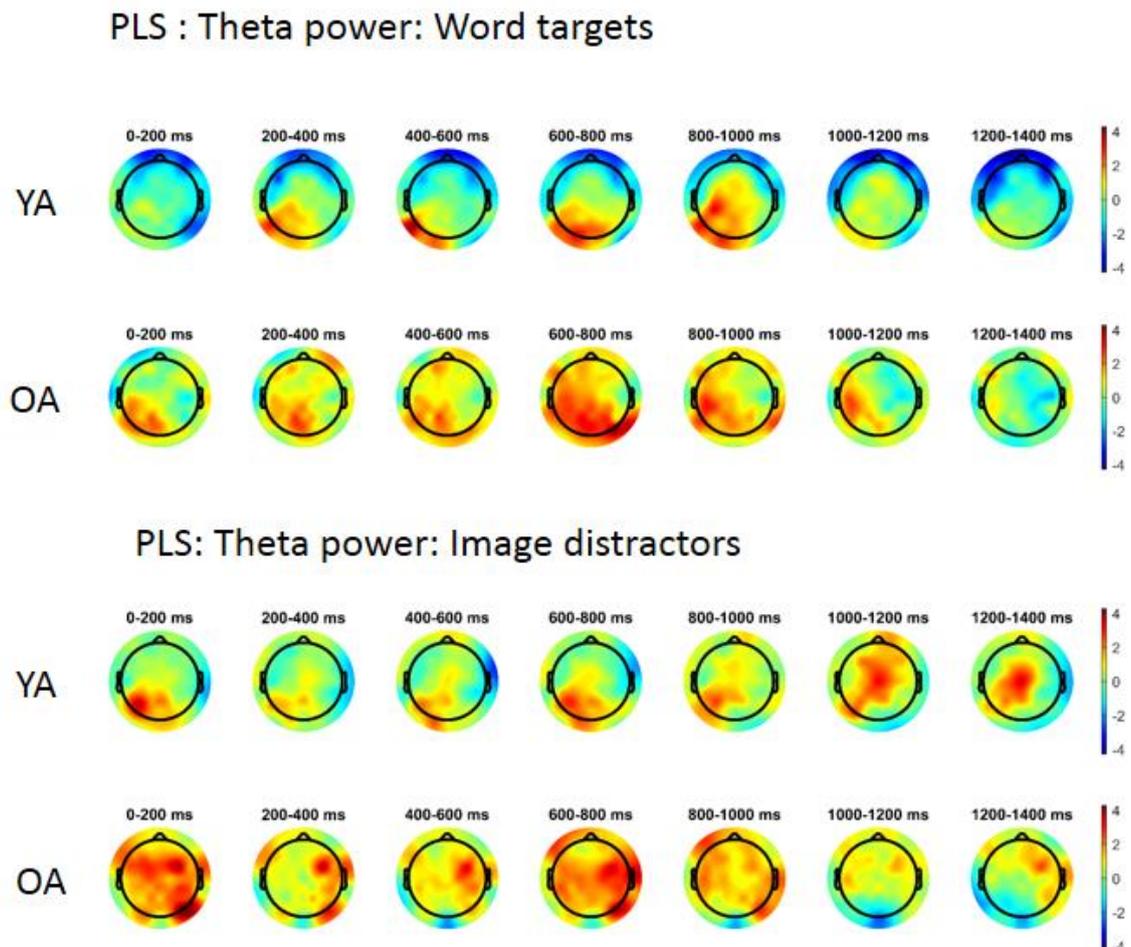
Figure 8.10 Scalp topographies of electrode saliences to bootstrapped standard error ratios for old/new contrasts in the whole-head PLS analysis on ERSP in the theta band. These plots show the reliability of old/new effects for target Words (upper) and distractor Images (lower) separately for younger (YA) and older (OA) groups. The bootstrap ratios are approximately equivalent to z scores; values > 1.96 indicate electrodes and time points that reliably show more positive ERSP amplitudes (i.e. event-related synchronisation) for old than new items, and values < -1.96 indicate electrodes and time points that reliably show more negative ERSP amplitudes (i.e. event-related de-synchronisation) for old than new items.

In sum, the ERP and time-frequency ERSP analyses revealed rather different results. In the ERP analysis, old/new ERP differences for Words and Images in the younger group were either very reduced or absent in the older group. In the ERSP analysis however, old/new differences in alpha and theta power were similar across groups and even somewhat (but not significantly) stronger in the older group. Both groups showed increased theta power when recognising old target Words and old distractor Images, compared to new Words and Images. Both groups also showed increased alpha power when recognising old target Words compared to new target Words, but reduced alpha power for old distractor Images compared to new distractor Images.

9. General discussion

This research explored age-related differences in episodic memory, with a particular focus on the brain processes that underlie unintentional and intentional recognition. The study investigated behavioural and electrical brain activity markers of intentional recognition biases caused by unintentional recognition of distractors using a Memory Stroop task (Anderson et al., 2011), exploring potential differences in ERP effects and brain oscillations between older and younger adults, extending on Bergström et al. (2016). The results revealed similar behavioural recognition biases in young and old groups, but markedly different ERP effects. In contrast, alpha and theta oscillations were more similar across age groups, showing that the type of EEG analysis performed in studies of neurocognitive aging might lead to very different conclusions regarding whether or not young and old people differ in their memory processes.

This research showed that both older and younger adults exhibit unintentional recognition of distractor foils during a target recognition task. Although older adults had significantly poorer memory for targets, they showed a similar effect size for the 'distractor congruency effect'. That is, for both old and young groups, target recognition decisions were more accurate when the distractor image was of the same episodic status ("old" or "new") as the target word, with no group difference in this congruency pattern. This lack of a difference was somewhat surprising given other evidence in the literature that older adults exhibit greater processing of distractors (de Fockert et al., 2009; Weeks & Hasher, 2014). In Anderson et al. (2011), young adults only showed a substantial distractor congruency effect when their attention was divided with a secondary task, whereas older adults showed this effect even without a secondary task. In my study, both young and old groups were given a WM task that has been found to increase distractor processing in other

paradigms (De Fockert et al., 2001), and I therefore predicted that the congruency effect would be even larger in the older group (Anderson et al. never tested an older group with a secondary task), but this prediction was not confirmed.

One reason for not seeing a greater congruency effect size in the older group may be that they were likely better educated than was typical for their age category (see the

Participants section) indicating a probable greater level of preservation of cognitive function than is common for their age group (Nyberg, et al., 2012). It is thus possible that the older group did indeed experience increased unintentional recognition of the distractors, however their spared executive functions may have been able to override influences of such unintentional recognition on target decisions. If this was the case, I would have expected to see neural evidence of increased distractor recognition in the older group. However, in the ERP domain, the FN400 effect for old distractors that was previously interpreted as indexing unintentional recognition (Bergstrom, et al., 2016) was in fact smaller in the old group than in the young group, inconsistent with this view. In the oscillation domain, old and young groups showed more similar effects for unintentional recognition, but there was no significant increase in distractor old/new effects in the old group in either the theta or alpha bands. Thus, there was no evidence in the current study that older adults experienced increased distractor recognition. Furthermore, the average educational level of my sample (16.5 years) was fairly similar to Anderson et al.'s (2011) sample (15.1 years), suggesting that these groups should be comparable.

An alternative possibility is that the difficult nature of the WM load task that the older adults were placed under in my study *reduced* rather than increased the distraction effects, similar to findings from an auditory distraction paradigm. Berti & Schröger (2003) investigated differences in behavioural and ERP distraction effects between low and high

WM load conditions and found reduced effects in the high load condition, conflicting with other research that argues that WM load increases distractor processing (De Fockert et al., 2001). Thus, by adding a WM load task, the older group may have shown less of a congruency effect than they would have otherwise. Furthermore, since accuracy rates were so high for both groups, it is possible that some group differences may have been masked by ceiling effects. Future studies should be designed so that target recognition performance is lower, which might enhance distractor effects.

Given the rather similar recognition performance in the two groups it was somewhat surprising that the FN400 ERP correlate of familiarity that was found for both distractor images and word targets in the younger group (Bergström et al., 2016), was so reduced in the older group. Separate group analyses revealed that the older group showed no significant FN400 effect for targets, and a significant but small effect for distractors, in comparison to a much larger effect size found for the young group, however the group interaction analysis itself only revealed a trend affect ($p=.051$) . The young group also showed a left parietal old/new effect for targets only that has been linked with recollection (Rugg & Curran, 2007), but this effect was absent in the old group despite high levels of performance in the target recognition test. Furthermore, visual inspection of the ERPs when splitting the older adults into two based on higher/lower accuracy failed to exhibit any clear evidence of these effects even in the higher performing group whose behavioural performance in fact slightly exceeded that of the younger group. It was also not the case that FN400 and left/parietal old/new effects were present but that they had shifted into a slightly different time window, something which may have been expected due to slower processing times in the older group. This account was tested with a PLS analysis of the whole epoch ERP data, which did reveal significant old/new differences for distractors in both the young and old groups that were similar in polarity, timing and spatial distribution,

albeit with a smaller effect size in the older group. In contrast, old/new ERP effects for targets were qualitatively different across groups, as there was a significant PLS interaction between target old/new status and age group. Whilst the younger group exhibited the commonly found positive old/new differences for targets, in the older group this effect was in the *opposite* direction with a sustained, late negativity for old targets that was widely distributed and peaked over central electrode cites. Importantly this late negativity is distinct from the LPN effect which explicitly has a posterior distribution (Mecklinger et al., 2016). Instead, this finding is consistent with Duarte et al., (2006) who found a similar widespread negative slow wave in low-performing older adults which they linked with recollection. Thus, my results suggest that a possible reason for not detecting typical FN400 and left parietal ERP effects in the older group might be that they were exhibiting compensatory activity (Cabeza et al., 2002) which could lead to typical old/new effects becoming 'lost' when combined with other temporally overlapping stronger neural components.

As it was unclear what the age group differences in ERPs indicated in the face of comparable behavioural responses, an investigation of the decomposed raw EEG signals was warranted. Since raw EEG signals represent the summation at the scalp of brain activity from many regions, each possibly having different amplitudes, frequency levels and phase offsets, decomposing these signals into different frequency bands can facilitate a clearer view of the underlying neural activity. Thus, time-frequency decomposition techniques may be more robust than ERPs for assessing neural activity when component overlap or temporal jitter is occurring. Therefore, I performed ERSP analyses of brain oscillations, focusing on the theta (4-7 Hz) and alpha (8-11 Hz) frequency bands. My findings supported the view that ERP results were distorted by component overlap, since the ERSP measure of alpha and theta power revealed similar neural evidence of target and

distractor recognition in young and old participants, consistent with the similar levels of behavioural performance in the two groups.

In the theta band, both groups exhibited broadly similar patterns of greater power for old compared to new items for both intentional target recognition and unintentional distractor recognition, providing neural evidence that the older group were also recognizing the distractors. These effects were very similar across the left parietal scalp for both groups (see Figure 8.9), in particular in the 300-800ms time window, in line with previous research which often found increased left parietal theta during episodic retrieval (e.g. Gruber et al., 2008) including in older adults (Strunk et al., 2017). The results demonstrates an initial desynchronisation in theta power when processing stimuli, which is greater and more prolonged when the target and distractor are both novel. This pattern is consistent with a model proposed by Hanslmayr et al. (2016) that suggests that subsequent triggering of any memories in response to a stimulus would lead to an earlier theta resynchronisation than if no memory is reactivated. It is interesting to note the similar timing of the event-related synchronisation/desynchronisation (ERS/ERD) theta effects in the two groups across parietal electrodes, which implies that the memories for previously seen stimuli were reactivated at comparable times in the two groups and that the subsequent delays in responding (on average older adults were 213ms slower than younger adults) were due to differences in post-retrieval processing, for example due to a reduced ability to link memories to the required decisions in the task. This pattern is thus consistent with other research that has showed that strategic retrieval processes are particularly affected by ageing (Morcom, 2016).

Another interesting aspect of the findings is the presence of significant old/new differences in theta power for both intentional target recognition and unintentional distractor recognition. This finding contrasts with research that has linked theta specifically

with recollection (Gruber et al., 2008) and is consistent with findings that familiarity is also associated with theta power increases (Klimesch, Doppelmayr, Stadler, et al., 2001). Since recollection is characterised as a relatively intentional process (e.g. Yonelinas & Jacoby, 2012) and has been associated with the left parietal old/new ERP effect (Rugg & Curran, 2007; Bergstrom et al., 2016) that was only associated with target recognition in the current study, these results indicate that theta power is not simply a marker of recollection. Instead, theta oscillations may be associated with a more general/core retrieval process that is common to both familiarity and recollection, and that is insensitive to retrieval intentionality. Taken together these findings further support existing evidence of theta's fundamental role in memory retrieval, and indicate that this retrieval-related brain process may be less effected by ageing than processes measured with FN400 and left parietal ERPs.

In addition to theta power, the PLS analysis of the whole epoch also found old/new effects in alpha power for targets and distractors, and again there was no evidence for significant differences in these old/new effects between the two age groups. Alpha ERD has been widely found to be associated with episodic memory retrieval (see Klimesch, 1999; for a review) and has recently been argued to reflect reactivation of perceptual and conceptual memory details in neocortical regions during retrieval (Hanslmayr et al., 2016). Interestingly, my study showed a reversal in old/new differences in alpha power between targets that showed a positive old/new difference, and distractors that elicited a negative old/new difference. However, it is unclear whether this alpha difference between targets and distractors is related to differences in the intentionality of retrieval, or alternatively due to the stimuli material (words for targets and images for distractors). Indeed, differences in both the power and the scalp topography of alpha changes have been found between word and face stimuli (Burgess & Gruzelier, 2000). Future research could address this issue by

replicating Experiment 2 from Bergström et al., (2016), which used images as targets and words as distractors, with older adults, and examine the brain oscillations associated with recognition of word distractors. If recognition of word distractors is also associated with alpha power reductions, it would suggest that the alpha ERD is related to unintentional retrieval. If recognition of word distractors is associated with alpha power increases however, it would suggest that the current results were caused by material effects.

In the current study, the experiment protocol was kept consistent with that of a previous study with younger adult participants (Bergström et al., 2016) to facilitate direct comparison between the two groups, which meant that I was unable to analyse EEG oscillations in lower frequencies than 4Hz due to the relatively short pre-stimulus period. Furthermore, the technique of "mirroring" the eeg baseline signal has the potential to introduce additional artificial frequencies with this being dependent upon the gradient of the signal at the mirror point with steeper gradients introducing higher frequency 'noise'. In retrospect an alternative technique, such as (i) not performing any baseline correction at all or (ii) using a much longer section of EEG signal from another part of the recording during a non-test phase (e.g. during an inter-block test phase) should have reduced the risk of such artefacts. However as all analyses were focused on comparing between different conditions that did not differ in their baseline (and was not focused on absolute values) any such effects should not have impacted on the conclusions made regarding condition differences. Nevertheless, any future EEG studies further exploring this topic would be advised to use an extended prestimulus period to avoid artefacts, and also facilitate time-frequency decomposition of lower frequency (delta) oscillations, which are known to also be associated with memory (Jacobs, 2014) .

It is also unclear whether the congruity of the target and distractor stimuli acts to boost accuracy compared to if no distractor had been present, or whether the incongruity

impedes it. Adding a control condition to a future study that includes new/old targets and no distractor image should clarify this point. Future research may also consider changing the type of WM load task participants perform in conjunction with the recognition test.

The instruction to 'sub-vocalise' the numeric string by rehearsing the numbers verbally (e.g. "four, one, three, two") used as the WM-load task may have introduced interference with the target stimuli which were also words. In retrospect, an instruction to "form a mental picture" of the number string may have helped to reduce any such conflict. In their paper Anderson et al., (2011) also use a number based WMload task however they do not state whether any guidance was given to participants regarding any particular techniques they should employ to facilitate their remembering the string. Thus, future research could give more specific instructinos, or change the WM load task to non-verbal materials.

9.1. Conclusions

This thesis explored age differences in the biasing effect of unintentional recognition of distracting stimuli on the intentional recognition of targets. Previous research had shown that older adults are more susceptible to distraction-induced recognition biases than younger adults (Anderson et al., 2011) and that intentional and unintentional recognition involved dissociable memory processes as evidenced by ERPs (Bergström et al., 2016). This thesis replicated the basic Memory Stroop congruency effect in older adults with a similar effect size as in younger adults, despite a reduction in target recognition accuracy in the older group. Thus, aging had a different effect on target versus distractor recognition, supporting the view that intentional and unintentional recognition processes are dissociable, and more generally that intentional memory processes are particularly affected by aging (Morcom, 2016). The ERP effects that had been found in the younger group were markedly different in the older adults, whereas a subsequent detailed

investigation of theta and alpha brain oscillations did reveal broadly similar patterns in the two groups with clear neural evidence of both intentional and unintentional recognition in the older group. This pattern of findings illustrate how different EEG analysis methods might lead researchers to draw different conclusions about aging effects on memory - the ERPs indicate that old and young participants engaged qualitatively different retrieval processes, whereas theta and alpha oscillations highlight similarities between the age groups. Thus, these methods provide complementary and sometimes conflicting sources of information about the neurocognitive mechanisms that underlie episodic memory. As a whole, the results indicate that older adults exhibit similar unintentional recognition processes as young adults, whereas their intentional recognition processes are different.

10. References

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11. Appendix A

10.1. PLS Design Contrasts

10.1.1. Word x Image
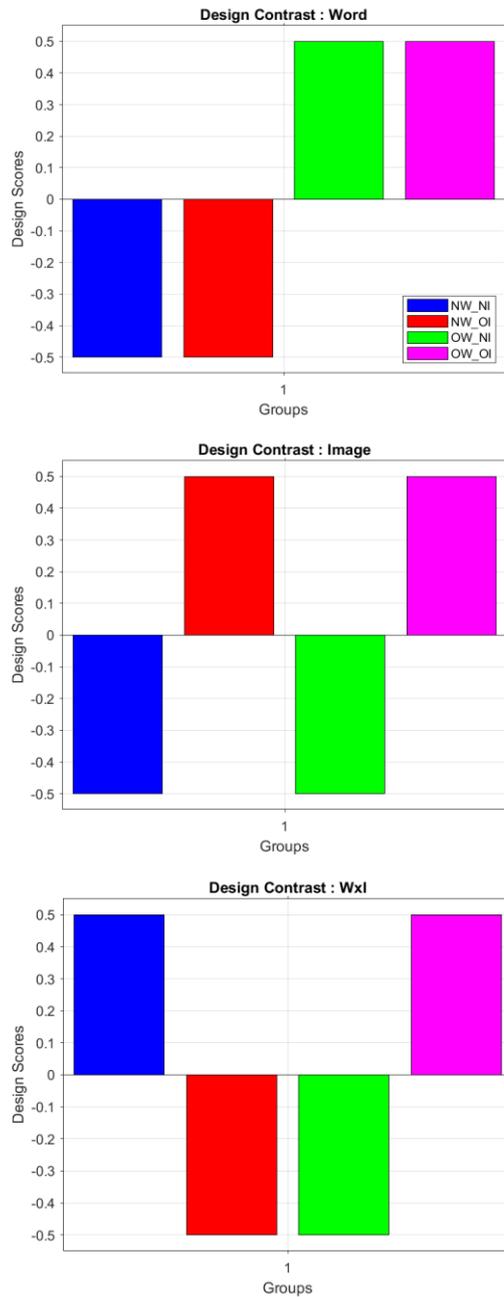
Figure 11.1 PLS Design contrasts for Word x Image

11.1.8. Word x Image x Group
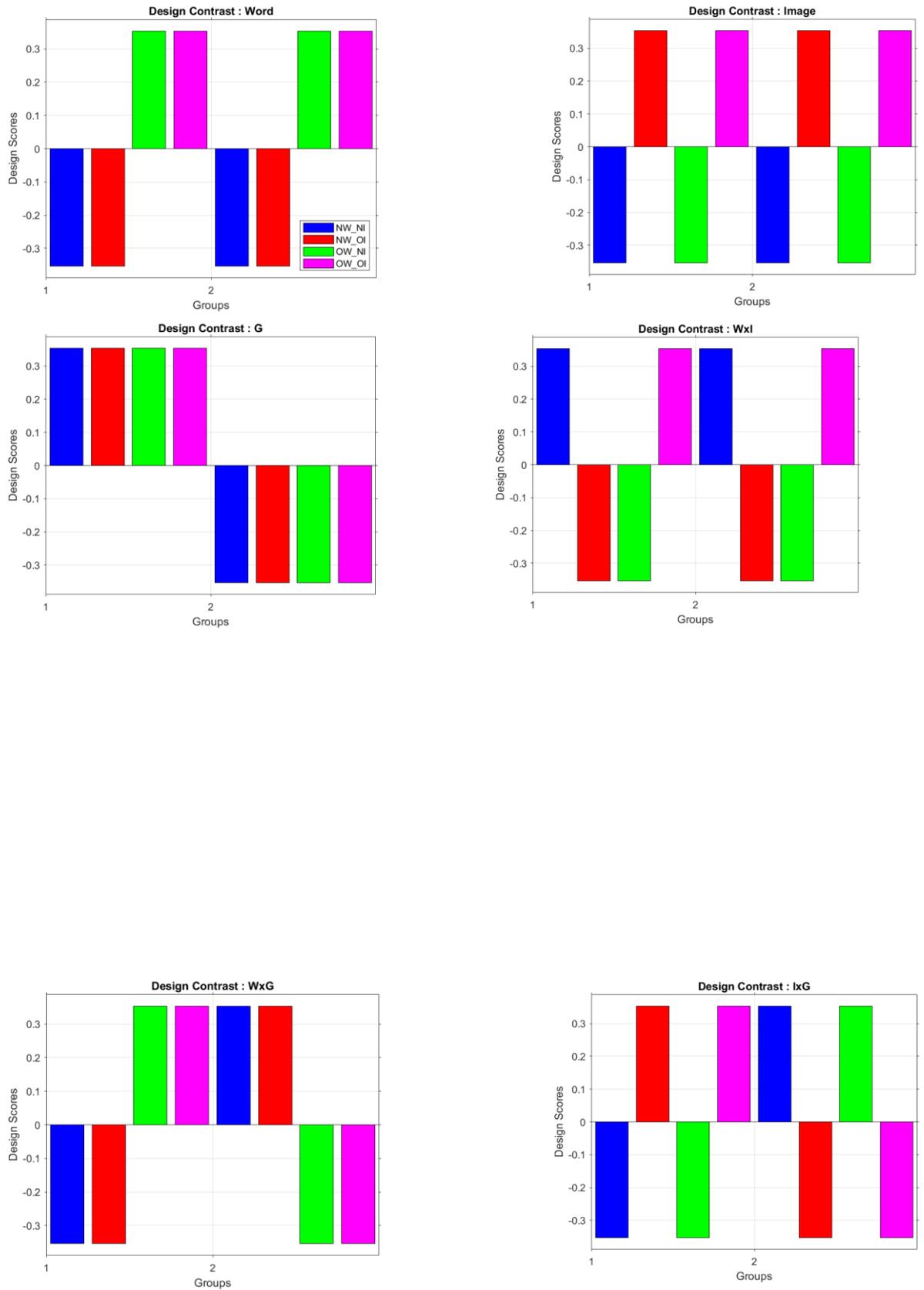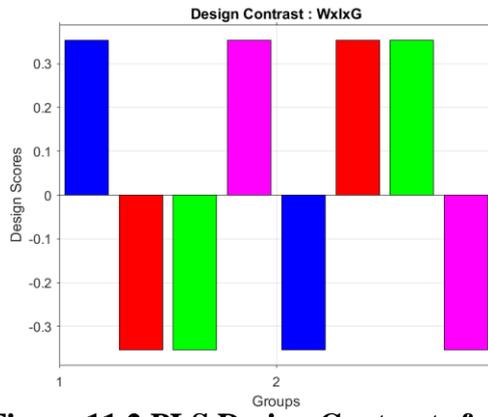
Figure 11.2 PLS Design Contrasts for Word x Image x Group