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Altered Prefrontal Function with Aging: Insights into Age-associated Performance Decline

Anne-Kristin Solbakk^{a,b,c}, Galit Fuhrmann Alpert^a, Ansgar J. Furst^a, Laura A. Hale^a, Tatsuhide Oga^a, Sundari Chetty^a, Natasha Pickard^a, and Robert T. Knight^a

^aDepartment of Psychology and the Helen Wills Neuroscience Institute, University of California, Berkeley, USA

^bDepartment of Neuropsychiatry and Psychosomatic Medicine, Division of Clinical Neuroscience, Rikshospitalet University Hospital, Oslo, Norway

^cDepartment of Psychology, University of Oslo, Norway

Abstract

We examined the effects of aging on visuo-spatial attention. Participants performed a bi-field visual selective attention task consisting of infrequent target and task-irrelevant novel stimuli randomly embedded among repeated standards in either attended or unattended visual fields. Blood oxygenation level dependent (BOLD) responses to the different classes of stimuli were measured using functional magnetic resonance imaging. The older group had slower reaction times to targets, and committed more false alarms but had comparable detection accuracy to young controls. Attended target and novel stimuli activated comparable widely distributed attention networks, including anterior and posterior association cortex, in both groups. The older group had reduced spatial extent of activation in several regions, including prefrontal, basal ganglia, and visual processing areas. In particular, the anterior cingulate and superior frontal gyrus showed more restricted activation in older compared with young adults across all attentional conditions and stimulus categories. The spatial extent of activations correlated with task performance in both age groups, but the regional pattern of association between hemodynamic responses and behavior differed between the groups. Whereas the young subjects relied on posterior regions, the older subjects engaged frontal areas. The results indicate that aging alters the functioning of neural networks subserving visual attention, and that these changes are related to cognitive performance.

Keywords

Attention; fMRI; Frontal lobe; Neural networks; Oddball

1. Introduction

Healthy aging affects many aspects of cognitive functioning, including declines in sensory-perceptual processing and executive control processes (Verhaeghen and Cerella, 2002).

Correspondence should be addressed to Dr. Anne-Kristin Solbakk, Department of Neuropsychiatry and Psychosomatic Medicine, Division of Clinical Neuroscience, Rikshospitalet University Hospital, 0027 Oslo, Norway. Phone: + 47 23074925. Facsimile: + 47 23074170. E-mail: E-mail: anne-kristin.solbakk@rikshospitalet.no.

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Slowed processing speed and reduction of cognitive resources in several domains are fundamental characteristics of age-related changes in performance on cognitive tasks (Kok, 2000) and provide a parsimonious account of the performance declines observed on a variety of tasks. Other research has examined whether aging affects more specific cognitive mechanisms such as the ability to selectively focus attention to relevant information. Literature reviews have suggested that selective attention is relatively well preserved with aging (Kok, 2000; Verhaeghen and Cerella, 2002; Madden and Whiting, 2004).

However, selective attention is a multifaceted concept and different aspects of attention may show a differential sensitivity to the healthy aging process. Although basic selection mechanisms may be intact, there is evidence that age-related decline in executive control mechanisms contribute significantly to performance decrement on attention demanding tasks (Madden and Whiting, 2004). For instance, age-related decline has been documented (Madden, 2007; Verhaeghen and Cerella, 2002) when dividing attention between dual-tasks (Verhaeghen et al., 2003), inhibiting prepotent or automatic responses (Butler and Zacks, 2006), and intentionally inhibiting task-irrelevant or distractive information. Several studies have reported a decreased ability to ignore irrelevant events in older adults (Kok et al., 1995; McDowd and Filion, 1995; West, 1996; Chao and Knight, 1997; Colcombe et al., 2003; Gazzaley et al., 2005; Gazzaley and D'Esposito, 2007).

Changes in the structure and function of the prefrontal cortex are believed to mediate many of the performance declines seen with aging. Structural neuroimaging studies indicate that prefrontal cortex shows the highest degree of age-related atrophy (Raz et al., 1997; Jernigan et al., 2001; Salat et al., 2001), and synaptic density seems to decline preferentially in the frontal lobes with advancing age (Masliah et al., 1993). Moreover, functional neuroimaging studies have reported age-related changes in activation patterns within prefrontal cortex during working memory and attention tasks, often showing less activity in older compared with young adults (Milham et al., 2002; Reuter-Lorenz, 2002). However, many functional magnetic resonance imaging (fMRI) studies using perceptual and episodic memory tasks have reported that prefrontal activation can be greater in either intensity or spatial extent for older adults (Grady, 2000; Cabeza, 2002). This enhanced activation is often proposed to index a compensatory recruitment of attentional functions mediated by the frontal lobe, perhaps in response to disconnection of frontal from posterior regions due to age-related white matter changes.

Functional neuroimaging and electrophysiological studies have shown that attention is mediated by distributed neural networks. A posterior orienting system involving the parietal lobe and thalamic structures is concerned with sensory input selection and the spatial allocation of attention (Posner and Petersen, 1990). An anterior or "executive" attention system that involves the prefrontal and anterior cingulate cortices controls working memory, processing of stimulus characteristics in posterior areas, and response selection in non-routine tasks (Barcelo et al., 2000; Bush et al., 2000; Yago et al., 2004). There is additional evidence that these networks interact to implement attentional control (Banich et al., 2000; Fan et al., 2007).

The "oddball" paradigm is commonly used to index activity in attention networks. This task consists of repeated "standard" and occasional deviant "target" stimuli. Sometimes a distractor or novel stimulus is added to assess automatic attention. Deviant stimuli evoke widespread neural activity that is reflected in both electrophysiological and hemodynamic responses. Event-related potential (ERP) studies show that controlled attention to task-relevant targets generate large parietal and smaller frontal P3 (P3b) components, whereas unexpected novel stimuli evoke a differential increase in prefrontal P3 (P3a) amplitude that is associated with an automatic orienting response (Knight, 1996; Opitz et al., 1999). Scalp-recorded and intracranial

ERPs indicate that spatially remote regions of prefrontal and posterior association cortex respond to target and novel stimuli (Ranganath and Rainer, 2003).

Studies adopting the oddball design for use with event-related fMRI have generally corresponded well with these results, and have identified involvement of additional subcortical structures (McCarthy et al., 1997; Menon et al., 1997; Opitz et al., 1999; Yoshiura et al., 1999; Clark et al., 2000; Kirino et al., 2000; Strange et al., 2000; Downar et al., 2001; Kiehl et al., 2001; Ardekani et al., 2002; Bledowski et al., 2004). Detection of a target elicits BOLD activation in prefrontal and parietal cortices in young adults. Activation of the middle frontal gyrus has been consistently reported (e.g. McCarthy et al., 1997; Kirino et al., 2000), and anterior cingulate cortex activation has been reported in some studies (e.g., Menon et al., 1997; Kiehl et al., 2001; Ardekani et al., 2002; Yamaguchi et al., 2004; Crottaz-Herbette and Menon, 2006). Bledowski et al. (2004) reported that visual targets and novels engaged a common neuronal system (right prefrontal cortex and bilateral temporal-parietal junction) for the detection of rare events. Altogether, the results of the hemodynamic and electrophysiological research confirm that a distributed neocortical-limbic circuit is activated by detection of task-relevant targets as well as unexpected novel events in young adults.

Aging ERP studies report a substantial reduction in the amplitude of both target and novelty P3s during the adult life span. Moreover, targets often elicit longer latency P3bs at parietal sites in older than in young adults. Collectively, these results support an age-dependent decline in the intensity of attentional orienting and speed of target identification (Kok, 2000). A robust finding is that target and novel P3s have a more similar scalp distribution in older subjects (Friedman et al., 1997; Fjell et al., 2005) due to the more frontal distribution of the target P3b in older subjects. ERPs in focused attention paradigms suggest that older subjects are more distracted by irrelevant peripheral stimuli (Kok, 2000). ERP studies using other paradigms (i.e. Simon task, Eriksen task, Stroop task) to study attentional control, have provided additional support for decreased inhibitory control in older adults (Zeef et al., 1996; West and Alain, 2000; Van der Lubbe and Verleger, 2002).

While numerous studies have focused on the effects of normal aging on ERP activation patterns, in particular in terms of P3 magnitudes, less is known about the spatial localization of the underlying networks. The lack of such information is mainly due to the low spatial resolution of the EEG recordings. Madden et al. (2004) conducted an fMRI study that used a visual three-stimulus oddball design to determine the effect of aging on the neural networks that underlies the response to target and novel stimuli. Targets activated several prefrontal areas and deep grey matter regions. Prefrontal activation was similar for young and older adults, whereas deep gray matter activation was relatively greater for the older adults. Novels activated occipital regions, and this activation was relatively reduced for older adults. Furthermore, in a visual search task, Madden et al. (2007) reported overall greater frontal and parietal BOLD activation in older compared to young adults. The finding concurs with other neuroimaging studies suggesting age-related change within the dorsal component of the fronto-parietal attention network. Activation of frontal regions has a tendency to increase with normal aging. This may reflect increased engagement of attentional control processes subserved by prefrontal regions. However, additional evidence linking age-related increase in frontal networks activation with performance is needed before firm conclusions regarding compensatory mechanisms can be made (Madden, 2007).

The influence of aging on selective attention and deviance detection has not been systematically studied using fMRI. Here we examined how healthy aging affects neural networks supporting visuo-spatial stimulus selection and executive control of attention. We adopted a bi-field covert selective attention paradigm previously employed by Yamaguchi et al. (2004), but used a shortened version to counteract the potentially confounding effects of fatigue in older

participants. Three classes of stimuli were randomly presented in either attended or unattended visual fields. Infrequent targets were to be discriminated from frequent standards based on the spatial orientation of the stimuli, and task-irrelevant pictures were used as novel stimuli. Previous bi-field attention paradigms have shown that unpredictable novel pictures generate behavioral and physiological changes associated with the orienting response (Suwazono et al., 2000). The task we employed involved executive control processes such as selecting stimuli to be attended, inhibiting distracting stimuli, and overtly switching attention between different spatial locations of stimulus presentation.

We used an event-related design and a rapid pace of stimulus presentation which closely replicates oddball designs used in ERP studies. Blood oxygenation level dependent (BOLD) responses were measured to target, novel, and standard stimuli in attended as well as unattended visual fields. Anatomical regions of interest (ROIs) were defined a priori and included bilateral frontal cortex, posterior cortex, and deep gray matter structures, regions known implicated in the processing of visual target and novel events. Because inter-individual differences in brain activation tend to be pronounced, particularly in aging and neurological diseases, group analysis in standard space was not used (see also Madden et al., 2004; Vandenbroucke et al., 2004; Madden et al., 2007). Instead, we focused on the analysis of individual differences in regional activations.

The bi-field oddball task used in the present study was predicted to be sensitive to the effects of normal aging, both at the behavioral and the neurophysiological level. Target hit rate is typically high in this task (Yamaguchi et al., 2004). Thus, performance differences between the age groups were predicted to be more evident in reaction time than in response accuracy. Commission errors were recorded as a behavioral measure of executive control since distractibility, or difficulty with response inhibition, may result in an increased tendency to respond to non-targets.

Due to the proposed sensitivity of frontal cortex to the healthy aging process, we hypothesized that the task's demand for controlled attention would engage the anterior cingulate cortex and prefrontal regions, and that these areas would show age-related functional differences. Following the results of Madden and coworkers we would expect either comparable prefrontal activation for young and older participants as shown with a visual oddball task (Madden et al., 2004), or greater prefrontal activation as demonstrated with a visual search task (Madden et al., 2007). In contrast, a general decline in attentional resources with age, or decline in the intensity of attentional orienting and speed of target detection as suggested by ERP studies (Kok, 2000) would be expected to be accompanied by a reduction in the spatial extent of brain activations. This would likely affect several components within the fronto-parietal attention network. Finally, we predicted that significant age-related changes in the hemodynamic responses of attentional networks would be accompanied by changes in task performance. Accordingly, we performed correlation analyses to examine the within-group relationships between neurophysiological activation and behavior.

2. Results

Behavioral responses

Mean reaction time, percent detected targets, percent false alarms to non-targets, and significance levels for group comparisons are reported in Table 1. Behavioral results were collapsed across the three experimental runs. Analysis of variance for hit rate showed no significant difference between the age groups. Both groups detected > 97 % of the attended field targets. The older group responded significantly slower to targets ($F(1,23) = 8.0, p < .007$; Young group = 622 msec; Older group = 695 msec) and committed a greater number of false alarms to non-targets relative to the young group ($F(1,23) = 4.5, p < .046$; Young group

= 0.5; Older group = 2.1). Inspection of error types showed that false alarms committed by both young and older participants mainly occurred to standards in the attended hemifield and in the first session of the experiment.

Size of regions of interest

A presentation of the size of the ROIs (total number of voxels averaged over hemispheres) is found in Table 2. The analyses showed significantly smaller ROIs for older compared with young participants in the caudate ($t(23) = 2.1, p < .043$), thalamus ($t(23) = 2.5, p < .018$), fusiform gyrus ($t(23) = 2.6, p < .017$), and middle frontal gyrus ($t(23) = 2.3, p < .031$).

Hemodynamic responses

The figures for attended (Figure 2, Figure 4, and Figure 6) and unattended (Figure 3, Figure 5, and Figure 7) visual fields illustrate the spatial extent of activation for both targets and novels and for both age groups.

All ANOVAs showing main effects or interactions involving Group were repeated using “size of ROI” as covariate due to the significant group difference in the size of the ROIs representing a subset of anatomical regions (Table 2.). All reported effects involving Group remained significant when controlling for the number of voxels in ROI.

Frontal regions—Data for the frontal regions are presented in Figure 2 and Figure 3.

Anterior cingulate cortex: The analysis revealed a main effect of Condition ($F(1,23) = 4.6, p < .042$) that was modified by a Condition $\times$ Stimulus interaction ($F(1,23) = 13.1, p < .001$). Follow-up analyses showed that the extent of activation was greater for targets compared to novels in the attended field ($F(1,23) = 4.3, p < .049$), and for novels relative to targets in the unattended field ($F(1,23) = 8.8, p < .007$). Similar significant Condition $\times$ Stimulus interactions were found for the majority of ROIs and follow-up analyses consistently showed the same pattern of experimental effects, but will not be reported in any further detail. Moreover, a main effect of Group ($F(1,23) = 13.1, p < .001$) reflected that the young group had more distributed anterior cingulate activation than the older group across attention conditions, stimulus categories, and hemispheres.

Superior frontal gyrus: The data again showed a significant effect for Condition ($F(1,23) = 5.6, p < .026$) and a Condition $\times$ Stimulus interaction ($F(1,23) = 9.5, p < .005$). A main effect of Group ($F(1,23) = 4.3, p < .049$) reflected that young adults generally had a more distributed activation than older adults.

Middle frontal gyrus: Analysis of the extent of activation revealed main effects of Condition ($F(1,23) = 5.4, p < .029$), and Hemisphere ($F(1,23) = 19.8, p < .0001$), reflecting that the activation was more broadly distributed for attended stimuli, and for the right hemisphere, respectively. These effects were modified by an Condition $\times$ Stimulus $\times$ Hemisphere interaction ($F(1,23) = 8.4, p < .008$). Follow-up tests showed that the right hemisphere activation was significantly more extensive for targets than for novels in the attended field. The overall analysis showed a non-significant trend for the young group to have more broadly distributed activation than the older group, Group ($F(1,23) = 3.6, p < .070$).

Inferior frontal gyrus: The analysis showed the common Condition $\times$ Stimulus interaction ($F(1,23) = 16.4, p < .0001$). A main effect of Group ($F(1,23) = 5.2, p < .032$) reflected that the young group overall had a greater extent of activation than the older group, but a Condition $\times$ Stimulus $\times$ Group interaction ($F(1,23) = 5.4, p < .029$) showed that the effect of age was most pronounced for attended targets.

Motor cortex: A significant Condition $\times$ Stimulus interaction ($F(1,23) = 9.3, p < .006$) was found. A main effect of Hemisphere ($F(1,23) = 4.8, p < .04$) was due to more distributed activation for the left compared to the right motor cortex. Decomposition of a Condition $\times$ Stimulus $\times$ Hemisphere $\times$ Group interaction ($F(1,23) = 4.3, p < .049$) revealed significantly more extensive left motor cortex activation to attended targets in the young compared with the older group.

Summary of main age-related findings for frontal regions: The young group overall had more distributed responses than the older group in the anterior cingulate and the superior frontal gyrus. In the inferior frontal gyrus, young adults had a greater spatial extent of activation for attended targets across hemispheres compared with older adults. The young group also had a greater extent of left motor cortex activation to attended targets compared with the older group.

Posterior regions—The data for posterior regions are presented in Figure 4 and Figure 5.

Hippocampus: The analysis showed an effect of Hemisphere ($F(1,23) = 6.9, p < .015$) due to more extensive *left* than right hemisphere activation. There was a Condition $\times$ Stimulus effect ($F(1,23) = 6.9, p < .015$), and a Condition $\times$ Stimulus $\times$ Hemisphere interaction ($F(1,23) = 8.6, p < .007$), reflecting more distributed *left* hippocampal activation to novels in the unattended hemifield. A Condition $\times$ Stimulus $\times$ Group interaction ($F(1,23) = 5.9, p < .024$) reflected that the young group had a larger extent of activation to attended targets, and across unattended stimuli relative to the older group.

Temporal-parietal junction: There was a Condition $\times$ Stimulus ($F(1,23) = 14.6, p < .001$), and an additional Condition $\times$ Stimulus $\times$ Group ($F(1,23) = 6.1, p < .022$) interaction. The latter interaction primarily reflected that the young group had a tendency ($p < .052$) for more distributed activation to novels in the unattended field than the older group.

Superior parietal lobule: Significant effects of Condition ($F(1,23) = 6.3, p < .019$), and Condition $\times$ Stimulus interaction ($F(1,23) = 10.2, p < .004$) followed the same general pattern as for the other ROIs. There were no significant effects of age group.

Fusiform gyrus: The Condition $\times$ Stimulus interaction was again significant ($F(1,23) = 7.8, p < .010$). An additional main effect of Group ($F(1,23) = 4.5, p < .044$) reflected that the young group generally had more broadly distributed activation than the older group.

Lateral occipital gyrus: The data showed effects of Hemisphere ($F(1,23) = 21.6, p < .0001$), and Condition $\times$ Stimulus ($F(1,23) = 13.9, p < .001$) that were modified by a Condition $\times$ Stimulus $\times$ Hemisphere interaction ($F(1,23) = 4.9, p < .036$). Follow-up tests on separate conditions showed trend-level Stimulus $\times$ Hemisphere interactions (p 's $< .086$), suggesting more distributed left than right hemisphere activation for targets in the attended field and for novels in the unattended field. A Condition $\times$ Stimulus $\times$ Group interaction ($F(1,23) = 6.2, p < .020$) was consistent with a significantly greater extent of activation to attended field targets in the young group.

Summary of main age-related findings for posterior regions: The young group had a greater extent of hippocampal activation to attended targets than the older group. The young participants also had a greater extent of fusiform gyrus activation across conditions, and more distributed lateral occipital gyrus activation to attended field targets relative to the older group.

Deep gray matter regions—The data for deep gray matter regions are displayed in Figure 6 and Figure 7.

Caudate: Targets had more broadly distributed activation than novels, Stimulus ($F(1,23) = 9.8, p < .005$). A main effect of Group ($F(1,23) = 8.4, p < .008$) was consistent with more extensive activation for the young group. An additional Stimulus $\times$ Hemisphere $\times$ Group interaction ($F(1,23) = 7.1, p < .014$) reflected that the young subjects had a trend ($p < .065$) towards more extensive *left* caudate activation to targets than their older counterparts.

Putamen: A significant Condition $\times$ Stimulus $\times$ Group interaction ($F(1,23) = 5.0, p < .035$), was due to a greater extent of activation for unattended novels in the young relative to the older group.

Thalamus: The spatial extent data showed a Condition $\times$ Stimulus interaction ($F(1,23) = 11.1, p < .003$), and a Condition $\times$ Stimulus $\times$ Group interaction ($F(1,23) = 7.9, p < .010$). The latter reflected that the young group had a significantly greater extent of activation to targets in the attended field, and a tendency ($p < .054$) for more extensive activation to novels in the unattended field compared to older adults. Figure 6 suggests that the older group had more distributed activation to novels in the attended field, but the effect was non-significant.

Summary of main age-related findings for deep gray matter regions: Across attended stimuli, the young group had more extensive activation than the older group in the caudate. Older adults had less distributed activation for unattended novels relative to young adults in the putamen. For the thalamus, the young group had a greater extent of activation to targets in the attended field, and to novels in the unattended field relative to the older group.

Correlation between spatial extent of activation and performance

The relationship between spatial extent of activation in each ROI and task performance (target hit rate and reaction time, false alarms to non-targets) was examined by means of Pearson product-moment correlation coefficients (two-tailed test). Data for the right and left hemisphere were collapsed to limit the number of variables included in the analyses.

The results of the correlation analyses are shown in Table 3. The analyses were performed for each age group separately and separate analyses were conducted for BOLD responses to attended targets and unattended novels within each group. BOLD responses to novels in the unattended hemifield may represent the purest measure of involuntary attention to salient and potentially significant events.

Activation to attended field targets – Young group—There was a significant correlation between target detection accuracy and fusiform gyrus activation ($r = -.65, p < .023$). The negative relationship indicated that increasing signal extent correlated with lower target detection accuracy.

Hippocampus activation correlated positively with reaction time ($r = .58, p < .049$), reflecting that increasing signal extent was related to increasing response time. There were significant positive relationships between false alarm rate and lateral occipital gyrus ($r = .76, p < .004$) as well as thalamus ($r = .62, p < .031$) activation. Increasing activation extent was related to increasing false alarm rate.

Activation to unattended field novels – Young group—Behavioral responses were not significantly associated with BOLD responses recorded after presentation of novels in the ignored visual field.

Activation to attended field targets – Older group—The analyses revealed significant associations between target hit rate and activation in the anterior cingulate ($r = -.65, p < .017$)

as well as the superior frontal gyrus ($r = -.81, p < .001$). The negative correlations suggest that increasing extent of activation was associated with lowered hit rate. There was a trend-level correlation between target reaction time and extent of activation in the caudate nucleus ($r = .54, p < .058$). The direction of the associations indicated that increasing activation extent was related to increasing reaction time. False alarm rate did not correlate significantly with ROI activation.

Activation to unattended field novels – Older group—The extent of anterior cingulate activation following novels in the unattended hemifield correlated significantly with false alarm rate ($r = .66, p < .014$), and with target reaction time ($r = .58, p < .040$). The positive correlations indicate that participants with more spatially extensive activation committed more false alarms to non-targets and were slower responders than those with less extensive activation.

3. Discussion

We examined the influence of healthy aging on the neural networks engaged during a visuo-spatial selective attention task requiring target detection and flexible shifting of covert attention to cued locations. Both young and older subjects identified targets in the attended hemifield with a high degree of accuracy ($> 97\%$), but the older group had more false alarms. These commission errors may be due to difficulties with stimulus discrimination and/or inhibitory control of erroneous responses. Older subjects had prolonged RTs to targets in agreement with the notion that behavioral slowing due to reduction in sensory-perceptual and response execution processes is a cardinal characteristic of normal aging (Cerella, 1985; Salthouse, 1996; Madden and Whiting, 2004). Age-related changes in the efficiency of top-down control processes subserved by frontal regions may have influenced both response time and false alarm rate, although the overall good performance does not indicate any major executive control deficit.

The experimental design used here requires a number of cognitive processes for optimal performance, including preparatory attention, covert shifting of attention to the appropriate hemifield according to spatial cues, working memory, target detection as well as execution of responses to targets, inhibition of responses to non-targets, and monitoring of response accuracy. Because most of these cognitive processes are mediated by the coordinated activity of multiple brain regions rather than by a circumscribed area, performance on this task would be expected to engage activity within a spatially distributed set of brain regions that support these processes. Indeed, attended target and novel stimuli activated widely dispersed attention networks including anterior and posterior association cortex as well as subcortical structures in both age groups.

The experimental manipulation of attentional condition (attended versus unattended hemifield) had similar effects on both age groups. Targets presented in the attended hemifield evoked a greater spatial extent of activation than attended novel stimuli across age groups and for most ROIs. This may reflect the recruitment of a distributed network for executive control that allocates a greater amount of attentional resources to task-relevant targets relative to equiprobable, but task-irrelevant, novels. Conversely, for the unattended condition, novels elicited more distributed BOLD responses than targets for the majority of ROIs. Thus, irrespective of age, a wide-spread neural system for rapid automatic detection of potentially significant novel events was more responsive to unattended novels than to unattended targets. This is in accord with prior ERP and fMRI evidence that novel events capture attention even in unattended spatial locations (Yamaguchi et al., 2004).

Hemispheric asymmetry of BOLD responses was observed for certain brain regions. For both targets and novels presented to both attended and unattended fields, the right middle frontal gyrus was more responsive than the homologous region of the left hemisphere. This finding is in line with previous fMRI studies reporting relatively greater hemodynamic responses to deviants in right compared with left hemisphere regions of prefrontal cortex (McCarthy et al., 1997; Kirino et al., 2000; Huettel and McCarthy, 2004). The results support the proposal that the right hemisphere is differentially engaged in the attentional allocation to salient stimuli, independent of stimulus modality or laterality of sensory input (Pardo et al., 1991). This hemispheric asymmetry was preserved in older participants, as was also reported by Stevens et al. (2005) for auditory oddballs.

Although the older group was as sensitive to the experimental context as the young group, there were age-related differences in the activity of several components in the attention circuit. The results showed systematic differences in the spatial extent of activation for several ROIs.

The hemodynamic responses in the anterior cingulate and superior frontal gyrus were less spatially distributed for both classes of deviants, and for both attended and unattended hemifields, in the older compared with the young group. It has been difficult to distinguish the functions of the dorsal anterior cingulate cortex and the adjacent superior frontal gyrus, the latter region partly corresponding to the pre-supplementary motor area, and both regions have been implicated in executive control functions (Cole and Schneider, 2007; Rushworth et al., 2004). The anterior cingulate cortex is known to serve as a key structure of the executive attention network that is involved in the top-down regulation of attention (Devinsky et al., 1995; Fan et al., 2007). There is converging evidence that the anterior cingulate is involved in target detection, response selection, and response monitoring. Early PET studies showed that whatever the type of target, the anterior cingulate was active, either alone, or in conjunction with other frontal areas (Posner and Raichle, 1995). These findings are in line with later fMRI studies that report an involvement of the anterior cingulate in target detection irrespective of task modality (Menon et al., 1997; Huettel and McCarthy, 2004; Crottaz-Herbette and Menon, 2006). The findings may support the notion that the anterior cingulate has a general alertness, or orienting, function in addition to its well known function in response monitoring (Dreher and Berman, 2002).

Recent models of attentional control have emphasized the involvement of the anterior cingulate in evaluatory processes based on findings showing this region to play a critical role in conflict monitoring and error detection (Gehring and Fencsik, 2001; Rushworth et al., 2005). It has been argued that the anterior cingulate not only detects errors, but is also activated during correct behavior with both these functions regulated by lateral prefrontal cortex (Gehring and Knight, 2000). The finding that anterior cingulate activity is also found in the absence of an overt error indicates that it contributes to the prevention of errors through online monitoring of performance (Ullsperger and von Cramon, 2001; Huettel and McCarthy, 2004).

In a review of the role of the superior frontal gyrus in task control, Rushworth et al. (2004) include anticipatory preparation and selection of stimulus-response rules in addition to monitoring of response conflict. Nagahama et al. (1999) showed that the medial superior frontal gyrus contributed to attention set shifts between object features in a card sorting task. Moreover, du Boisgueheneuc et al. (2006) demonstrated that the lateral portions of the superior frontal gyrus are involved in higher executive aspects of working memory processes (monitoring and manipulation). Using a modified Stroop task, Alexander and coworkers showed that lesions in an area that included the pre-supplementary motor area as well as anterior and dorsal cingulate correlated with errors on targets (Alexander et al., 2007). Altogether, the results point to a key role for both the superior frontal gyrus/pre-supplementary motor area and the anterior

cingulate cortex in certain cognitive control processes (Cole and Schneider, 2007; Dosenbach et al., 2006).

It has been suggested that age-related changes of anterior cingulate activity may reflect a decrease in the effectiveness of cognitive control in older adults (Milham et al., 2002). Cognitive control is a continuous process. Thus, in regions that support the control of attention or working memory, there might be a state change of enhanced activity throughout a task (Dosenbach et al., 2006; Petit et al., 1998). In the present study one may speculate that the reduced extent of anterior cingulate and superior frontal gyrus activation seen across classes of deviants and attention conditions in older adults reflects a reduction in a continuous process associated with sustained monitoring of target detection and performance. One might further speculate that the behavioral slowing and commission errors in the older group are related to changes in frontal functioning during aging.

Additional frontal and non-frontal brain areas showed age-related differences as well. For attended hemifield targets the older group had a smaller extent of activation bilaterally in the inferior frontal gyrus relative to the young group. There is accumulating evidence for the role of the inferior frontal gyrus in cognitive control. This region is activated when tasks are complex and the demands on attentional resources are high (Derrfuss et al., 2004). There is neuroimaging evidence that both inhibitory processes (Aron et al., 2004; Hopfinger et al., 2001; Langenecker et al., 2004), and the rehearsal system of working memory depends on the inferior frontal cortex (e.g., McDermott et al., 2003). Persson and coworkers (2004) reported less activation in the left inferior frontal gyrus and the anterior cingulate in older compared with young subjects during a verb generation task. Although the latter task was quite different from the present target detection task, both tasks demanded cognitive control that may depend on a network encompassing the anterior cingulate and the inferior frontal gyrus.

The inferior frontal gyrus has extensive reciprocal connections with the anterior cingulate cortex, which in turn projects to subcortical nuclei such as the caudate and the putamen (Tekin and Cummings, 2002). The basal ganglia play a central role in the processing of attentional and preparatory activities, as well as in motor behavior. In line with the results for prefrontal areas, the older participants had less extensive caudate, putamen, and thalamus activations for most task conditions relative to the young adults.

There were also significant age-related differences in hippocampus activation. This structure is part of both memory and executive control networks that are recruited in tasks that demand detection of deviant events (Yoshiura et al., 1999). Moreover, it is a crucial component of the attentional network supporting the involuntary orienting response evoked by novel or highly salient stimuli (Knight, 1996; Bledowski et al., 2004; Yamaguchi et al., 2004). As for the frontal ROIs, and at trend-level for the temporal-parietal junction, there was also a reduction in the extent of hippocampal activation to stimuli in the unattended hemifield for the older group. The finding that older participants were less responsive to unattended novel stimuli is in line with electrophysiological studies showing that older adults have smaller amplitude of the novelty P3 component than young adults and further suggests a reduction in automatic orienting to novelty with advancing age (Knight 1987; Yamaguchi and Knight, 1991; Friedman and Simpson, 1994).

There was also an age-related reduction in the extent of activation to attended targets in the hippocampus. Decreased spatial extent of activation indicates more localized activation in older compared to young adults. Visual inspection of the individual ROIs representing the hippocampus also indicated more clustering of hippocampus activation relative to most other regions in older subjects. In addition to showing prefrontal shrinkage, both cross-sectional and longitudinal studies have shown substantial hippocampal volume reductions, with advancing

age in healthy adults (Raz et al., 2005; Zimmerman et al., 2006; Raz et al., 2007). Although speculative at this point, more localized activation in the older group may be partly driven by neuronal loss and/or decrease in neuronal density in subregions of the hippocampal system (Uylings and de Brabander, 2002; Driscoll et al., 2003; Kril et al., 2004) similar to that proposed for cognitive aging in the cortex.

In addition to the age-related changes described above, the older group generally had less spatially distributed activation in the fusiform gyrus, and in the lateral occipital gyrus to attended targets. This finding concurs with several neuroimaging studies which have reported decreases in the extent of activation in occipital cortex with normal aging (Grady et al., 1994; Madden et al., 2005; Madden et al., 2004). According to Madden et al. (2007), an age-related decline in visual cortex activation is consistent with a reduction in the efficiency of bottom-up processing.

Altogether, the general pattern of results indicates substantial qualitative similarities between the age groups with regard to BOLD signal sensitivity to experimental context. However, quantitative analyses suggest more localized recruitment of systems known to be involved in attention control, motor behavior, and visual sensory processing in older relative to young adults. The age-related reduction in the extent of activation in several brain regions may reflect a general reduction in the resources needed for both voluntary orienting to task-relevant targets, and involuntary shifts of visuo-spatial attention to salient stimuli in the unattended field. However, studies of the effects of aging upon the fMRI derived hemodynamic response, caution against making strong inferences based on spatial extent data because a smaller extent of activation in older adults can be attributed to lower signal-to-noise ratios in activated voxels in older compared to young adults (Huettel et al., 2001; D'Esposito et al., 1999). Our findings argue against interpreting the spatial extent results as primarily reflecting increased voxel-wise noise in the elderly. Firstly, spatial extent of activation varied consistently, and similarly for both age groups, with stimulus category (target vs novel) and the attentional instructions (attend vs ignore). Moreover, the observed interactions of stimulus type and attention set are in agreement with previous electrophysiological and fMRI studies using the oddball paradigm. Secondly, spatial extent of activation correlated with behavioral task performance and added valuable information on the functional meaning of the brain activation effects. Interestingly, in the older group there were significant relationships between task performance and activations in frontal regions that showed significant spatial extent differences between young and older adults.

We found that increasing spatial extent of activation was associated with deteriorating performance in both age groups. Hemodynamic responses to novels in the unattended field did not significantly correlate with performance in the young group, but anterior cingulate activation to these stimuli was significantly associated with number of false alarms and target reaction time in the older group. The direction of the correlations indicates that individuals with more distributed responses in anterior cingulate committed more false alarms and had prolonged response speed. Moreover, older subjects with more extensive anterior cingulate and superior frontal gyrus activation to attended field targets had lower target detection accuracy. The finding that the pattern of anterior cingulate activation to both attended and unattended events correlates with task performance fits well with the role of this region in attention control, response selection, and task monitoring (Bush et al., 1998).

Studies have shown that the magnitude and spatial extent of brain activation increases with cognitive effort (Grady et al., 1994; Raichle et al., 1994) and our results on the age-independent effects of stimulus context and instruction also indicate that voluntary (effortful) or involuntary allocation of attentional resources influences activation extent. Older subjects who had an increased spatial extent of activation to irrelevant novels in the unattended field, and targets in

the attended field, tended to have poorer performance. It may be that increasing extent of activation in frontal regions reflects that the task was more demanding for those older adults and that increased effort played a compensatory role. The results for both older and younger adults, however, suggest that increased attentional effort or recruitment of neural resources, is not necessarily sufficient, or even advantageous for performance (Otten and Rugg, 2001). In support of this inverse relationship, in the young group, increasing spatial extent of activation to attended targets in the fusiform gyrus, lateral occipital cortex/thalamus, and hippocampus correlated with diminishing hit rate, increasing false alarm rate, and increasing target reaction time, respectively.

The results reveal notable age-related differences in what regions of the brain were associated with task performance. The young group recruited posterior brain regions such as visual processing areas, thalamus and hippocampus for performance. In contrast, the older group engaged components of a frontal circuit. The results concur with those reported by Madden et al. (2007) in an fMRI study of visual search. When the task required executive control, performance was associated with fronto-parietal activation for older adults, but with occipital (fusiform) activation for young adults. At the anatomical level, the results from the present study suggest an age-related shift in the regional recruitment of brain areas along the anterior-posterior axis during task performance, progressing in the posterior-frontal direction with age (Davis et al., 2008; Grady, 1998). At the cognitive level, the findings may indicate an age-related shift along the continuum from relatively automatic to more controlled processing, as has also been suggested by others (Heuninckx et al., 2005).

The sample sizes of the present study, as well as the correlative nature of the analyses, suggests some caution in generalizing the interpretation of the results. However, the findings from the within-group analyses of brain-behavior relationships provide valuable information on the functional significance of age-related changes in brain activation. Moreover, the findings are in agreement with other studies reporting associations between performance and electrophysiological indices of change in frontal function with advancing age.

ERP studies report age-related changes in the scalp distribution of P3s evoked by targets in the oddball task, and relate these changes to task performance. Fabiani and Friedman (1995) reported that elderly adults who showed a frontal-maximal P3 scalp distribution during target detection had lower performance on neuropsychological tests of executive function than those who showed the posterior-maximal scalp topography typically seen in young adults. In addition, a study by Tays and colleagues showed that despite high accuracy in both young and older groups, their ERP responses to targets and distracters in a working memory task were markedly different. Older adults did not show an early target-selective P3a response and failed to generate a medial frontal negativity (MFN) to distracting stimuli. In contrast, older adults showed a large frontal positivity to distracters that did not serve a compensatory role as it was associated with poorer task performance (Tays et al., 2008). The ERP findings represent an electrophysiological parallel to our finding that increasing extent of anterior BOLD activation relates to declining performance in older adults.

Most fMRI studies have focused on the amplitude/intensity of hemodynamic responses, but in fact, both the amplitude as well as the spatial extent of BOLD activation can be indicative of brain activations underlying fluctuations in task performance and attention. In this study, we examined spatial extent of event-related BOLD activation and found its correlation with task performance. Our results suggest that the spatial extent of activation is a valuable approach to the analysis of fMRI data in the elderly. This is also supported by the study of Voyvodic (2006) who tests the stability of fMRI activation maps across time and scanning conditions when subjects performed a simple motor behavioral task. He reported that absolute peak activation values within ROIs were variable, whereas the relative spatial distribution of task-

dependent BOLD activity remained stable both within and across scans. Together, these findings suggest that the spatial extent of activation may be a more robust and reliable measure of brain activation than activation amplitude. Testing for spatial extent activations may be particularly useful when studying groups that show increased trial to trial fluctuations in attention and performance.

In summary, young and older healthy adults exhibited fundamental similarities in several qualitative aspects of the BOLD signal and behavioral responses to the bi-field selective attention task. Target and novel stimuli evoked widespread neural networks activation in both age groups, and activation was similarly modulated in both groups by attentional condition. However, a reduction in older subjects in the spatial distribution of activation in frontal, basal ganglia and visual processing areas, indicate age-related changes in cognitive control as well as in sensory-perceptual and motor-related processes. Examination of performance-activation relationships suggests that dynamic modulation of anterior hemodynamic responses is key to optimal performance in older adults. The findings further highlight the importance of taking cognitive performance data into account when making inferences regarding the significance of group differences in patterns of brain activation.

4. Experimental Procedure

Participants

A group of 13 healthy older volunteers (6 male, 7 female) 59–70 years of age (mean age = 65.7 ± 3.8 ; mean education = 17.0 ± 2.4) participated in this study. Participants had a minimum score of 28 on the Mini-Mental Status Examination (Folstein et al., 1975).

A comparison group of 12 healthy young students (6 male, 6 female) in the age-range 19–25 years (mean age = 22.5 ± 1.7 ; mean education = 15.0 ± 1.3) was recruited. Results of the between-group comparisons of demographic data are presented in Table 1. The older group had significantly higher education than the young group ($F(1,23) = 6.4$, $p < .019$).

A questionnaire was used to screen the participant's general health. Criteria for exclusion in both groups were: a) history of head trauma or neurological/cerebrovascular disease, b) history of psychiatric disturbance, and c) high blood pressure. Participants were not taking medications known to influence cerebral blood flow or cognitive functioning. Structural MRI images revealed no signs of pathology in the aged cohort. All participants were right-handed and reported normal acuity or vision corrected by optical lenses.

The study was performed in accordance with the principles stated in the Declaration of Helsinki. Subjects gave written informed consent prior to participating in the study. The experimental procedures were approved by the Human Subjects Institutional Review Board (IRB) of the University of California, Berkeley.

fMRI paradigm – Novelty oddball task

The visual stimulus material was designed and delivered using Presentation Software (<http://nbs.neuro-bs.com>). The stimuli were presented on a liquid crystal display projector and back-projected onto a translucent Plexiglas screen mounted on the scanner head RF coil. The screen was positioned at a distance of 50 cm from the angled mirror in the head coil. BOLD responses to attended and unattended stimuli were recorded while the participants performed a bi-field visual selective attention paradigm (Fig. 1). The stimuli were divided into three classes, high probability (82 %) standard stimuli, and low-probability target (9 %) and novel stimuli (9 %). Standard and target stimuli were triangles ($7.3^\circ \times 5.3^\circ$), and the target triangle was tilted 10° clockwise relative to the upright standard triangle. Novel stimuli were 72 different colored images ($7.3^\circ \times 5.3^\circ$) such as pictures of animals, buildings, or landscapes,

which were selected in a random fashion from a picture database (Suwazono et al., 2000). Pictures with affective content were not included. All stimuli were presented in pseudo-random order in either the right or left visual field with an eccentricity of 7.5° to the center of the screen. Participants were asked to keep their eyes fixated on a centrally presented diamond ($0.5^\circ \times 0.5^\circ$) throughout the experiment, and to covertly (without moving the eyes) direct the focus of attention to stimuli occurring in the designated visual field, while ignoring all stimuli in the opposite field. The brighter side of the diamond signaled the visual field to be attended. Stimulus duration and inter-stimulus interval (ISI) for standard/target and novel stimuli were 150 ms (517 ms ISI), and 200 ms (467 ms ISI), respectively. The longer stimulus duration for novel stimuli was adopted so that the peripherally presented complex novel stimuli would be more likely to capture attention. These short presentation times and ISIs prevented participants from making saccades to stimuli in the to-be-ignored visual field.

The direction of attention alternated every 36 s between the right and left visual field. Each attentional instruction repeated alternatively 3 times in one experimental session, for the total of 3 sessions per experiment. We obtained a total of 72 event-related responses to target and novel stimuli, respectively. The number of events required to yield stable activation maps for event-related studies based on the spatial extent of activation has been determined to be approximately 25 (Murphy and Garavan, 2005). Each event class occurred with varied ISIs of 4 ~ 26 s, which was suitable for event-related fMRI analysis.

The participants were instructed to press a response button with their right-hand index finger as fast as possible when detecting a target in the attended visual field. They were instructed to ignore stimuli in the opposite field.

Before entering the scanner the participants underwent a training session consisting of only target and standard stimuli. They were not informed that novel pictures would be included in the actual experiment. The importance of maintaining a central fixation throughout the session was stressed. The fast rate of stimulus delivery forced the participants to sustain selective attention to the designated visual field.

MRI data acquisition

Images were acquired with a 4 Tesla Varian INOVA MR scanner (<http://www.varianinc.com>) and a TEM-send and receive RF head coil (<http://www.mrinstruments.com>). Functional images were obtained using a two-shot gradient-echo echo-planar (EPI) sequence with a repetition time (TR) of 1 s per half of k -space (echo time of 28 ms, and flip angle of 20°). Each volume consisted of eighteen 5 mm axial slices with a 0.5 mm interslice gap, and provided near full-brain coverage. Each slice was acquired with a 22.4 cm^2 field of view with a 64×64 matrix size, giving an in-plane resolution of 3.5×3.5 mm. High-resolution (0.875×0.875 mm) gradient-echo multislice (GEMS) T1-weighted anatomical images were also acquired and regions of interest (ROIs) were subsequently drawn on these images. In addition, high-resolution magnetization prepared fast low-angle shot three-dimensional (MPFLASH 3D) T1-weighted scans were obtained to aid the identification of anatomical ROIs. Foam padding was used to limit head movements.

MRI data analyses

Pre-processing of functional data—The functional images were subjected to temporal alignment, using sinc-interpolation, to correct the slice-timing skew within a TR. Image volumes were then corrected for movement using a six-parameter automated algorithm. Neither additional spatial smoothing nor normalization of the data was performed (see also Madden et al., 2004; Madden et al., 2007).

A canonical hemodynamic response function (HRF) was employed to model task-related activity. fMRI BOLD signal changes evoked by each stimulus category (target, novel, and standard) were modeled by means of covariates composed of HRF estimates, and the results were entered into the modified general linear model (Worsley and Friston, 1995) for analysis using VoxBo (<http://www.voxbo.org>). Contrasts of parameter estimates across sessions comparing novel versus standard stimuli and target versus standard stimuli, separately for attended and unattended conditions, were calculated in a voxel-wise manner for each participant. Further analysis of BOLD signal changes were conducted using custom-developed MATLAB (Mathworks, Natick, MA) scripts.

Region of interest analysis—The analysis was restricted to a priori defined anatomical ROIs. The following regions were selected based on their known participation in attention networks commonly activated by oddball tasks. A total of 13 ROIs were subdivided into three main categories: 1) frontal regions included superior, middle, and inferior frontal gyri, motor cortex, and anterior cingulate cortex; 2) posterior regions included hippocampus, temporal-parietal junction, superior parietal lobule, fusiform gyrus, and lateral occipital gyrus; and 3) deep gray matter regions included caudate, putamen and thalamus. The ROIs were drawn manually on the structural T1-weighted images of each subject's brain, for each hemisphere, and on all slices determined to encompass the critical region. The regions were identified by comparison to a brain atlas (Duvernoy, 1991), the template brain provided by MRICro (<http://www.sph.sc.edu/comd/rorden/mricro.html>) combined with a display of the high-resolution MPFLASH three-dimensional T1-weighted images. All ROIs were drawn by the first author. The ROIs were then evaluated by a neurologist (R.T. K.) with MRI neuroanatomical experience and adjusted if needed. Illustrations of the traced ROIs are presented in Figure 2–Figure 7.

Analysis of BOLD signal changes within each participant's ROIs was conducted using custom-developed MATLAB scripts.

Post-processing of functional data

Spatial extent of event-related activation: For each ROI, stimulus type (target and novel), hemisphere (left and right), and condition (attended and unattended hemifield), the percentage of voxels, out of total number of voxels in the ROI, which had exceeded a *t*-value of 2.0 (e.g., Voyvodic, 2006) was computed and used as a measure for spatial extent of activation.

In another analysis, we calculated the mean of the *t*-values for the 10 % voxels in each ROI that yielded the highest *t*-values, without setting a *t*-value cutoff. The latter analysis yielded results that broadly concurred with the results obtained when analyzing the percentage of suprathreshold voxels. Only results using the latter approach are presented.

Statistical analysis—SPSS 11.0 for Windows (SPSS Inc.) was used for all statistical analyses. Testing of group differences in demographic variables (sex and education) and performance scores (hit rate, false alarm rate, and reaction time) were calculated using simple factorial analysis of variance (ANOVA) with group as between-subjects factor. Comparison of ROI sizes for the two age groups was performed with *t*-test.

Repeated-measures ANOVA for mixed designs was used to test for condition and group differences in hemodynamic responses. For each ROI, the ANOVAs for BOLD responses (the percentage of voxels exceeding the specified *t*-value threshold) were defined by three repeated measure factors, attention condition (attended versus unattended hemifield), stimulus type (target versus novel), and ROI laterality (right versus left hemisphere) and one between-subjects factor (young group versus older group). Significant interaction effects were decomposed using additional ANOVAs.

Pearson product-moment correlation coefficients were used to test the within-group relationships between performance scores and hemodynamic responses. Alpha for all statistical analyses was set to .05.

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Figure 1. Stimulus paradigm in a bi-field selective attention experiment

Figure 2. Attended hemifield hemodynamic responses for anterior ROIs

Spatial extent of hemodynamic responses for anterior ROIs are displayed as a function of age group, stimulus type, and hemisphere for the attended hemifield. For each ROI, an example is shown of one representative T1-weighted slice, but the data were averaged across all slices within an ROI. ROI = region of interest; SFG = superior frontal gyrus; MFG = middle frontal gyrus; IFG = inferior frontal gyrus; ACC = anterior cingulate cortex; Motor = motor cortex.

Figure 3. Unattended hemifield hemodynamic responses for anterior ROIs

Spatial extent of hemodynamic responses for anterior ROIs are displayed as a function of age group, stimulus type, and hemisphere for the unattended hemifield. An example of each ROI is displayed. ROI = region of interest; SFG = superior frontal gyrus; MFG = middle frontal gyrus; IFG = inferior frontal gyrus; ACC = anterior cingulate cortex; Motor = motor cortex.

Figure 4. Attended hemifield hemodynamic responses for posterior ROIs

Spatial extent of hemodynamic responses for posterior ROIs are shown as a function of age group, stimulus type, and hemisphere for the attended hemifield. An example of each ROI is shown. ROI = region of interest; HIP = hippocampus; TPJ = temporal-parietal junction; SPL = superior parietal lobule; FFG = fusiform gyrus; LOG = lateral occipital gyrus.

Figure 5. Unattended hemifield hemodynamic responses for posterior ROIs

Spatial extent of hemodynamic responses for posterior ROIs are shown as a function of age group, stimulus type, and hemisphere for the unattended hemifield. An example of each ROI is displayed. ROI = region of interest; HIP = hippocampus; TPJ = temporal-parietal junction; SPL = superior parietal lobule; FFG = fusiform gyrus; LOG = lateral occipital gyrus.

Figure 6. Attended hemifield hemodynamic responses for deep gray matter ROIs

Spatial extent of hemodynamic responses for posterior ROIs are shown as a function of age group, stimulus type, and hemisphere for the attended hemifield. An example of each ROI is displayed. ROI = region of interest; CAU = caudate; PUT = putamen; THA = thalamus.

Unattended hemifield

Spatial extent (% voxels)

Hemisphere

Figure 7. Unattended hemifield hemodynamic responses for deep gray matter ROIs

Spatial extent of hemodynamic responses for posterior ROIs are shown as a function of age group, stimulus type, and hemisphere for the unattended hemifield. An example of each ROI is shown. ROI = region of interest; CAU = caudate; PUT = putamen; THA = thalamus.

Table 1

Demographic and behavioral data for the young and the older group.

	Young group	Older group	ANOVA/Chi square
Education (years)	15.0 (1.3)	17.0 (2.4)	*
Sex	6 M/6 F	6 M/7 F	ns
RT targets (ms)	622 (41)	695 (76)	*
Hits targets (%)	98.8 (2.4)	97.4 (4.3)	ns
False alarms (no.)	0.5 (0.5)	2.1 (2.5)	**

Values are means (SD) per whole session. M = males; F = females; no. = number; ANOVA = analysis of variance; ns = non-significant;

*
< .05

**
< .001

Table 2

Size of region of interest.

	Young group	Older group	t-test
Frontal			
Superior frontal gyrus	888 (124)	885 (114)	ns
Middle frontal gyrus	1303 (226)	1116 (179)	*
Inferior frontal gyrus	352 (67)	370 (101)	ns
Anterior cingulate cortex	209 (46)	183 (29)	ns
Motor cortex	295 (112)	297 (40)	ns
Posterior			
Hippocampus	185 (44)	176 (20)	ns
Temporal-parietal junction	779 (86)	745 (127)	ns
Superior parietal lobule	253 (107)	208 (67)	ns
Fusiform gyrus	220 (39)	185 (27)	*
Lateral occipital gyrus	365 (100)	374 (58)	ns
Deep gray matter			
Caudate	67 (8)	59 (10)	*
Putamen	66 (10)	60 (10)	ns
Thalamus	139 (32)	110 (24)	*

Values are mean number (SD) of voxels averaged over all participants within each age group; ns = non-significant;

*
p < .05

Table 3

Brain – behavior correlation result

Variable	Hits	RT	FA	Older group			
Young group							
Extent of activation to attended targets							
ACC	-.01	.29	.40	-.65	.34		-.24
SFG	-.26	.49	.35	-.81	.38		-.17
MFG	-.14	.45	.44	-.32	.17		.29
IFG	-.08	.49	.46	-.30	.03		-.24
MOT	.10	.40	.53	.10	-.02		.46
CAU	-.08	.21	.25	-.47	.54		.44
PUT	.01	.33	.12	-.06	.03		.24
THA	-.01	.06	.62	-.35	.24		-.27
HIP	-.30	.58	-.01	.06	-.01		-.01
TPJ	-.10	.41	.46	-.02	.04		-.01
SPL	.12	.42	.53	.04	-.31		.12
FFG	-.65	.48	.04	.12	-.05		-.22
LOG	.12	.34	.76	-.01	.19		-.11
Extent of activation to unattended novels							
ACC	.24	.01	.46	.05	.58		.66
SFG	-.02	.29	.21	.06	.44		.23
MFG	-.10	.13	.32	.04	.44		.45
IFG	-.20	.37	.45	-.19	.53		.39
MOT	-.21	.21	.36	-.16	.31		.45
CAU	-.08	.46	.06	.16	.35		.36
PUT	.15	-.12	.36	-.10	.10		.04
THA	-.16	.30	-.04	.11	.37		.31
HIP	-.26	.56	.01	-.01	.14		.32
TPJ	.04	.08	.31	.06	.31		.39
SPL	.08	.29	.05	.09	-.03		-.20
FFG	-.18	.18	.15	.10	.39		.45
LOG	.10	-.13	.10	.03	.44		.51

Variable	Hits	RT	FA	Hits	RT	FA
Reaction time, hits and false alarms were averaged over all experimental runs. Pearson correlation coefficients were computed for each age group. Statistically significant ($p < .05$) correlations are highlighted. Hits = hit rate; RT = reaction time; FA = false alarm rate. SFG = superior frontal gyrus; MOT = motor cortex; ACC = anterior cingulate cortex; IFG = inferior frontal gyrus; FFG = fusiform gyrus; TPJ = temporal-parietal junction; HIP = hippocampus; LOG = lateral occipital gyrus; CAU = caudate.						