

**The Neural Correlates of Priming Specificity:  
Age-Related Changes in Visual Object Priming  
for Multiple Presentations of Similar Items**

Master's Thesis

Presented to

The Faculty of the Graduate School of Arts and Sciences  
Brandeis University  
Program in Neuroscience

Angela Gutchess, Advisor

In Partial Fulfillment  
of the Requirements for

Master of Science

By  
Joseph Poley Wolf

May 2011

## ***Acknowledgements***

---

I would like to express my deepest gratitude for the support and guidance of my advisor, Dr. Angela Gutchess, without whom this work could not have been possible. Her encouragement, enthusiasm, and dedication truly inspired me to conduct this research.

I would further like to thank members of my thesis committee, Dr. Don Katz and Dr. Art Wingfield, for their support in reviewing this material. Warm thanks are also extended to Brittany Cassidy and Margeaux Auslander for helpful troubleshooting during the fMRI analyses, and to all members of the Aging, Culture and Cognition Lab for their camaraderie and assistance.

*Abstract*

---

The Neural Correlates of Priming Specificity:  
Age-Related Changes in Visual Object Priming for Multiple Presentations of Similar Items

A Thesis Presented to the Program in Neuroscience

Graduate School of Arts and Sciences  
Brandeis University  
Waltham, Massachusetts

By Joseph Poley Wolf

Despite extensive declines in various explicit memory processes, priming, a form of implicit memory, may be spared in cognitive aging. However, the nature of age-related neural changes in priming tasks utilizing repetitions of perceptually similar objects, which are different exemplars of the same item, is only beginning to be understood. In the present neuroimaging study, we evaluated behavioral and neural priming for multiple presentations of similar visual objects in 18 young adults and 17 older adults. Consistent with prior work, we found comparable behavioral performance across age groups in a similar object priming task, and further observed similar patterns of engagement across age groups in the left fusiform, demonstrating that this region has a role in priming specificity for older adults. Age differences were however observed in other perceptual regions involved in priming such as parahippocampal areas and anterior portions of the left middle occipital gyrus, as well as in bilateral interior frontal areas and left middle temporal areas involved in the semantic/conceptual components of

repetition priming. No systematic age differences based on the number of repetitions were discovered in either behavioral or neural measures. These results suggest that in similar visual object priming tasks, older adults might maintain behavioral performance by relying on the utilization of compensatory neural processes, yet may also depend on the engagement of the same neural networks (i.e. left fusiform) utilized in young adults for priming specificity.

## ***Table of Contents***

---

<b>Acknowledgements .....</b>	<b>ii</b>
<b>Abstract.....</b>	<b>iii</b>
<b>List of Tables and Figures.....</b>	<b>vi</b>
<b>Introduction.....</b>	<b>vi</b>
<b>Methods.....</b>	<b>13</b>
Participants.....	13
Materials and Procedures .....	14
<b>Results .....</b>	<b>17</b>
Behavioral Priming Results .....	17
Functional MRI Data .....	17
<b>Discussion .....</b>	<b>21</b>
<b>References.....</b>	<b>31</b>
<b>Tables .....</b>	<b>36</b>
<b>Figures.....</b>	<b>39</b>

## **List of Tables and Figures**

Table 1: Demographic and neuropsychological data

Table 2: Conjunction Analyses Activation Peaks

Table 3: Age Differences Analyses Activation Peaks

Figure 1: Medium Study Set

Figure 2: Behavioral Results- Reaction Times by Repetition Number

Figure 3: Conjunction Analyses Regions of Interest

Figure 4: Age-Differences Analyses Regions of Interest

## ***Introduction***

---

Aging has been linked with selective cognitive deficits, manifested by impairments to effortful processing as opposed to relative preservation of automatic processing (see reviews, Hedden and Gabrieli, 2004; Reuter-Lorenz and Park, 2010; Schacter et al., 2007). Furthermore, extensive studies have associated declines in explicit (conscious) memory with age to robust neural underactivations in the associated medial temporal lobe (MTL) regions (e.g. Grady et al., 1995; Gutchess et al., 2005; Park et al., 2003). On the contrary, implicit memory processes, as evidenced in tasks such as repetition priming, are thought to be intact with age. Behaviorally, repetition priming has been observed to have similar benefits in the processing of repeated vs. novel stimuli for older individuals as compared to their younger counterparts (Koutstaal, 2003; La Voie and Light, 1994; Schacter and Buckner, 1998). However, as both similar and differential patterns of neural activity have been found across age-groups in priming tasks, our understanding of the neural processes sub-serving priming with age is still evolving.

Elucidating the nature of neural changes in priming processes may reveal specific memory vulnerabilities, or even possibly advantages, that develop with healthy aging and could shed further light upon the functional framework of the aging mind. The discovery of dissociable memory processes that show conservation of function with age could indicate successful neural plasticity mechanisms in older adults (Reuter-Lorenz and Cappell, 2008), and might also be promising for the development of therapeutic approaches focusing on prevention and rehabilitation of age-related cognitive dysfunctions. Such research is especially relevant for a country like the USA, where a recent estimation predicts that within the next 20 years, over

72 million Americans will be over the age of 65 (Federal Interagency Forum on Age-Related Statistics., July 2010).

### ***Behavioral Changes in Priming and Implicit Memory Processes with Age***

Behavioral data generally shows a relative conservation of implicit memory function and priming processes with age, especially in comparison to vast declines in other domains of memory such as explicit memory, which involves deliberate recall and recognition of information. One form of priming that is generally conserved with age is repetition priming, a form of implicit memory that creates a change in behavior or neural response upon stimulus presentation based on prior exposure to the same or similar stimulus (Schacter and Buckner, 1998; Tulving and Schacter, 1990). Though small behavioral differences in priming have been found between younger and older adults (see meta-analysis: La Voie and Light, 1994), these differences are likely to be attributed to task-related issues of explicit memory contamination due to the subject's awareness of a memory test. Thus, another more recent analysis shows no age differences in implicit memory after explicit memory contamination was accounted for and removed (Mitchell and Bruss, 2003).

Behavioral repetition priming is often tested by comparing response time reductions upon viewing repeated vs. novel stimuli. Though response time reductions are generally similar across age groups, some studies find that response times are faster for younger adults (Lustig and Buckner, 2004), whilst others have gone on to note that once subjects who had explicit contamination were removed, older adults were actually seen to have faster response times (Light and Albertson, 1989; as discussed in Mitchell and Bruss, 2003). Yet other studies observe that older adults have faster response times than young for both visual object priming (Koutstaal, 2003) and word stem completion priming (Daselaar et al., 2005). Faster response times in older



adults might be task-induced because older adults may feel the need to work through self-paced tasks quicker, but it is also thought that better object knowledge in older adults may lead to faster responses in visual object priming as seen in Koutstaal (2003) and better vocabulary knowledge may lead to the faster responses in word stem completion priming in Daselaar et al. (2005).

Though priming is relatively conserved with age on behavioral measures, there have been further inconsistent findings on whether age differences in priming are more prevalent in conceptual tests, affected by the degree of semantic processing, or perceptual tests, dependant on the physical features of the primed stimulus. Some studies indicate that age-related declines occur in the perceptual aspects of priming, as seen in a study assessing pictorial implicit memory under data-driven (perceptual) vs. conceptually-driven encoding conditions (Cherry and St. Pierre, 1998). Recently, studies have come to suggest that aging affects both perceptual and conceptual priming processes (Daselaar et al., 2005). More behavioral data, however, seems to suggest that perceptual priming processes are spared with age, with declines more evident in the conceptual/semantic aspects of priming (Jelicic et al., 1996; Rybash, 1996). Behavioral studies also show that older adults do successfully encode perceptual details but may not use them effectively at recall (Koutstaal, 2003). Furthermore, greater sparing of perceptual priming as compared to conceptual/semantic priming seems plausible as brain regions involved in semantic processing (namely frontal and temporal areas) tend to have greater volume decreases with age than brain regions involved in perceptual functions (Good et al., 2001).

It has been hypothesized that perceptual repetition priming operates as part of a pre-semantic perceptual representation system (Tulving and Schacter, 1990). Behavioral studies of visual agnosics have demonstrated that whilst these patients cannot use visual input to access semantic or associative information about objects, they are able maintain intact performance on

tests emphasizing the structural features of visual objects. Patients with visual agnosia thus make the same judgments when viewing objects shown from different viewpoints (Warrington, 1975). This suggests that access to structural knowledge of visual objects does not require explicit access to the semantic system (Tulving and Schacter, 1990), and thus with cognitive aging we may expect to see more similar patterns of neural activation in the perceptual components of priming.

### ***Overview of Neural Changes in Priming with Age***

How could neural changes occur despite a conservation of behavioral function in priming with age? As stated by Park et al. (2003), “differential neural engagement” can occur despite “behavioral equivalence”. Evidence has indicated that spared cognitive function with age can be linked to compensatory neural processes, as evidenced in tasks such as the successful encoding of pictures (Gutchess et al., 2005). Several models of cognitive aging build upon this concept and offer insight into the mechanisms of neural changes with aging. The compensation-related utilization of neural circuits hypothesis (CRUNCH) postulates that neural over-activations in frontal regions of older adults could be due to compensation for decreased neural efficiency, forcing the recruitment of a greater number of neural circuits (Reuter-Lorenz and Cappell, 2008). This is thought to account for a behavioral age-invariance for low-demand tasks.

Furthermore, compensatory patterns of neural engagement in older adults often appear in tasks that demand top-down processing. It is thought that older adults may fail to engage top-down processing in the same way as younger adults, and thus may compensate for this with greater engagement and activation of frontal regions to mediate processing (Velanova et al., 2007). This could also be consistent with another model, the Scaffolding Theory of Aging and Cognition, which suggests that neural overactivations observed with intact cognitive function

with age could be the result of the brain forming alternate networks, or “scaffolds,” as a result of an increased neural burden due to various degenerative processes (Park and Reuter-Lorenz, 2009). As priming and implicit memory processes are intact with age for many behavioral measures, compensatory patterns of neural activity may be responsible for the preservation of function.

Functional magnetic resonance imaging has been utilized to evaluate priming-related neural processes with aging. In general, neuroimaging studies have revealed that priming is associated with a decreased hemodynamic response in the brain activations of certain frontal, temporal and occipital regions when identifying stimuli that have already been encountered, or primed (Henson, 2003). This decrease in hemodynamic response to repeated presentations of stimuli is termed repetition suppression. Frontal areas, namely left inferior frontal gyrus as well as certain inferior and lateral temporal regions, have been found to be involved in the conceptual/semantic components of priming. Repetition suppression has also been observed in occipital and posterior temporal areas, which are associated with perceptual processing of the stimuli in the priming task (see review Schacter et al., 2007).

Across age-groups, studies demonstrate similar patterns of neural activity in certain frontal regions such as the left inferior frontal gyrus, showing consistent repetition-related reductions of activity in a word priming task (Lustig and Buckner, 2004). Other studies reveal a tendency toward certain neural response differences between young and old age groups (Bergerbest et al., 2009; Daselaar et al., 2005). Significant additional activity reductions in anterior portions of the left superior temporal gyrus and the cerebellum have been observed in younger adults during a word-stem completion task (Daselaar et al., 2005). Older adults on the other hand had a trend for greater activity reductions in right prefrontal cortex (Daselaar et al.,

2005) and right inferior frontal gyrus (Bergerbest et al., 2009), as compared to young adults. However, most investigations of priming with aging may find similar patterns of neural activity across age groups as they utilize tasks with repetitions of the same stimulus and thus do not reveal possible neural differences in the perceptual components of priming. As dissociable components have been found to exist in priming processes (Henson et al., 2000), priming with repetitions of stimuli that have slight perceptual differences might reveal neural age-related changes priming tasks, and potentially highlight regions that are acting in compensatory ways to maintain behavioral priming performance.

### ***Specificity in Priming Processes***

Stimulus specificity, or the degree of perceptual similarity in visual objects, has been found to be one factor that can affect the degree of priming in both behavioral and neural measures. Varying the level of stimulus specificity in visual object priming tasks thus draws heavily on perceptual processing in young adults. To evaluate this, visual object priming has been utilized to discern the amount of repetition priming that occurs for same (identical) items as opposed to similar items which have the same name, but appear perceptually different (i.e. pictures of different keys). Though priming effects are thought to be greatest upon exposure to the same item, studies have found that similar items still have greater priming-related reductions in neural activity as opposed to novel items (Koutstaal et al., 2001).

Neurally, differential engagement of brain regions has also been observed in priming for same vs. similar objects. Anterior portions of the left inferior prefrontal cortex have been found to differentiate between novel and repeated items but generalize across repeated same and similar items that are different exemplars of the same object (Simons et al., 2003). In young adults, identical objects also yielded greater activations in bilateral middle occipital,

parahippocampal and fusiform cortices as opposed to priming for similar objects with same name. Furthermore, laterality effects have been observed in the fusiform cortex, with priming effects seen in the right fusiform for identical items as opposed to a spread to more bilateral priming effects engaging both left and right fusiform for similar items (Koutstaal et al., 2001). Subsequent memory paradigms have suggested that right fusiform cortex is associated with successful encoding of specific visual features, which is congruent with the neural priming effects evident in the right fusiform for identical rather than similar stimuli (Garoff et al., 2005). It has also been found that right fusiform demonstrates repetition suppression only if objects are repeated with the same viewpoint, while left fusiform is less specific in its response and may code for elements of shared visual features, such as the shared structural features in a set of items like tables or chairs (Vuilleumier et al., 2002). The role left fusiform cortex is thus less clear, and it is hypothesized to be involved in general object memory, thus enabling it to have more priming-related effects for similar objects as its activations are not thought to be driven as much by the visually specific perceptual aspects of the stimuli. This notion is consistent with behavioral findings from divided visual field studies, which indicates that perceptual regions in the left hemisphere respond to more abstract visual properties as stimuli which were similar rather than identical in nature were more rapidly classified by the left hemisphere (Marsolek, 1995).

Neural differences in priming for same vs. perceptually similar objects might arise due to differences in the types of details which perceptual regions respond to, moving from posterior to anterior areas along the ventral visual stream (see review, Schacter et al., 2007). Posterior occipital areas have been found to respond to a high degree of stimulus specificity, whilst more anterior occipital areas and posterior inferior temporal areas tend to respond to more general properties of stimuli, such as shared structural features. For example, early visual areas located

in the posterior portions of the lateral occipital complex appear to have a high degree of stimulus specific priming effects and are affected by changes in stimulus viewpoint, size, illumination, and position (Grill-Spector et al., 1999). In more anterior portions of the lateral occipital complex however, there seem to be more generalized responses as priming effects in these regions are relatively constant despite changes in stimulus size and position, though they are still modulated by changes in viewpoint and illumination (Vuilleumier, 2005). Moving into posterior temporal areas, it has been found that these regions have even less stimulus specific priming effects as seen in the left fusiform gyrus (described above) and also in parahippocampal areas. One study has revealed that part of the parahippocampal cortex has been identified in neural priming for repetition of places (Bunzeck et al., 2006) and another study has found that neural priming in parahippocampal regions occurs for repetition of background scenes (Goh et al., 2004). It is thus assumed that more anterior areas of the perceptual stream are involved in “nonspecific priming” and may respond to shared structural features, such as the characteristic structural features shared between different exemplars of items like bikes or chairs.

### ***Priming Specificity with Age***

Investigating priming specificity across age groups could reveal age-related differences in implicit memory, such as compensatory patterns of activation or the engagement of alternate neural networks to maintain behavioral performance. However, priming for similar objects in older adults has not been investigated neurally. In behavioral measures, priming specificity in older adults has been found to be comparable to the pattern observed in young: priming occurs for both identical and similar exemplars, but there is greater priming for the identical as opposed to the similar items. Furthermore, although overall levels of behavioral priming differed between age groups, there were no age differences when subtracting similar item response times

from identical item response times. This demonstrates that across both age groups, greater priming for identical items as compared to similar items was elicited to the same extent (Koutstaal, 2003). These behavioral data suggest that certain neural regions might play a similar role with age for priming specificity, namely the fusiform gyrus which was found to play an important role in priming specificity for younger adults (Koutstaal et al., 2001). Similar neural engagement of the fusiform with age could also be expected as neuroimaging studies of emotional memory have found similar fusiform activations in young and older adults (Kensinger, 2008).

Other studies related to stimulus specificity might however suggest neural differences in similar object repetition priming with age. In a subsequent memory paradigm used by Graham et al (2000), healthy individuals as well as patients with semantic dementia were shown objects during the study phase and later tested on recognition memory using same or perceptually similar objects (Graham et al., 2000). Though no significant differences were found for recognition memory of same objects, the semantic dementia group had impaired recognition memory for the perceptually similar items, accompanied by less activation in the posterior inferior temporal gyrus. We could thus hypothesize that healthy older adults may have neural differences in repetition priming when perceptual features of the objects are changed as this could possibly increase the demands of the priming. This would be consistent with the finding by Lustig and Buckner (2004) indicating increased right occipito-temporal activations in a word priming task for cognitively impaired older adults. These increased activations are most likely involved top-down processing of perceptual features, as previous studies have found repetition priming in inferior temporal areas to be amodal and independent of stimulus-driven processing (Buckner et al., 2000). We thus may expect to see increased neural activations in inferior temporal areas in

healthy older adults during a priming task that involves similar visual objects, as older adults might need to compensate for age-related difficulties in top-down processing.

Repetition priming of perceptually similar visual objects may also lead to differential neural activations in frontal areas with aging. Age-related compensatory processes favoring neural overactivation and bilateral recruitment of frontal regions have been observed in many studies (see review, Reuter-Lorenz and Park, 2010), and an interesting recent finding in a word repetition priming study shows that successful priming was localized unilaterally to left inferior prefrontal cortex regions for young adults. In older adults however, it was observed that bilateral activations extending to the right inferior prefrontal cortex were implicated with successful priming (Bergerbest et al., 2009). This could be further consistent with the Velanova et al (2007) finding that older adults may fail to engage top-down processing in the same way as younger adults, and thus have greater frontal activations to mediate processing. Increased recruitment of frontal regions with aging may thus become evident in a repetition priming task using perceptually similar objects, as the task may require more top-down processing in order to semantically relate the different exemplars of the same object. In line with the CRUNCH hypothesis, increased frontal activations might occur early on in the priming task and then possibly diminish as older adults max out their cognitive resources (Reuter-Lorenz and Cappell, 2008).

### ***Priming across multiple repetitions***

The number of repetitions of familiar stimuli in a priming paradigm has also been implicated in modulating the level of priming related neural activity, yet remains largely uninvestigated as a function of age and across multiple repetitions of similar as opposed to identical items. Some studies have found that neural priming responses occur in a continuous



linear fashion across multiple presentations of stimuli, as seen when comparing 2 repetitions to 5 repetitions of familiar visual objects (Henson et al., 2000). Another study investigating up to 8 repetitions of identical pictures in a priming task found that repetition suppression in bilateral ventral occipito-temporal cortex and the fusiform saturated after the second repetition due to a development of visual expertise (Reber et al., 2005). Yet another study indicates that priming related repetition suppression is evident in the fusiform for the first repetition, yet subsequently becomes evident in prefrontal and parietal areas during the third repetition (Soldan et al., 2010). This may indicate that different neural processes become engaged as the number of repetitions increases, as brain regions that respond to shared visual or semantic features in the stimuli may become more activated as the level of shared features increases.

The nature of age-differences in priming effects across multiple repetitions of similar items however remains unclear. Behavioral studies have demonstrated that the study of a large number of categorically-related exemplars (i.e. pictures of different cats) later results in greater difficulty in a subsequent test phase in discerning between items that were previously seen and those that were not (Koutstaal and Schacter, 1997). In their study, it was further found that older adults have more difficulties with this recognition memory than young, as older adults might rely on the perceptual and conceptual similarities between objects to a greater extent. In terms of implicit memory and priming, this might further suggest that older adults will show greater activations and engagement of the neural regions that respond more generally to shared features in stimuli, i.e. posterior prefrontal regions for nonspecific conceptual priming (Simons et al., 2003), and anterior portions of the lateral occipital complex (Koutstaal et al., 2001) and parahippocampal cortex (Goh et al., 2004) for nonspecific perceptual priming.

### ***Present Study and Specific Aims***

In the present study, we will use functional magnetic resonance imaging (fMRI) to neurally investigate age-differences in priming specificity over the course of viewing multiple exemplars of perceptually similar objects. Multiple exemplars of categorically-related items, such as pictures of different types of keys or different types of chairs, will be presented and priming effects across age groups will be assessed on both behavioral measures (response time reductions) and neural measures. We thus hypothesize that:

- 1) There will be behavioral equivalence in repetition priming for similar visual objects as observed in Koutstaal et al. (2003), confirming the ability of older adults to encode differing perceptual details. However, differences across age groups are expected to occur based on the repetition number, as previous studies have found older adults to have difficulties in explicit recognition memory as a function of object set size at encoding (Koutstaal and Schacter, 1997).
- 2) Aging will lead to neural differences in both the conceptual and perceptual components of repetition priming for similar objects. This is expected to occur as cognitive aging is associated with difficulties in engaging top-down processing, increased reliability on shared features of stimuli in certain memory tasks, and general changes in functional connectivity leading to compensatory or alternate patterns of neural activity.
- 3) Priming effects in certain neural regions will remain age-invariant. This could be the case for regions previously found to play a role in priming specificity in young adults, such as the left fusiform. This region has been shown to have robust repetition suppression for similar object priming in young adults (Koutstaal et al., 2001; Simons et al., 2003), and thus is expected to have the same activity in older adults.

## ***Methods***

---

### ***Participants***

#### *Subject Pool*

Twenty three young adult participants aged 18-35 ( $M=24.8$ ,  $SD=5.2$ ) and nineteen older adults aged 61-80 ( $M=72.4$ ,  $SD=5.8$ ) were recruited to partake in the study. Seven additional participants (5 younger & 2 older adults) were eliminated. All eliminated subjects completed less than 85% of the encoding judgments, in comparison to the average response percentages of 94.3% ( $SD=7.2$ ) for young adults and 96.5% ( $SD=3.4$ ) for older adults. After these eliminations were made, the final sample contained 18 young adults and 17 older adults, with 8 male and 10 female participants in the young adult group and 8 male and 9 female participants in the older adult group. Eligibility criteria included right handedness, English as a native language, absence from medications known to affect the central nervous system, and the absence of neurological, psychological, or physical conditions contraindicated for MRI scanning. All participants provided written informed consent for a protocol approved by Harvard University and Partners Institutional Review Board.

#### *Neuropsychological Tests*

To further characterize our sample, participants performed the digit comparison task (Park, 2002) to assess speed of processing and completed a demographics questionnaire. Results of the neuropsychological and demographics measures are presented in Table 1. All participants across both age groups had at least some college education, and older adults were found to have a comparable level of education to younger adults. Participants across both age groups also had good self-reported health as compared to others of the same age, but older adults had diminished

performance as compared to young on the digit comparison (speed-of-processing) task, which is an expected finding in studies of cognitive aging (Salthouse, 1996). The results of these measures thus show that our samples are characteristic of samples encountered in aging studies with high-functioning older adults.

## ***Materials and Procedures***

### *Priming Task*

Participants viewed 468 pictures of single objects whilst making a yes/no button press to decide whether the object depicted is something they would use or interact with during an average day. Multiple exemplars of each object were drawn from 54 sets of objects (i.e., chairs, umbrellas, cats), with small study sets containing four studied exemplars, medium study sets containing eight studied exemplars, and large studied sets containing fourteen exemplars (refer to Figure 1 for an example). Pictures were presented for one second followed by a blank interval of one second. Photo CDs (Hemera Technologies, Gatineau, Quebec) were used to select pictures. Both encoding and recognition trials were randomly ordered in a jittered blocked design (Dale, 1999) with fixation cross trials that participants passively viewed. Trial presentation and behavioral data acquisition was performed with E-Prime software (Psychology Software Tools, Pittsburgh, PA).

### *Functional MRI Image Acquisition*

A Siemens Avanto 1.5 Tesla whole-body scanner (Siemens, Erlangen, Germany) was utilized to acquire the images. Thirty-two slices 3.2mm thick with a .3mm skip between slices were acquired with an echo-planar imaging (EPI) sequence (TR = 2000 msec, TE = 30, FOV = 200mm, and a flip angle = 90°). 212 measurements were collected during each of the three runs.

### *Functional MRI Image Preprocessing*

Preprocessing was conducted using SPM8 software (Wellcome Department of Cognitive Neurology, London, UK) and consisted of five modules:

- 1) Slice-time correction was performed to correct for differences in the acquisition time of each slice within a TR.
- 2) Realignment was performed to correct for movement by putting images in the same space as the first acquired functional image. Movement in each subject was further manually checked to ensure that there were no large movements that were likely to be poorly corrected by realignment (spikes >3mm or 1 degree and overall movement greater than 6mm or 3 degrees).
- 3) Co-registration of the functional images with the anatomical image acquired.
- 4) Normalization of the images to the Montreal Neurological Institute (MNI) template, which involves resampling to a voxel size of 2 cubic millimeters.
- 5) Smoothing the image volume to a 6-mm full-width half maximum isotropic Gaussian kernel in order to suppress noise as well as differences in the functional and gyral anatomy when averaging across subjects.

### *Functional MRI Data Analysis*

Data Analysis was conducted using SPM8 software (Wellcome Department of Cognitive Neurology, London, UK). Model specification was performed with three regressors: “early repetitions”, “middle repetitions”, and “late repetitions”. The early repetitions were modeled to contain repetitions 2, 3 and 4 of exemplars (which occurred across all three set size categories), middle repetitions were modeled to contain repetitions 5, 6, 7, 8 of exemplars (which occurred only across medium and large set size categories), and the late repetitions contained repetitions 9, 10, 11, 12, 13 and 14 (which only occurred in the large set size categories). The model was convolved with the functional images using a canonical hemodynamic response function (HRF),

and t-contrasts were performed in each subject for early vs middle repetitions and middle vs late repetitions. Subsequently, these contrasts were pooled across subjects in two-sample independent t-test contrasts to determine differences across the two age groups and were tested at a threshold of  $p < .001$  (uncorrected), with a voxel extent threshold of  $k=5$  voxels. Conjunction analyses were also performed to determine neural activity that was in common for young and old age groups. A mask of voxels significant at  $p < .03$  was created for the young age group and then used to test overlapping activity in the old age group at a threshold of  $p < .03$ ,  $k=5$  voxels. The overall probability was thus  $p < .001$  in accordance with Fisher's method (Fisher, 1950; Garoff-Eaton et al., 2006). Brain regions and Brodmann's areas for clusters of significant voxels were estimated from the Montreal Neurological Institute stereotaxic axis (Evans, 1993). Activations in specific regions of interest were further characterized with MarsBaR (Brett et al., 2002) to obtain percentage signal change related to each of our individual conditions. Signal changes were extracted from peak clusters of activation apparent in regions of interest in our age difference and conjunction analyses.

## ***Results***

---

### ***Behavioral Priming Results***

To compare reaction times for multiple repetitions of similar visual objects across age groups, we conducted a 2 x 14 mixed ANOVA. Age (young/old) was the between-subject variable, and the repetition number (1-14) was the within-subject variable. We found a main effect of repetition  $F(13, 429) = 40.04$ ,  $p < .001$ ,  $\eta_p^2 = .55$ , whilst no significant effects were observed for age,  $F(1,33) = .050$ ,  $p > .80$ ,  $\eta_p^2 = .002$  and the interaction of age and repetition,  $F(13,429) = .595$ ,  $p > .55$ ,  $\eta_p^2 = .018$ . These behavioral results converge with previous behavioral studies comparing similar visual objects priming across age groups (Koutstaal, 2003).

To further characterize the main effect of repetition, we ran planned comparisons contrasting repetition 1 vs the early repetitions (reps 2, 3, 4), early repetitions vs middle repetitions (reps 5, 6, 7, 8), and middle repetitions vs late repetitions (reps 9, 10, 11, 12, 13, 14). See Figure 2 for a graphical presentation. We found significant differences across all three contrasts, indicating faster reaction times in repetition 1 vs the early repetitions,  $F(1,33) = 77.156$ ,  $p < .001$ , faster reaction times in early vs middle repetitions,  $F(1,33) = 76.001$ ,  $p < .001$ , as well as faster reaction times for middle vs late repetitions,  $F(1,33) = 15.361$ ,  $p < .001$ .

### ***Functional MRI Data***

We aimed to identify the neural regions involved in repetition priming for similar visual objects across age groups. In order to better reveal priming effects, we collapsed our multiple repetitions into three groups: early repetitions consisting of repetitions 2, 3, and 4, middle repetitions consisting of repetitions 5, 6, 7, and 8, and late repetitions consisting of repetitions 9,

10, 11, 12, 13, and 14. As items were drawn from 54 sets of categorically related objects, we had 18 small sized sets comprising of 4 items, 18 medium sized set comprising of 8 items, and 18 large sized sets comprising of 14 items. Thus for each subject, 162 items were pooled into the early repetitions group, 144 items were pooled into the middle repetitions group, and 108 items were pooled into the late repetitions group. Collapsing across repetitions in this way is thought to better reveal regions responding to priming for similar visual objects, as abstraction of shared visual features between objects has been shown to increase as a function of set size in previous explicit memory studies evaluating recognition memory for small (4 items), medium (8 items) and large (14 items) sets of similar visual objects (Gutchess and Schacter, 2011; Koutstaal et al., 1999).

Conducting our investigation, we first performed conjunction analyses to determine regions with similar patterns of activations across age groups in contrasts of early repetitions vs middle repetitions and middle repetitions vs. late repetitions. We then conducted analyses to determine age differences in neural activations between young and older adults by creating contrasts of contrasts, assessing subtractions of Young-Old and Old-Young for both early repetitions vs. middle repetitions and middle repetitions vs late repetitions.

### *Conjunction Analyses*

A number of regions were revealed in the conjunction analysis to have common patterns of activation across age groups in our priming task, as seen in Table 2. These regions included perceptual areas such as the left middle occipital gyrus and fusiform gyrus, as well as portions of certain frontal and temporal areas. We selected the left fusiform and a posterior portion of the left middle occipital gyrus as regions of interest for further characterization of the percent signal change. The left fusiform has been previously associated with repetition priming for similar



visual objects in young adults (Koutstaal et al., 2001; Simons et al., 2003). Posterior portions of the left middle occipital gyrus, part of the lateral occipital complex, have been found to demonstrate priming-related effects when there is high degree of stimulus specificity, and diminished response if there are changes in stimulus viewpoint, size, position, and illumination (Grill-Spector et al., 1999). Figure 3 shows the responses in these regions in our priming task.

Analysis of the percentage signal change in the both the left fusiform and the posterior left middle occipital gyrus in the conjunction analysis for Early Repetitions>Middle Repetitions shows similar patterns of repetition suppression, with higher levels of activation for the early repetitions than the middle repetitions in both younger and older adults.

#### *Age Differences Analysis*

Regions with differential patterns of activation between the young and old age groups are shown in Table 3. These regions include both left and right inferior frontal areas associated with the conceptual components of repetition priming (see review Schacter et al., 2007), left parahippocampal areas associated with nonspecific priming (Bunzeck et al., 2006; Goh et al., 2004), as well as middle temporal areas that are associated with the semantic/conceptual components of repetition priming and have also been associated with greater subsequent false recognition memory in older adults (Gutchess et al., 2009). Furthermore, differential patterns of activation were found in anterior portions of the left middle occipital lobe, part of the lateral occipital complex (LOC), which is associated with less stimulus specific priming effects than more posterior portions of the LOC (Grill-Spector et al., 1999). We thus selected the following regions for further analysis of percentage signal change: an anterior left middle occipital region in the Young-Old for Early Reps>Middle Reps contrast; right inferior frontal, left inferior frontal (left insula), left parahippocampal regions, as well as a middle temporal regions in the Old-

Young for Early Reps>Middle Reps contrast, and another left middle temporal region in the Young-Old for Middle Reps>Late Reps contrast.

Figure 4 shows the responses in the six selected regions with age differences in neural activation during our priming task. In the left middle occipital region (-32, -64, 36), right inferior frontal region (32, 26, -16), and left insula region (-32, 20, -10), age differences result due to reversals in activation between the age groups rather than a failure to engage by one group. The left middle occipital region demonstrates repetition suppression in young adults whilst repetition enhancement of activation occurs in older adults. In the inferior frontal areas, young adults are deactivating these regions for early repetitions and then activating for middle repetitions, whilst old activate for the early repetitions and deactivate these regions for the middle repetitions. In the left parahippocampal regions, age differences occur due to deactivation in young as opposed to a pattern of activation and repetition suppression in older adults. In the left middle temporal region appearing in the Old-Young for Early Reps>Middle Reps contrast, age differences result due to a reversal of activation in both groups, with older adults activating this region for early reps and subsequently deactivating for middle reps, and the opposite in young adults. Differences in activation patterns are further evident in the left middle temporal area in the Young-Old for Middle Reps>Late Reps contrasts, with a pattern of deactivation in both middle and late repetitions in young adults, while older adults move from a pattern of deactivation in middle repetitions to a back to a pattern of activation in late repetitions.

## *Discussion*

---

In this visual object priming study, we explored priming specificity with aging by evaluating behavioral and neural priming in young and older adults for multiple presentations of similar visual objects. Consistent with much of the prior work suggesting few age differences in repetition priming on behavioral measures, we found no differences in priming across age groups in response times for making judgments on similar visual objects. Furthermore, no age differences were found behaviorally across early repetitions (reps 2-4), middle repetitions (reps 5-8) or late repetitions (reps 9-14). However, upon examining the neural substrates of this priming with functional magnetic resonance imaging, we observed patterns that are consistent with the prior work exploring the role of certain perceptual regions involved in repetition priming, such as age-invariance in the engagement of the left fusiform (Grill-Spector, 1999; Koutstaal et al., 2001; Simons et al., 2003) and age differences in the engagement of portions of the parahippocampal areas and the lateral occipital complex (Goh et al., 2004; Grill-Spector et al., 1999). However, our findings also show several additional differences with age, as compared to prior literature, in bilateral inferior frontal areas and left middle temporal areas (Bergerbest et al., 2009; Lustig and Buckner, 2004) involved in the semantic/conceptual components of repetition priming.

We further found that there were no systematic neural age differences based on the number of repetitions. This was evaluated by collapsing our multiple repetitions into three groups: early, middle and late repetitions. Collapsing across repetitions in this way can better elucidate regions responding to priming for similar visual objects, as it has been found that abstraction of shared visual features between objects increases as a function of object set size in

previous explicit memory studies evaluating recognition memory (Gutchess and Schacter, 2011; Koutstaal et al., 1999). As the repetition number of similar visual objects increases, we thus would be more likely to reveal brain regions that vary response based on the level of shared visual or semantic features in the stimuli. Since there were no systematic age differences in neural activations based on the number of repetitions in our priming task, it could be suggested that priming processes are conserved with age across the number of repetitions. Age-differences based on the number of repetitions of similar objects therefore only arise in explicit memory retrieval processes, as determined in previous behavioral studies (Koutstaal and Schacter, 1997).

### ***Common Patterns of Neural Priming across Age Groups: Role of the Left Fusiform***

Our neuroimaging findings demonstrate similar patterns of repetition suppression across age groups in a portion of the left fusiform gyrus, an occipito-temporal region previously implicated in priming specificity (Koutstaal et al., 2001), and thought to be involved both in the late perceptual stream and also in the conceptual stream (Simons et al., 2003). Based on behavioral findings from divided visual field studies (Marsolek, 1995), it is thought that the left fusiform is engaged more in feature-based processing, thus enabling it to sustain neural priming effects for items that have similar features rather than ones that are exactly the same. This lesser degree of sensitivity in left fusiform to perceptual changes between items has been demonstrated for young adults, as repetition suppression has been implicated in repetition priming using different exemplars of the same item (Koutstaal et al., 2001) as well as in word-pair priming of semantically-related words (Wheatley et al., 2005). Our finding of age-invariant repetition suppression in the left fusiform in similar object priming thus supports and extends the Koutstaal (2003) behavioral data which shows that older adults still maintain priming benefits (in the same pattern as young) for exemplars of visual objects that are similar but not exactly the same.

In the present study, we observed neural priming in the left fusiform only in the early repetitions>middle repetitions contrast, which is somewhat inconsistent with prior findings indicating that priming activity in the fusiform does not extend past the first repetition due to the development of visual expertise (Reber et al., 2005). However, our task differed from the one used by Reber et al. (2005) in that we only used repetitions of similar items and had no repetitions of items which were exactly the same, so participants would be less likely to develop visual expertise because all stimuli were perceptually different. However, priming-related repetition suppression could be occurring due to experience with shared visual elements in our stimuli.

Our observation of left fusiform priming effects across early repetitions could also be due to the possible role of the fusiform in naming stimuli that are recognizable. Based on studies of patients undergoing epileptic surgery, the fusiform has been implicated as part of a basal temporal language area which could be involved in memory retrieval for language processing and object naming (Luders, 1991). Thus, we may be observing repetition suppression in the fusiform across the early repetitions as the subjects encounter the first few exemplars of items in all of the categories represented (i.e. the first few presentations of different exemplars of keys, chairs, etc) and must process items with from categories with different names. This activity could then saturate in later repetitions as the items encountered are still different exemplars, but have the same names as items seen earlier. The left fusiform region could thus possibly have a role in mediating both the perceptual and lexical/semantic components of visual object priming, with consistent repetition suppression effects across age groups.

### *Neural Priming in Perceptual Regions across Age Groups*

Despite similar patterns of neural activity in the left fusiform across age groups, we observed differential activity in other regions associated with the perceptual components of priming. Previous behavioral data supports the notion of conserved perceptual priming with age (see review Rybash, 1996), which is consistent with our finding of similar patterns of activation across age groups in certain brain regions associated with perceptual priming, such as the left fusiform and posterior portions of the left middle occipital gyrus. However, recent neuroimaging evidence also suggests that certain age differences do indeed exist in the perceptual domain (Daselaar et al., 2005), which would be consistent with our findings of differential patterns of activation across age groups in perceptual regions such as the parahippocampal area as well as more anterior portions of the left middle occipital gyrus.

Examining early visual areas, we observed similar patterns of priming-related repetition suppression across age groups in a posterior portion of the left middle occipital region (part of the lateral occipital complex) in the conjunction early>middle contrast. Yet, in a more anterior portion of this region for the age difference early>middle contrast, we observed enhancement of activation with increased repetition in older adults<sup>1</sup>, while younger adults showed a pattern of repetition suppression. Previous neuroimaging studies have identified posterior areas of the lateral occipital complex (LOC) as more sensitive to the degree of stimulus specificity (i.e. viewpoint, illumination, size and position), while more anterior areas of the LOC have responses that are less “stimulus specific” and thereby not affected by changes in stimulus size and position as compared to viewpoint and illumination (Grill-Spector et al., 1999). It could thus be

---

<sup>1</sup> An additional anterior left middle occipital activation (MNI -34, -62, 36) appeared as part of the conjunction analysis for med>small contrasts, but subsequent characterization in MarsBaR revealed differential patterns of activity across age groups (possibly due to high variability), with repetition suppression in young adults and enhancement in older adults.

postulated that while older adults follow a similar pattern of repetition suppression in early visual areas, they switch to a differential pattern of engagement moving along on the ventral visual stream possibly because they are making more connections between the more “nonspecific” features of the stimuli, such as structural features that are shared across exemplars within a set of visual objects like chairs or bikes. This could be in part due to the idea that semantic memory is conserved with age despite declines in other forms of memory (Light, 1992), and thus older adults may revert to the use of conceptual knowledge in guiding interpretation of more general visual features to a greater extent than younger adults.

Differential patterns of engagement across age groups were further observed in a left parahippocampal region, which, like anterior portions of the LOC, is also thought have a role late in the perceptual stream for nonspecific priming (Bunzeck et al., 2006; Goh et al., 2004). In our present experiment, we observed greater deactivation of the left parahippocampal gyrus in young adults for the small set size as compared to the medium set size, while the older adults displayed a pattern of repetition suppression. This could suggest that the left parahippocampal area, like the anterior portions of the middle occipital lobe, may have a differential pattern of activity with age as older adults may revert to pre-existing representations to guide non-specific priming for similar visual objects, whilst younger adults might suppress these pre-existing representations due to the availability of better sensory/visual information. Alternatively, this could be consistent with older adults greater utilizing a pre-semantic representation system for shared structural features, which has been suggested to be in a posterior cortical location (La Voie and Light, 1994; Tulving and Schacter, 1990; Warrington, 1975).

Furthermore, it is interesting to note that age differences in the engagement of brain regions involved in perceptual priming occurs mainly in more anterior portions of posterior

regions (i.e. anterior left middle occipital and left parahippocampal gyrus), which could be linked to the posterior-anterior shift with aging (PASA). Though the PASA model mainly describes diminished occipital activations with age accompanied by compensatory increases in frontal regions (Davis et al., 2008), there could be elements of this shift in functional connectivity which lead to compensatory differential patterns of engagement in the anterior portions the ventral perceptual pathway of older adults, as observed in our study. This relates to a finding that suggests older adults may have lower neural priming responses than younger adults in certain perceptual areas such as the right occipital lobe (Daselaar et al., 2005).

### ***Neural Priming in Conceptual Regions across Age Groups***

In addition to a perceptual priming component, our task also had semantic components. For example, in making judgments on the objects, participants utilized semantic information such as knowing where they see such objects in everyday life as well as ways in which the objects are used. Previous literature also suggests that visual object priming tasks often lead participants to implicitly generate names for the objects they encounter or otherwise identify the objects as recognizable (Koutstaal et al., 2001), which might be a reason for similar patterns of activity in the left fusiform across age groups as it is thought to be at least partially involved in these semantic processes (Luders, 1991).

We found several differences across age groups in conceptual/semantic priming regions, namely left middle temporal regions as well as in bilateral inferior frontal regions. Differences in both left and right inferior frontal activations appeared in the Old-Young for Small>Med contrast, demonstrating greater activation of this region in the early repetitions for older adults as compared to young. This could be potentially related to a recent finding of Bergerbest et al. (2009), which suggests that in repetition priming of words, right prefrontal activations in older



adults are related to better priming-related performance with aging. Bergerbest suggests that while priming related repetition suppression in the left inferior PFC is relatively age invariant, greater repetition suppression in older adults in the right inferior PFC may indicate an age-related bilateralization of function with aging. Age-invariance for word repetition priming in another left inferior frontal region, the left inferior frontal gyrus, was also confirmed by Lustig and Buckner (2004). Our results however indicate differential patterns of activity across age groups in left inferior frontal regions as older adults tend to activate for the early repetitions and deactivate for the middle reps, while the opposite occurs in young. It is important to note, however, that our priming task varied from that of Bergerbest (2009) and Lustig and Buckner (2004) in that we utilized different exemplars of visual objects, and never had repetitions of identical items. More posterior inferior frontal areas may thus have age-differences in our similar object priming task as it has been found that more posterior inferior frontal regions are more exemplar specific than more anterior inferior frontal regions (Simons et al., 2003). Simons et al (2003) suggests that more posterior inferior frontal regions may become activated when stimulus-driven retrieval processes are not immediately successful and thus require top-down control of semantic information (i.e phonological codes). Age-differences in frontal activations might thus reflect compensatory activations in older adults, as previous findings suggest older adults may fail to engage top-down processing in the same way as young adults.

We further found age differences in left middle temporal regions in two age differences contrasts: Old-Young for Early Reps>Middle Reps and Young-Old for Middle Reps>Late Reps. Patterns of activation for older adults for early repetitions in former contrast and late repetitions in the latter contrasts (as compared to deactivations in younger adults) might indicate age-related cognitive dysfunction as activations in this region have been associated with subsequent false

memory in explicit memory tasks for young adults (Gutchess et al 2011). However, though lateral temporal areas have been correlated with behavioral priming benefits, analysis using TMS has not demonstrated a causal link between these areas and behavioral priming (Wig et al., 2005). Thus, age differences in these regions might be indicative of certain age-related deficits at encoding that do not have an impact on behavioral priming, but may foreshadow problems in explicit memory domains.

### ***Limitations and Future Directions***

Limitations of the present study include the lack of correlations between neural priming effects and behavior, as we were not able to identify regions where activity correlated with behavioral response times. Furthermore, we might have interference due to the mixed presentation of 54 different categories of exemplars, possibly leading to decreased sensitivity of our priming task. Interference in this study could result due to participants gaining additional experience/benefit as certain categories of objects might be semantically related, such as categories like chairs, beds, lamps and shelves which could all be identified under the name of “furniture.” These semantic overlaps could thus lead to additional facilitation in the similar object priming which might possibly cover up certain age differences.

In future studies, it could be useful to compare age differences in priming effects across multiple repetitions for similar visual objects in relation to repetitions of identical visual objects. This would allow for better comparisons with previous studies, as most studies compare priming for similar objects with priming for same (identical) objects or novel objects. Furthermore, it may be interesting to investigate the role of regions involved in category specific priming with age. A variety of category specific neuronal representations have been linked to specific semantic representations, such the left ventral premotor areas responding to viewing of graspable

tools such as keys (Cattaneo et al., 2010). In this case, left ventral premotor areas might be responding selectively to a category of tools because it could be involved in the motor planning required to use the object. Another example of a category specific region is the lateral portion of the fusiform gyrus, where activations have been linked specifically to viewing pictures of animals (Chao et al., 1999). Category specific neural regions could thus selectively activate with priming for different categories of stimuli, and may be involved in further preservation of priming with age as older adults are thought to have better established semantic representations. Identification of the priming effects in regions with category specificity was not performed in our present study, as we did not sort our repetitions by the categories from which the objects were drawn. In order to better explore the role of category specific neural regions in maintaining priming with age, it would be further crucial to choose categories of stimuli which have been previously linked to selective activations in specific brain regions, such as graspable tools and animals for example.

Further explorations of priming specificity with aging may reveal more systematic differences between age groups for priming across multiple presentations of stimuli, which could highlight specific memory vulnerabilities with aging and better elucidate whether age-related compensatory processes are responsible for up keeping behavioral performance in the perceptual and the conceptual domains of repetition priming. This could give valuable insight for better understanding neural changes taking place with cognitive aging in healthy older adults.

### ***Conclusions***

This visual object repetition priming study importantly differs from other investigations of priming in that similar, but not identical, visual objects were utilized. Despite the perceptual differences between exemplars, our results coincide with much of the prior literature in

demonstrating behavioral equivalence across age groups. However, we reveal that neural responses for priming do differ across age groups in regions involved in the conceptual/semantic aspects of priming (i.e. temporal and inferior frontal regions) as well as in perceptual regions (i.e. anterior portions of the left middle occipital lobe and the left parahippocampal area). Age differences in these activations could be due to compensatory mechanisms in older adults or possibly even the engagement of alternate neural networks to maintain behavioral equivalence in the face of diminishing cognitive resources. On the other hand, equivalent neural responses across age groups in areas such as the left fusiform suggest that elements of the neural network associated with priming for similar visual objects do remain in place with age.

## ***References***

---

- Bergerbest, D., Gabrieli, J.D.E., Whitfield-Gabrieli, S., Kim, H., Stebbins, G.T., Bennett, D.A., and Fleischman, D.A. (2009). Age-associated reduction of asymmetry in prefrontal function and preservation of conceptual repetition priming. *Neuroimage* 45, 237-246.
- Brett, M., Anton, J.L., Valabregue, R., and Poline, J. (2002). Region of interest analysis using an SPM toolbox. *Neuroimage* 16, 1140.
- Buckner, R.L., Koutstaal, W., Schacter, D.L., and Rosen, B.R. (2000). Functional MRI evidence for a role of frontal and inferior temporal cortex in amodal components of priming. *Brain* 123, 620-640.
- Bunzeck, N., Schütze, H., and Düzel, E. (2006). Category-specific organization of prefrontal response-facilitation during priming. *Neuropsychologia* 44, 1765-1776.
- Cattaneo, Z., Devlin, J.T., Salvini, F., Vecchi, T., and Silvanto, J. (2010). The causal role of category-specific neuronal representations in the left ventral premotor cortex (PMv) in semantic processing. *Neuroimage* 49, 2728-2734.
- Chao, L.L., Haxby, J.V., and Martin, A. (1999). Attribute-based neural substrates in temporal cortex for perceiving and knowing about objects. *Nature Neuroscience* 2, 913.
- Cherry, K.E., and St. Pierre, C. (1998). Age-related differences in pictorial implicit memory. *Experimental Aging Research* 24, 53.
- Dale, A.M. (1999). Optimal experimental design for event-related fMRI. *Human brain mapping* 8, 109.
- Daselaar, S.M., Veltman, D.J., Rombouts, S., Raaijmakers, J.G.W., and Jonker, C. (2005). Aging affects both perceptual and lexical/semantic components of word stem priming: An event-related MRI study. *Neurobiology of Learning and Memory* 83, 251-262.
- Davis, S.W., Dennis, N.A., Daselaar, S.M., Fleck, M.S., and Cabeza, R. (2008). Que PASA? The Posterior-Anterior Shift in Aging. *Cerebral Cortex* 18, 1201-1209.
- Evans, A.C. (1993). 3D statistical neuroanatomical models from 305 MRI volumes 1993 IEEE Conference Record Nuclear Science Symposium and Medical Imaging Conference.
- Fisher, R.A. (1950). *Statistical methods for research workers*, Vol no. 5, 11th , edn (New York: Hafner).

- Garoff, R.J., Slotnick, S.D., and Schacter, D.L. (2005). The neural origins of specific and general memory: the role of the fusiform cortex. *Neuropsychologia* 43, 847-859.
- Garoff-Eaton, R.J., Slotnick, S.D., and Schacter, D.L. (2006). Not all false memories are created equal: the neural basis of false recognition. *Cereb Cortex* 16, 1645-1652.
- Goh, J.O.S., Siong, S.C., Park, D., Gutchess, A., Hebrank, A., and Chee, M.W.L. (2004). Cortical Areas Involved in Object, Background, and Object-Background Processing Revealed with Functional Magnetic Resonance Adaptation. *The Journal of Neuroscience* 24, 10223-10228.
- Good, C.D., Johnsrude, I., Ashburner, J., Henson, R.N.A., Friston, K.J., and Frackowiak, R.S.J. (2001). Cerebral Asymmetry and the Effects of Sex and Handedness on Brain Structure: A Voxel-Based Morphometric Analysis of 465 Normal Adult Human Brains. *Neuroimage* 14, 685-700.
- Grady, C.L., McIntosh, A.R., Horwitz, B., Maisog, J.M., Underleider, L.G., Mentis, M.J., Pietrini, P., Schapiro, M.B., and Haxby, J.V. (1995). Age-related reductions in human recognition memory due to impaired encoding. *Science* v269, p218(214).
- Graham, K.S., Simons, J.S., Pratt, K.H., Patterson, K., and Hodges, J.R. (2000). Insights from semantic dementia on the relationship between episodic and semantic memory. *Neuropsychologia* 38, 313-324.
- Grill-Spector, K. (1999). Differential processing of objects under various viewing conditions in the human lateral occipital complex. *Neuron* 24, 187.
- Grill-Spector, K., Kushnir, T., Edelman, S., Avidan, G., Itzhak, Y., and Malach, R. (1999). Differential Processing of Objects under Various Viewing Conditions in the Human Lateral Occipital Complex. *Neuron* 24, 187-203.
- Gutchess, A., and Schacter, D.L. (2011). The neural correlates of gist-based true and false recognition. In Manuscript submitted for publication.
- Gutchess, A., Sokal, R., and Schacter, D.L. (2009). Effects of aging on the neural correlates of gist-based false recognition. In Talk presented at the annual meeting of the Society for Neuroscience (Chicago, IL).
- Gutchess, A.H., Welsh, R.C., Hedden, T., Bangert, A., Minear, M., Liu, L.L., and Park, D.C. (2005). Aging and the Neural Correlates of Successful Picture Encoding: Frontal Activations Compensate for Decreased Medial-Temporal Activity. *Journal of Cognitive Neuroscience* 17, 84-96.
- Hedden, T., and Gabrieli, J.D.E. (2004). Insights into the ageing mind: a view from cognitive neuroscience. *Nature Reviews Neuroscience* 5, 87-96.

Henson, R., Shallice, T., and Dolan, R. (2000). Neuroimaging evidence for dissociable forms of repetition priming. *Science* 287, 1269-1272.

Henson, R.N.A. (2003). Neuroimaging studies of priming. *Progress in Neurobiology* 70, 53-81.

Jelicic, M., Craik, F.I.M., and Moscovitch, M. (1996). Effects of Ageing on Different Explicit and Implicit Memory Tasks. *European Journal of Cognitive Psychology* 8, 225-234.

Kensinger, E.A. (2008). Neural processes supporting young and older adults' emotional memories. *Journal of Cognitive Neuroscience* 20, 1161.

Koutstaal, W. (2003). Older Adults Encode--But Do Not Always Use--Perceptual Details. *Psychological Science* 14, 189-193.

Koutstaal, W., and Schacter, D.L. (1997). Gist-Based False Recognition of Pictures in Older and Younger Adults. *Journal of Memory and Language* 37, 555-583.

Koutstaal, W., Wagner, A.D., Rotte, M., Maril, A., Buckner, R.L., Rosen, B.R., Dale, A.M., and Schacter, D.L. (1999). An event-related fMRI study of perceptual specificity effects in visual object priming. *Journal of Cognitive Neuroscience*, 38-38.

Koutstaal, W., Wagner, A.D., Rotte, M., Maril, A., Buckner, R.L., and Schacter, D.L. (2001). Perceptual specificity in visual object priming: functional magnetic resonance imaging evidence for a laterality difference in fusiform cortex. *Neuropsychologia* 39, 184-199.

La Voie, D., and Light, L. (1994). Adult age differences in repetition priming: A meta-analysis. *Psychology and Aging* 9, 539-553.

Light, L.L. (1992). The organization of memory in old age. In *The handbook of aging and cognition*. (Hillsdale, NJ, England: Lawrence Erlbaum Associates, Inc), pp. 111-165.

Light, L.L., and Albertson, S.A. (1989). Direct and Indirect Tests of Memory for Category Exemplars in Young and Older Adults. *Psychology and Aging* 4, 487-492.

Luders, R.P.L., J. Hahn, D. S. Dinner, H. H. Morris, E. Wyllie and J. Godoy (1991). Basal temporal language area. *Brain* 114, 743.

Lustig, C., and Buckner, R.L. (2004). Preserved neural correlates of priming in old age and dementia. *Neuron* 42, 865-875.

Marsolek, C.J. (1995). Abstract visual-form representations in the left cerebral hemisphere. *Journal of Experimental Psychology: Human Perception and Performance* 21, 375-386.

Mitchell, D.B., and Bruss, P.J. (2003). Age Differences in Implicit Memory: Conceptual, Perceptual, or Methodological? *Psychology and Aging* 18, 807-822.

- Park, D.C. (2002). Models of visuospatial and verbal memory across the adult life span. *Psychology and Aging* *17*, 299.
- Park, D.C., and Reuter-Lorenz, P. (2009). The Adaptive Brain: Aging and Neurocognitive Scaffolding. *Annual Review of Psychology* *60*, 173-196.
- Park, D.C., Welsh, R.C., Marshuetz, C., Gutchess, A.H., Mikels, J., Polk, T.A., Noll, D.C., and Taylor, S.F. (2003). Working Memory for Complex Scenes: Age Differences in Frontal and Hippocampal Activations. *Journal of Cognitive Neuroscience* *15*, 1122-1134.
- Reber, P.J., Gitelman, D.R., Parrish, T.B., and Mesulam, M.M. (2005). Priming effects in the fusiform gyrus: Changes in neural activity beyond the second presentation. *Cerebral Cortex* *15*, 787-795.
- Reuter-Lorenz, P.A., and Cappell, K.A. (2008). Neurocognitive Aging and the Compensation Hypothesis. *Current Directions in Psychological Science* (Wiley-Blackwell) *17*, 177-182.
- Reuter-Lorenz, P.A., and Park, D.C. (2010). Human Neuroscience and the Aging Mind: A New Look at Old Problems. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences* *65B*, 405-415.
- Rybash, J.M. (1996). Implicit memory and aging: A cognitive neuropsychological perspective. *Developmental Neuropsychology* *12*, 127-179.
- Schacter, D.L., and Buckner, R.L. (1998). Priming and the Brain. *Neuron* *20*, 185-195.
- Schacter, D.L., Wig, G.S., and Stevens, W.D. (2007). Reductions in cortical activity during priming. *Current Opinion in Neurobiology* *17*, 171-176.
- Simons, J.S., Koutstaal, W., Prince, S., Wagner, A.D., and Schacter, D.L. (2003). Neural mechanisms of visual object priming: evidence for perceptual and semantic distinctions in fusiform cortex. *Neuroimage* *19*, 613-626.
- Soldan, A., Habeck, C., Gazes, Y., and Stern, Y. (2010). Neural mechanisms of repetition priming of familiar and globally unfamiliar visual objects. *Brain Research*.
- Statistics., F.I.F.o.A.-R. (July 2010). Older Americans 2010: Key Indicators of Well-Being. In Federal Interagency Forum on Aging-Related Statistics. (U.S. Government Printing Office).
- Tulving, E., and Schacter, D. (1990). Priming and human memory systems. *Science* *247*, 301-306.
- Velanova, K., Lustig, C., Jacoby, L.L., and Buckner, R.L. (2007). Evidence for Frontally Mediated Controlled Processing Differences in Older Adults. *Cerebral Cortex* *17*, 1033-1046.
- Vuilleumier, P. (2005). Selective attention modulates neural substrates of repetition priming and implicit visual memory: suppressions and enhancements revealed by FMRI. *Journal of Cognitive Neuroscience* *17*, 1245.



Vuilleumier, P., Henson, R.N., Driver, J., and Dolan, R.J. (2002). Multiple levels of visual object constancy revealed by event-related fMRI of repetition priming. *Nat Neurosci* 5, 491-499.

Warrington, E.K. (1975). The selective impairment of semantic memory. *The quarterly journal of experimental psychology* 27, 635.

Wheatley, Weisberg, J., Beauchamp, M.S., and Martin, A. (2005). Automatic Priming of Semantically Related Words Reduces Activity in the Fusiform Gyrus. *J. Cognitive Neuroscience* 17, 1871-1885.

Wig, G.S., Grafton, S.T., Demos, K.E., and Kelley, W.M. (2005). Reductions in neural activity underlie behavioral components of repetition priming. *Nat Neurosci* 8, 1228-1233.

## ***Tables***

---

Table 1

Demographic and neuropsychological data for both age groups of participants.

	Young	Elderly	<i>p</i> -value
Years of Education	16.3 (2.7)	15.4 (2.4)	.249
Digit comparison	79.1 (12.0)	54.4 (10.1)	<.001
Self-rated Health *	3.89 (.676)	3.82 (.728)	.785

\* Self-rated health reflects a 5-point scale rating of one's health in comparison to others in one's age group. A rating of 3 indicates "average health compared to others" and a rating of 4 indicates "better than average health compared to others."

Table 2

This table lists activation peaks in Montreal Neurological Institute (MNI) coordinates for conjunction analyses elucidating similar patterns of activation across young and old age groups. Data is thresholded at  $p < .001$  (uncorrected), with a voxel extent threshold of 5 voxels. Labels correspond to the peak activated voxel, and no more than 3 local maxima at least 8mm apart are shown.

### Conjunction Analyses

Brain Region	BA	x	y	z	# voxels	t value
<b><u>A. Early Repetitions &gt; Middle Repetitions</u></b>						
L Superior Temporal Pole	38	-42	24	-16	15	3.63
L Pallidum	N/A	-16	10	12	14	3.42
R Cerebellum	30	10	-30	-22	15	3.34
R Supp Motor Area	32	10	26	48	7	3.32
L Fusiform	37	-30	-34	-20	19	3.07
L Middle Occipital	19	-34	-88	28	9	2.91
L Supp Motor Area	32	2	12	46	17	2.90
L Thalamus	N/A	-10	-10	8	17	2.87
L Precentral	6	-48	2	44	5	2.81
L Cuneus	18	-8	-80	20	5	2.56
L Superior Frontal	9	-22	26	40	13	2.54
<b><u>B. Middle Repetitions &gt; Early Repetitions</u></b>						
N/A (R Ventricle)	N/A	6	-12	26	13	3.55
L Middle Occipital	7	-34	-62	36	22	2.74
L Middle Cingulum	6	-12	-6	52	22	2.55
L Superior Frontal	10	-18	54	18	7	2.42
<b><u>C. Middle Repetitions &gt; Late Repetitions</u></b>						
No significant voxels						
<b><u>D. Late Repetitions &gt; Middle Repetitions</u></b>						
L Cerebellum	18	-6	-48	-10	6	3.26
L Pallidum	48	24	-4	-2	6	3.05
R Medial Frontal	10	8	54	-6	10	2.75
R Inferior Frontal	47	36	32	16	7	2.73
R Insula	48	34	-20	0	22	2.65
R Anterior Cingulate	32	14	42	10	6	2.55
N/A (White Matter)	N/A	-6	-12	-16	5	2.41

Table 3

This table lists activation peaks in Montreal Neurological Institute (MNI) coordinates for the age difference analyses. Data is thresholded at  $p < .001$  (uncorrected), with a voxel extent threshold of 5 voxels. Labels correspond to the peak activated voxel, and no more than 3 local maxima at least 8mm apart are shown.

<b>Brain Region</b>	<b>BA</b>	<b>x</b>	<b>y</b>	<b>z</b>	<b># voxels</b>	<b>t value</b>
<b><u>Early Repetitions vs Middle Repetitions</u></b>						
<b>A. Young-Old</b>						
N/A (R Ventricle)	N/A	8	-10	22	18	4.55
L Superior Frontal	6	-14	4	56	14	4.23
L Middle Occipital	7	-32	-64	36	16	4.15
R Superior Temporal	22	62	-20	24	6	3.79
<b>B. Old-Young</b>						
R Inferior Frontal	48	32	26	-16	42	5.17
R Insula	48	24	18	-16		4.40
N/A (Out of Brain)	N/A	4	-16	-32	12	4.96
L Parahippocampal	N/A	-28	-18	22	7	4.33
L Temporal Mid	20	-58	-14	-22	17	4.14
L Insula	47	-32	20	-10	12	4.13
N/A (R Ventricle)	N/A	24	20	36	7	3.46
<b><u>Middle Repetitions vs Late Repetitions</u></b>						
<b>C. Young-Old</b>						
L Insula	48	-28	8	-10	13	4.54
Temporal Mid L	21	-56	-2	-18	69	4.52
Temporal Mid L	20	-52	-12	-22		4.34
<b>D. Old-Young</b>						
No significant voxels						

## ***Figures***

---

### Figure Captions

#### **Figure 1: Medium Study Set**

Example of a medium study set of eight exemplars of the object set “chair.”

#### **Figure 2**

Reaction times are depicted across age groups for early repetitions (reps 2, 3, and 4), middle repetitions (reps 5, 6, 7, 8) and late repetitions (reps 9, 10, 11, 12, 13, 14).

#### **Figure 3: Conjunction Analysis Regions of Interest**

Depiction of the percentage signal change in two regions appearing the conjunction analyses: left fusiform gyrus (-30, -34, -20) and a posterior portion of the left middle occipital lobe (-34, -88, 28). Both regions demonstrate similar repetition suppression effects. Left fusiform repetition suppression reflects general object priming when repeated items are perceptually similar, but not identical. Posterior left middle occipital priming reflects a similar response across age groups to elements of visual stimulus specificity.

#### **Figure 4: Age-Differences Analysis Regions of Interest**

Depiction of the percentage signal change in six regions appearing in the age differences analyses: an anterior portion of the left middle occipital gyrus, a right inferior frontal region, left insula, left parahippocampal region, and two left middle temporal regions. Age differences largely result from the reversal of activation patterns across age groups. Differences in the frontal and temporal activation patterns may reflect age-related neural changes to the semantic/conceptual components of priming, while differences in occipital and parahippocampal regions may reflect age-related neural differences in the perceptual components of priming.

Figure 1



Figure 2

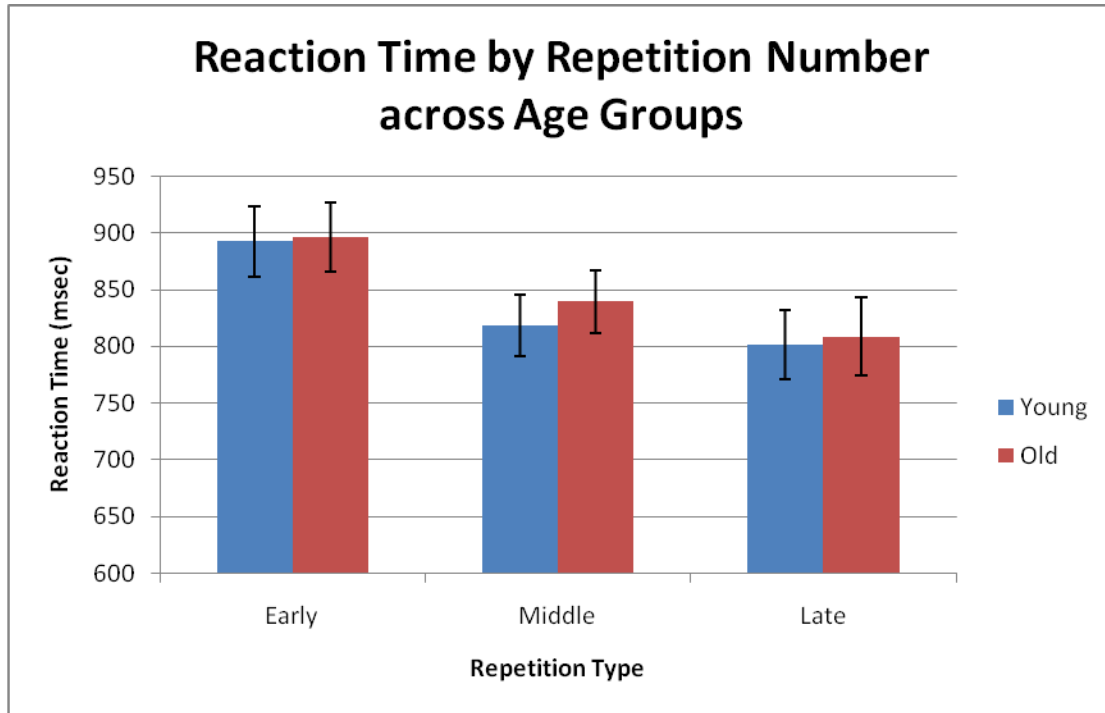


Figure 3

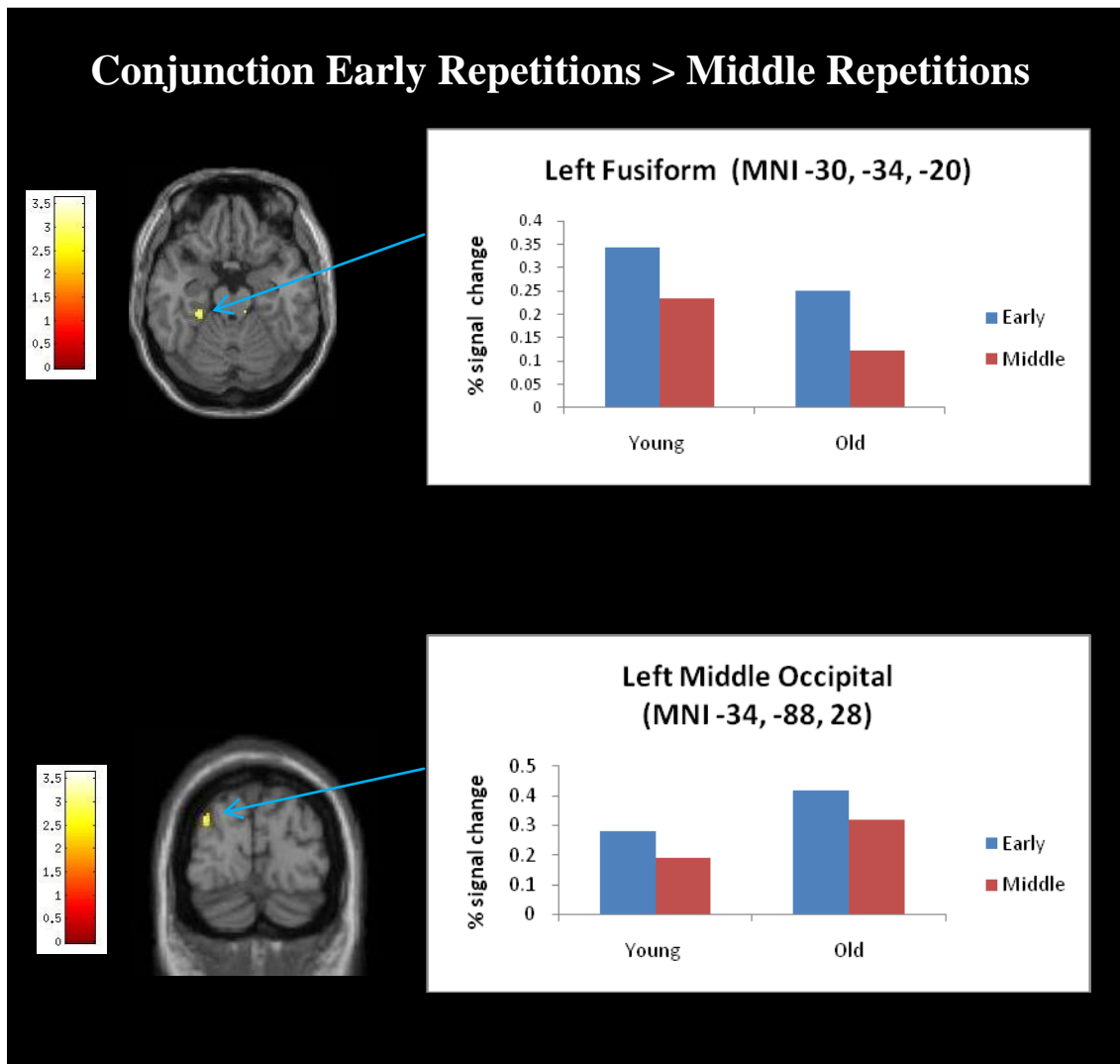
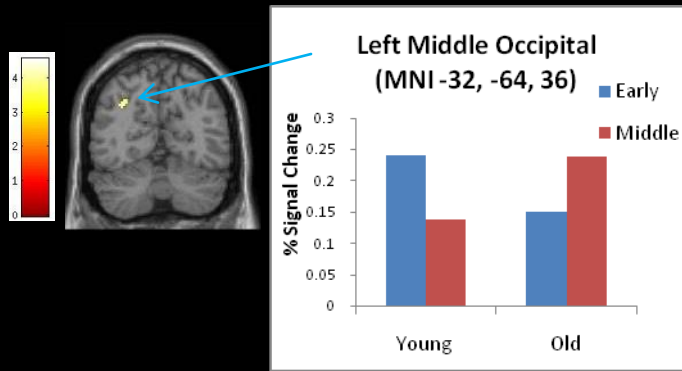




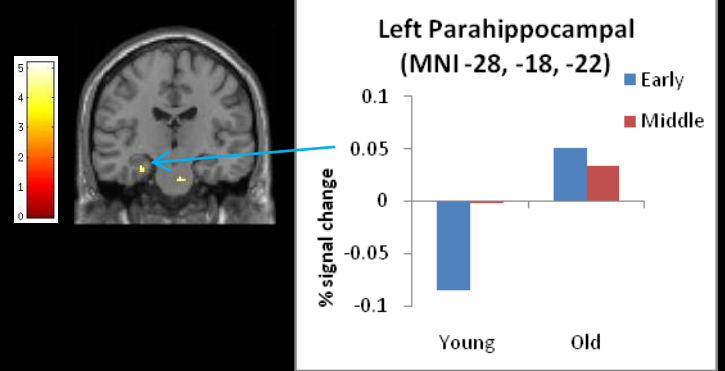
Figure 4

## Age Differences Contrasts

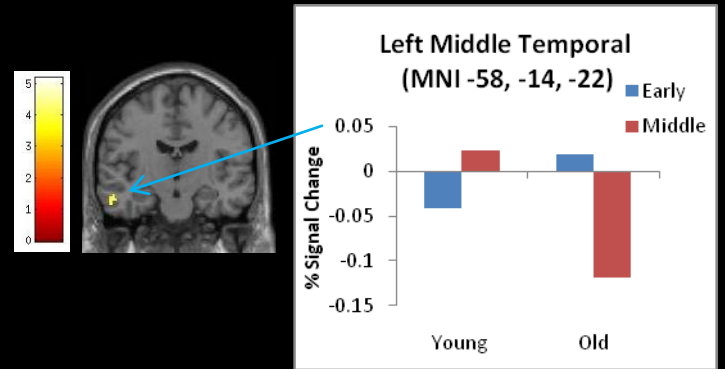
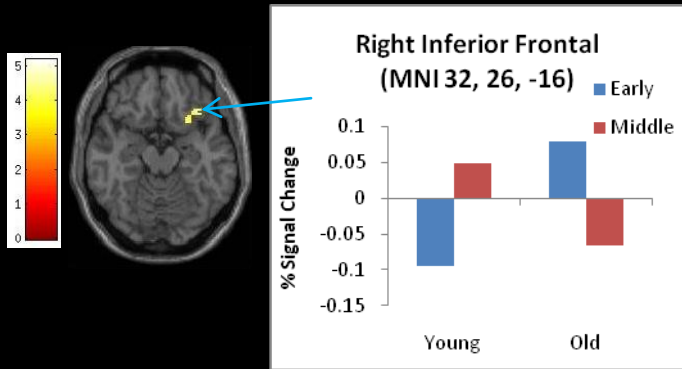
### A. Young-Old for Early Reps > Middle Reps



### B. Old-Young for Early Reps > Middle Reps (Continued)



### B. Old-Young for Early Reps > Middle Reps



### C. Young-Old for Middle Reps > Late Reps

